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Fish Health and Fisheries, Implications for Stock Assessment and Management: The Mediterranean Example

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Although fish health may influence key population-level processes, particularly those dealing with natural mortality, reproduction, and growth, which, in turn, affect stock productivity, little emphasis has been placed on the links between fish health and the management of marine fisheries. This article addresses this gap and illustrates how knowledge of fish health could provide insight for marine fisheries biologists, stock assessment modelers, and managers. The study proposes ways in which the consideration of condition indicators (energy reserves) and parasitism improves stock assessment and fisheries management, especially in situations of data shortage when standard methods cannot be applied, as is the case in many Mediterranean fish stocks. This article focuses on seven case studies of different fish species from the Mediterranean and Black Seas. Overall, and although the relationship between fish health and productivity cannot always be found or quantified, the article emphasizes the importance of the physical health of exploited stocks, particularly during critical life periods of the fish (e.g., prior to spawning, migration, or in the early life stages), as an essential element of sustainable and profitable fisheries. On the basis of these results, stock assessment and fisheries management implications are discussed.

Keywords fish condition, lipids, parasites, reproduction, stock assessment

INTRODUCTION

Population and individual parameters, such as stock abundance, biomass, growth, mortality, maturity, and recruitment, reflect the productivity of fish stocks and are necessary for eval-

uating the status of an exploited fish population. Knowledge of these parameters is increasingly recognized as an important criterion for effective management and conservation (reviewed by Young et al., 2006). Impaired health status has been suggested as one possible cause of the decline in catch and population biomass of several marine and freshwater fish populations, including cod (*Gadus morhua*) off Newfoundland (Lambert and Dutil, 1997), brown trout (*Salmo trutta*) (Zimmerli et al., 2007),

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and bluefin tuna (*Thunnus thynnus*) (Golet et al., 2007). In particular, condition (energy reserves) is an important indicator of the health of fish because it may have important consequences for their life history traits and, finally, for stock productivity and fishery yields (Shulman and Love, 1999; Marshall et al., 1999). For example, body condition factors for cod in the northern Gulf of St. Lawrence (Canada) declined throughout the early 1990s, leading to an increase in natural mortality, particularly for adults that had to invest energy reserves in reproduction, and it possibly contributed, beside a high fishing mortality, to the drastic decline of this stock (Lambert and Dutil, 1997, 2000; Dutil and Lambert, 2000). Similarly, cod and other groundfish species in the eastern Scotian Shelf and in the Sydney Bight (Canada) exhibited poor condition and growth during the same period, coinciding with their lowest abundance on record and poor recruitment (Fisheries and Oceans Canada, 2005). Also, significant declines in the somatic condition of northern bluefin tuna in the Gulf of Maine might have had unexpected and detrimental consequences for the rebuilding of stock (Golet et al., 2007). Furthermore, adult energetic condition at the end of the main feeding period correlates significantly with the variation in catches of sardines (*Sardina pilchardus*) on the Portuguese coasts one year later (Rosa et al., 2010). Despite the fact that in all these cases the changes in fishing yields and health status of individuals seem to be correlated, in some species, density-dependent effects have been found, but only at high population density. For example, the observed decline in lake whitefish (*Coregonus clupeaformis*) growth and condition in many Great Lakes populations (Canada) has been attributed in part to the increased abundance of these populations (Rennie et al., 2009). In general, the temporal and spatial variability of fish condition has been attributed to several factors, such as food availability, environmental factors, and fishing pressure (see, e.g., Lloret and Planes, 2003, 2005; Golet et al., 2007; Hidalgo et al., 2008; Lambert and Dutil, 2000; Giacalone et al., 2010; Rosa et al., 2010; Orlova et al., 2010).

Although the assessment of fish health is playing an increasing role in fisheries management and environmental monitoring policy in freshwater ecosystems (see, e.g., Goede and Barton, 1990; Sutton et al., 2000; Ebener and Arts, 2007; Brenden et al., 2010), the monitoring of fish health indicators in marine ecosystems is scarce, and the use of these indicators in stock assessment and management is practically non-existent. Typically, stock assessment and fisheries management of marine species have focused on specific individual and population parameters (e.g., growth and natural mortality), with no integration of fish health information. In particular, the relationship between health status and natural fish mortality (M) is relevant because M is one of the most influential parameters in fisheries stock assessment and management (Scientific, Technical and Economic Committee for Fisheries [STECF], 2009; National Marine Fisheries Service [NMFS], 2011). Estimates of natural mortality relate directly to the productivity of stock yields, sustainable exploitation rates, management quantities, and reference points. Unfortunately, in many oceans around the

world, fish health is not regularly monitored, and the links between population dynamics and fish health have been largely overlooked.

The aim of this article is to review and explore the potential implications of fish health for fisheries management. Hence, using “gray” literature (e.g., posters and oral communications presented in congresses), data, expert knowledge, and published papers, several examples and case studies in which fish health could be considered in stock assessment and management contexts are analyzed and reviewed. The focus is on seven case studies, spanning from economically valuable demersal and pelagic fish stocks to bycatch species from the Mediterranean and Black Seas: European eel (*Anguilla anguilla*), European anchovy (*Engraulis encrasicolus*), greater amberjack (*Seriola durmerili*), European hake (*Merluccius merluccius*), bluemouth (*Helicolenus dactylopterus dactylopterus*), lesser-spotted catshark (*Scyliorhinus canicula*), and ocean sunfish (*Mola mola*). Results are supported with literature from other Mediterranean and non-Mediterranean stocks. Also identified are the most suitable variables for describing fish health from a fish stock assessment and management perspective, and the importance of fish health monitoring in stocks is highlighted, where data availability prevents the carrying out of standard stock analysis (e.g., with Virtual Population Analysis [VPA] or Extended Survivor Analysis [XSA]), as is the case with a number of stocks in the Mediterranean Sea.

INDICATORS OF FISH HEALTH FROM A FISHERIES MANAGEMENT PERSPECTIVE

Fish health can be assessed by a variety of indicators, ranging from basic measurements of energy reserves using simple morphometric and organosomatic (biometrical) indices, such as condition factor and hepatosomatic index, to more complex biochemical measurements, such as proximate composition (protein, lipids, etc.), or via the evaluation of infectious diseases (parasitic, viral, fungal, or bacterial infections), physical damage, blood parameters, histopathological analysis, and RNA/DNA ratio (see, e.g., Handy et al., 2002; Woo, 2006; Leatherland and Woo, 2010; Woo and Bruno, 2011; Woo and Buchmann, 2012). Each of these measurements of health status has its own set of advantages and limitations, depending on the objectives of the particular study. In some cases, samples have to be processed and analyzed in the laboratory, which requires varying degrees of time, specialized training, instrumentation, and expense, as in the case of biochemical and pathological analyses. On the other hand, the determination of condition indices may involve only simple length and weight measurements. This article deals with fish condition (i.e., energy reserves) and the analysis of macroparasites because these are the two indices that can be most easily and accurately estimated at sea and that seem to have greater impact on the productivity of marine stocks (see, e.g., Shulman and Love, 1999; Marcogliese, 2004; Iwanowicz, 2011).

Condition (Energy Reserves)

Measuring the amount of stored energy through condition and organosomatic indices or through biochemical analyses have been the most commonly used methods of assessing the health of both individual fish specimens and fish populations. Morphometric indices, which assume that heavier fish of a given length are in better condition, are the simplest indicators of energy storage in many fish species (see, e.g., Blackwell et al., 2000; Cone, 1989; Bolger and Connolly, 1989). They are constructed with simple weight and length data that can easily be obtained from surveys or commercial landings using minimum and affordable equipment (i.e., ichthyometer and scale). Their use, however, is sometimes controversial. Blackwell et al. (2000) provided a review of the history of condition factors, together with the controversies surrounding their analysis and interpretation. As many benthic and demersal fish store their main energy reserves in the liver or in the mesentery, a liver (hepatosomatic) or a mesenteric fat index can be also used to roughly estimate fish condition when a large number of samples are available (Adams, 1999; Shulman and Love, 1999). Ideally, any study using morphometric, liver, or mesenteric fat indices should validate them against a suitable benchmark, e.g., a biochemical index (McPherson et al., 2011; Davidson and Marshall, 2010). Biochemical indices are by far the best indicators of fish condition. In this context, the determination of lipid content is the most appropriate biochemical parameter to evaluate fish energy reserves (Shulman, 1974; Shulman and Love, 1999; Adams, 1999). Lipids are used for functional activity (i.e., the rate and intensity of physiological processes) and as main energy stores in teleosts, and they are the first energy reserves to be catabolized during non-feeding and reproductive periods (Adams, 1999; Shulman and Love, 1999). Lipids are also known to play a role as regulators of body density, cellular metabolism, detoxification, and behavior (Shulman and Love, 1999; Adams, 1999). Low energy reserves may lower the chances of fish survival, leading to an increase of natural mortality (Sogard and Olla, 2000; Griffith and Kirkwood, 1995; Hutchings et al., 1999). Starvation due to exhaustion of energy reserves, particularly during non-feeding and reproductive periods, weakens fish and also renders them more susceptible to predation, diseases, and a variety of environmental stressors (Shulman and Love, 1999). Inadequate reserves (particularly during the pre-spawning phase) have been associated with lower growth rate (Rätz and Lloret, 2003) and reproductive potential through reduced fecundity and quality of eggs and larvae or delayed maturation (Marshall et al., 1999; Lambert et al., 2003; Koops et al., 2004).

Parasites

Fish serve as hosts to a range of parasites that are taxonomically diverse and that exhibit a wide variety of lifecycle strategies (Barber et al., 2000). Parasites are increasingly rec-

ognized as a good measurement of fish health since they affect the biology, survival, and population structures of host species (Sindermann, 1987; Marcogliese, 2004). Parasites can reduce growth, fecundity, and survival and change behavior and sexual characteristics of the infected host. These changes can have significant consequences, not only on the individual fish level, but on population, community, and ecosystem levels as well (Barber et al., 2000; Marcogliese, 2002; Iwanowicz, 2011). The host-parasite relationship is often unbalanced, and parasites can severely compromise the health of their hosts and even kill them (Jones et al., 2005). Most of the studies showing the effects of parasites on wild fish populations have been carried out in freshwater ecosystems. Parasitism can have a significant impact on the condition of freshwater fish populations, either directly through mortality or indirectly through a decline in recruitment success, alteration in host behavior, reduction in swimming speeds, and increased risk of predation or decline in growth (see, e.g., Neff and Cargnelli, 2004; Longshaw et al., 2010; Heins and Baker, 2011; Ferguson et al., 2011). For example, the larvae of the cestode *Schistocephalus solidus* are able to kill young-of-the-year three-spined sticklebacks (*Gasterosteus aculeatus*) in heavily infected individuals (Heins and Baker, 2011). Similarly, heavy loads of different parasites can affect coho salmon (*Oncorhynchus kisutch*), impacting its growth, immune system, adaptation to saltwater, swimming stamina, activity level, and ability to migrate (Ferguson et al., 2011). In marine ecosystems, most severe fish parasitic infections have been reported in aquaculture, normally related to artificial culture conditions, where fish densities are abnormally high (Rohde and Littlewood, 2005). Some of these farm-origin parasites spread and affect the survival of wild fish populations. Thus, for example, the rise of salmon farming has coincided with the emergence of parasite infestations of sympatric wild juvenile salmonids (Krkosek et al., 2006). Both anthropogenic and environmental factors can alter the host-parasite equilibrium and cause disease or mortality in fish (Iwanowicz, 2011). Fishing can affect the fitness and life history of host populations with cascading effects on parasite impact. Thus, for example, the hepatosomatic index of *Lithognathus mormyrus* in heavily exploited Mediterranean stock was severely impacted by the mouth-dwelling, blood-feeding isopod parasite *Ceratothoa italica*, whereas this parasite showed negligible virulence in stock of the same fish species subjected to lower harvesting pressure (Sala-Bozano et al., 2012). The effects of parasites on wild marine fish populations are often underestimated, and the relationship between parasitism, condition, reproduction, and natural mortality of marine exploited species remains largely unknown, particularly in the Mediterranean Sea. As a consequence, parasites are often overlooked in fish health assessments. Simple measurements of parasite infection include prevalence (the percentage of individuals of a particular host species infected by a particular parasite species), intensity (the number of individuals of a particular parasite species in a single infected host), and abundance (the total number of individuals of a particular parasite species in a sample of a particular host species divided by the total

number of individuals of the host species examined; Bush et al., 1997).

CASE STUDIES

European Eel (Anguilla anguilla)

An example of such a host–parasite relationship is the European eel *Anguilla anguilla* and its invasive nematode *Anguillicoloides crassus*. The European eel is an amphidromous species that has been exploited for centuries in the Mediterranean region, where it has been estimated that about 25,000 people were living from its exploitation in 2000 (Dekker, 2003; Stone, 2003). The Mediterranean eel population has declined sharply since the 1980s, and annual catches have decreased from 4,000 to 5,000 tons in the early 1980s to less than 1,000 tons in the late 2000s (FAO, 2008). Among several reasons for this decline (e.g., fisheries, pollution, development of estuaries, and shorelines; reviewed by Farrugio, 2010), the introduction of *Anguillicoloides crassus* in Europe in the early 1980s is a major one. This parasite has been extensively studied because of the potential effects on the eel and its migration toward the putative spawning grounds (reviewed by Kirk, 2003 and Kennedy, 2007). This nematode is a hematophagous complex lifecycle parasite that lives as an adult in the swimbladder of eels. The final host gets infected when consuming infected intermediate hosts, either invertebrates, such as copepods, or vertebrates, such as small fish, which are used as paratenic hosts. This parasite is known to damage the swimbladder of the eel and affect their physiology, which can have implications for eel reproduction. Infected eel migration may be impaired, as spawners can have difficulties in crossing the Atlantic Ocean and reaching breeding sites (Kirk, 2003; Kennedy, 2007). Moreover, recent studies have revealed the more subtle effects of *A. crassus* on the European eel, such as the differential expression of genes involved in the physiology of the eel depending on its parasitized status (Fazio et al., 2008). Genes involved in the response to environmental stresses (i.e., metallothionein), osmoregulation (i.e., Na⁺/K⁺ATPase), and silvering processes (i.e., rhodopsin pigments in the eyes) had differential expression depending on whether the eels were infected or not. As all gene expressions were in the same direction, infected eels appeared to migrate earlier by anticipating their silvering process (Fazio et al., 2008).

However, despite all these effects and the peculiar characteristics of this parasite (as an introduced hematophagous species), it remains difficult to demonstrate a negative effect on the morphometric condition index of the infected eel (Barus and Prokes, 1996; Koops and Hartmann, 1989), their hepatosomatic index (Möller et al., 1991), or their cell count or hematocrit (see Boon et al., 1989; Palikova and Navratil, 2001; Kangur et al., 2010). This suggests that naturally infected eels are able to compensate for the costs induced by the parasites. Besides the absence of significant negative effects, some studies have

even found a positive relationship between parasitism and condition factor (Möller et al., 1991; Costa-Dias et al., 2010). This counter-intuitive pattern—with greater condition in highly infected individuals—may be explained by greater food quantity (abundance) in the digestive tract for the parasites, more physical space available, and greater intake of food that may contain infective forms in fish with higher condition (Moreira et al., 2010).

European Anchovy (Engraulis encrasicolus)

The condition of anchovy in the Mediterranean, Azov, and Black Seas has been evaluated using several indicators. Since the different types of prey it consumes are utilized not only for energy reserves but also for protein biosynthesis in larvae, the RNA/DNA ratio has been used as an indicator of condition and food supply of anchovy larvae (Garcia et al., 1998, 2003; Chicharo et al., 2008; Diaz et al., 2008). On the other hand, the estimation of condition and food supply of adult Mediterranean anchovy has been carried out through the analysis of muscle lipid content (Shulman, 1974; Shulman and Love, 1999; Nikolsky et al., 2009) and growth rates (Basilone et al., 2004, 2006).

In particular, the most important indicator of condition and food supply for anchovy in the Azov and Black Seas has been the energy levels stored in the form of neutral lipids that individuals accumulate in their muscles at the end of the autumn feeding period (Shulman, 1974; Shulman and Love, 1999; Nikolsky et al., 2009). The evaluation of anchovy muscle lipid content has several implications for the management of anchovy populations. First, the spatial differences in muscle lipid levels reflect the marked differences in productivity between areas. Compared to Azov and Black Sea anchovy, whose muscle lipid content ranges between 15 and 20% of wet mass, respectively, at the end of the feeding season, Mediterranean anchovy accumulates less than 10% lipid in their muscles (Shulman, 1974; Zlatanov and Laskaridis, 2007). Similarly, Azov and Black Sea anchovy landings are higher than in the Mediterranean; in the Black Sea, landings have fluctuated between 250 and 400 thousand tons during the last 50 years, whereas Mediterranean anchovy landings have fluctuated between 80 and 160 thousand tons (FAO 2008). These differences in lipid content and landings may be explained by the higher food supply (i.e., higher zooplankton biomass productivity) in the Azov and Black Seas compared to the Mediterranean, which is likely to be linked to strong riverine nutrient inputs from the large rivers flowing into the Azov and Black seas (i.e., Danube and Dnieper Rivers in the Black Sea and Don and Kuban Rivers in the Azov Sea; Ludwig et al., 2009).

Second, the evaluation of muscle lipid content in Azov and Black Sea anchovy stocks, along with the analysis of sea temperature, can be used to forecast the start of the winter migration of these populations, which, in turn, has implications for stock availability to fisheries (Shulman, 1974, 2002; Nikolsky et al.,

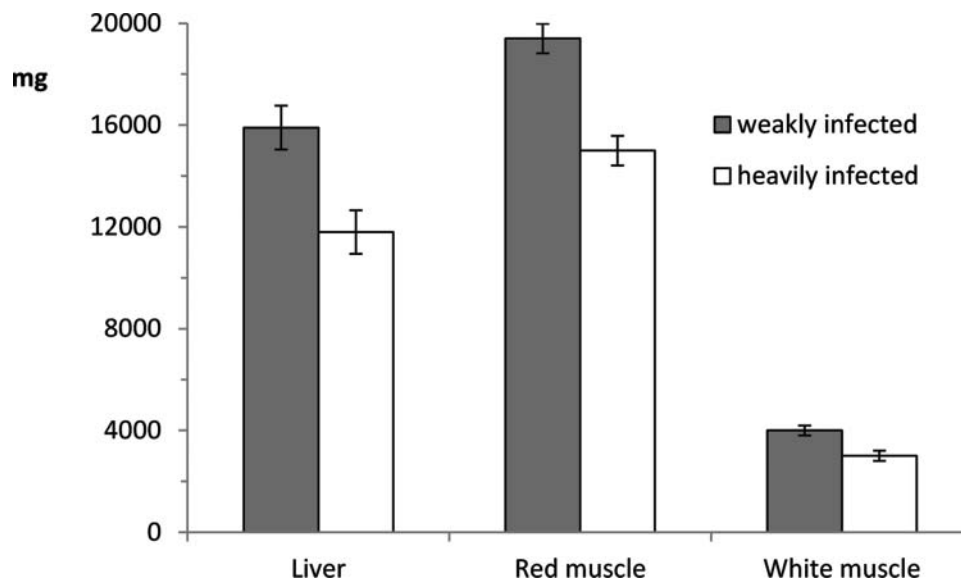


Figure 1 Average lipid content (mg of total lipid in 100 g wet mass) in different tissues of weakly and heavily infected anchovies (*Engraulis encrasicolus*) from the Black Sea in autumn (modified from Shchepkina, 1985).

2009). If anchovy fat levels are high, fish migrate to the south-eastern part of the Black Sea; if they are low, migration is limited to the central-eastern part (Shulman, 1974, 2002). Migration is also affected by the presence of parasites, which affects anchovy lipid content in the Black Sea (Shchepkina 1985), as well as food supply (Shulman, 1974, 2002). In particular, infection by helminthes is an important factor influencing the lipid content of the Black Sea anchovy population. In autumn, individuals with high levels of parasitism present lower levels of lipid content (Figure 1), particularly triglycerides, which reduce the state of readiness of the anchovy for migration and wintering and may, therefore, influence the reproduction of the species (Shchepkina, 1985).

The evaluation of muscle lipid content in anchovy revealed that lipid content can be a valuable indicator of anomalous environmental conditions. Stock abundance and landings of anchovy in the Black Sea increased strongly in the 1970s and approached their highest level in the first half of the 1980s (Black Sea Commission [BSC], 2009). This was mainly caused by a considerable increase in eutrophication, which was a result of the increasing input of river inflow nutrients of terrestrial origin. However, between the late 1980s and early 1990s, anchovy fat levels in the Black Sea decreased, and abundance and landings largely declined (BSC, 2009). This was attributed to the mass invasion of the ctenophore *Mnemiopsis leidyi*, which was introduced through the ballast waters of vessels arriving from the coastal regions of North America. This ctenophore largely undermined the food prey (i.e., mesoplankton biomass) of anchovy and heavily preyed on their larvae (BSC, 2009; Zaitsev and Oztiirk, 2001). From the second half of the 1990s, the abundance and biomass of the Black Sea anchovy stock were progressively restored but without reaching the levels observed in the first half of the 1980s (BSC, 2009; Leonart, 2008).

Greater Amberjack (*Seriola dumerili*)

The amberjacks (*Seriola* spp.) are fish highly valued on the world market. They are often adversely affected by single or mixed monogenean infections (Ogawa and Yokoyama, 1998; Grau et al., 2003; Nielsen et al., 2003; Montero et al., 2004). High intensities of skin or gill parasites have been reported to cause outbreaks of these parasites in cultured amberjacks (see Whittington and Chisholm [2008] for revision). For example, the ciliate skin parasite *Cryptocarium irritans* and the monogenean gill parasite *Zeuxapta seriolae* have been related to severe losses of cultured greater amberjacks (*S. dumerili*) (Montero et al., 2004, 2007). In the case of infections by *Z. seriolae*, the analyses of infected fish revealed that although up to 100% of the fish living in the affected tank died, fish aspects and condition factors were normal and only a decrease of the hematocrit level was found as these monogeneans are blood-feeders (Montero et al., 2004). Interestingly, similar epizootic episodes have also been reported in the wild. Lia et al. (2007) reported fish mortalities of wild greater amberjacks infected by *Z. seriolae* in Italian waters. The only suggestion indicating that the infection of *Z. seriolae* might have killed these fish was high parasite intensities, as usually fish dead in the wild cannot be properly analyzed. Nowadays, however, *Z. seriolae* is highly frequent and abundant in wild Mediterranean greater amberjacks. A recent study of fish captured by commercial boats off the Balearic Islands ($n = 175$) revealed that more than 90% of them were infected by *Z. seriolae*, and many individual specimens harbored more than 500 parasites each, even though they looked like healthy fish (Repullés-Albelda, unpublished data). Apparently, it would seem that direct evidence such as prevalence and intensity are not good indicators of fish health in this case.

Bluemouth (*Helicolenus dactylopterus dactylopterus*)

The bluemouth is a benthic species widely distributed in the Atlantic Ocean and in the Mediterranean Sea, inhabiting depths of between 100 and 1,000 m (Whitehead et al., 1986). Although historically there has been little commercial fishing interest in this species, partially due to its low accessibility, it is now of growing interest as fishing fleets try to find new resources after the depletion of traditional stocks. It is known that the risk of overexploitation for deep-sea species, such as bluemouth, is high, even at relatively low fishing mortality levels, since these species generally have low growth rates, late maturation, and a long life span (Heessen et al., 1996; White et al., 1998; Massutí et al., 2000; Muñoz et al., 2002; Abecasis et al., 2006; Sequeira et al., 2009; Consoli et al., 2010). In particular, the study of *H. dactylopterus* population dynamics is important because the status of this large-size sedentary slow-growing fish can be used as an index of overexploitation of fishing grounds (Pirrer et al., 2009).

The evaluation of the link between health and reproduction of this deep-sea species highlights the complex relationships between these variables. The bluemouth has large hepatic reserves of lipids, which are later transported and stored in the adipocytes of the bones and muscles, where they seem to function as an energy store and a hydrostatic agent (Mendez et al.,

1993). Hepatic reserves are basically used for the synthesis of vitellogenin during the reproductive process, while mesenteric lipid reserves are not mobilized until the end of the maturation process (Muñoz and Casadevall, 2002). Spawning is multiple, and the number of developing oocytes can be estimated as a function of the total length of the fish, its ovary mass, and its gonadosomatic index (Muñoz et al., 2010). The condition indices evaluated for bluemouth (hepatosomatic index, mesentery lipid index, Fulton's condition factor and relative condition index) did not contribute significantly to explaining the observed variations in fecundity at the individual level when all maturity stages are considered together (Muñoz et al., 2010). However, the relative condition of fish had a significant effect on the fecundity at the onset of spawning, when potential fecundity is determined (Figure 2). Apparently the bluemouth shows a mixture of capital and income breeding strategies, where recruitment of oocytes is partially dependent on female size and reserves, while oocyte development, which is a rapid process, is more dependent on concurrently gained energy. Therefore, only final potential fecundity fixed prior to spawning is dependent on the condition of the female at that specific moment, mainly on weight as an expression of female capacity to capture energy (Saborido-Rey et al., 2010). After spawning, which takes place between the end of December and April, a clear recovery of the fish condition begins, even though the hepatosomatic index

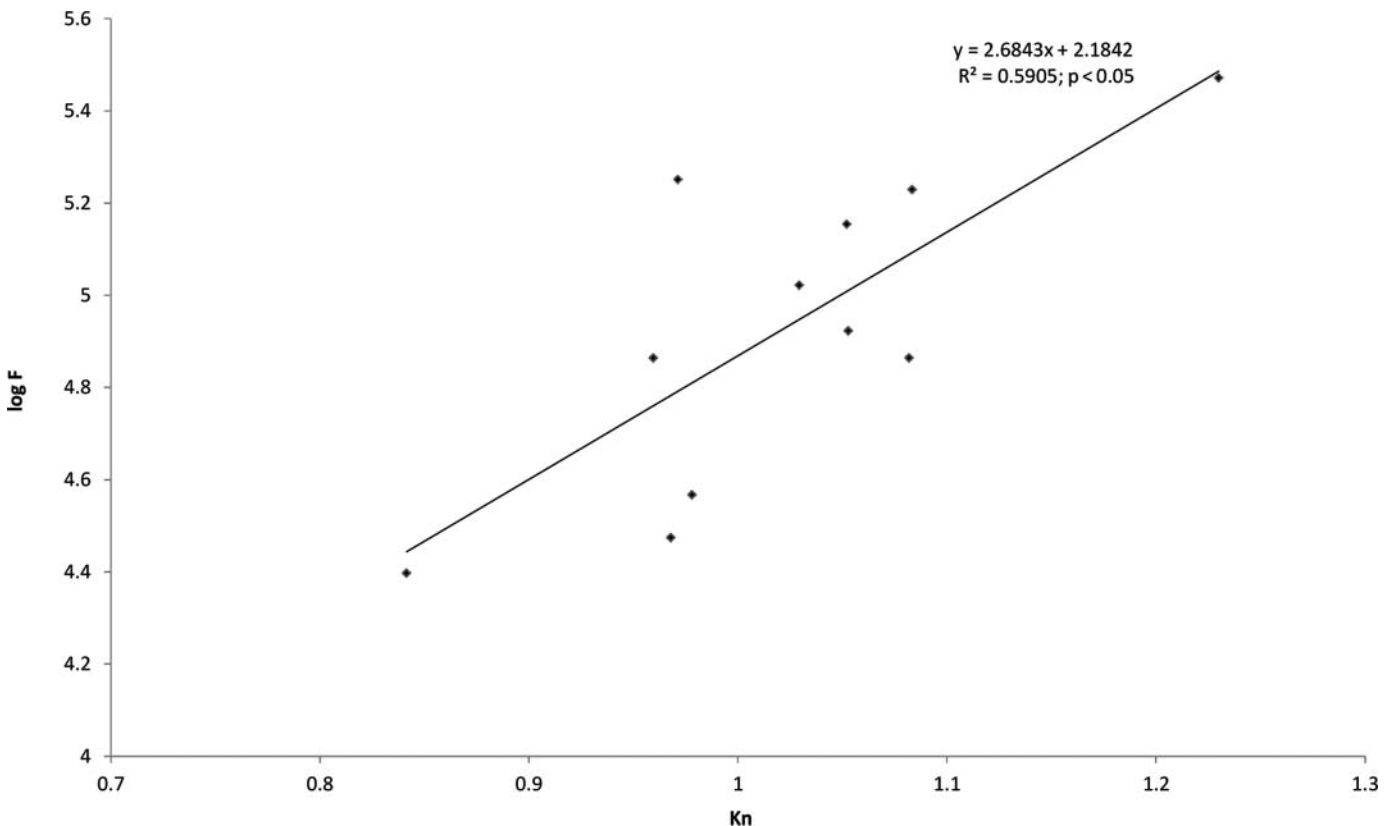


Figure 2 Relationship between the Le Cren relative condition factor (K_n) and fecundity (log transformed) of female bluemouth (*Helicolenus dactylopterus*) prior to spawning in the Gulf of Lions (northwest Mediterranean). The straight line represents the linear regression.

and the mesenteric fat index remain at low levels (Muñoz and Casadevall, 2002).

Small-Spotted Catshark (Scyliorhinus canicula)

The small-spotted catshark is one of the most abundant sharks in trawl fishery catches in the Mediterranean. It has little commercial value, and therefore, it is only retained for human consumption in some areas (it is mostly caught as bycatch and largely discarded). This shark is parasitized by a high number of species. A study on the infection of *S. canicula* by parasites in the Irish Sea showed about ten different species of macroparasites, including *Anisakis simplex* and *Pseudoterranova decipiens* (Anisakidae) in the viscera of this species (Moore, 2001). In the northwest Mediterranean coast, fishermen either discard the captured lesser-spotted dogfish (due to its low commercial value) or eviscerate the specimens on board in order to sell the muscle fillets in the market, disposing of the viscera at sea. McClelland et al. (1990) and Abollo et al. (2001) reported that the lesser-spotted dogfish can eat discarded viscera of their own species, leading to an increase in the prevalence of *Anisakis* in that species. Furthermore, other fish species could feed on these viscera, thus increasing their parasite loads as well.

A total of 128 small-spotted catshark individuals ranging between 383 and 512 mm in total length (36 females ranging from 383 to 456 mm and 92 males from 394 to 512 mm) were caught in the northwest Mediterranean shelf between December 2007 and February 2008 (Casadevall et al., 2010). Almost all individuals contained the parasite *Proleptus obtusus* (Figure 3) in the stomach (97.7% prevalence). Parasites were always adults, and some of them ovigerous females. Also one *A. simplex* was found in one individual of *S. canicula*. The number of parasites per stomach ranged between 0 and 177.

Furthermore, the Le Cren relative condition and the hepatoso-



Figure 3 Dissected small-spotted catshark (*Scyliorhinus canicula*) from the northwest Mediterranean showing a number of parasites of the species *Proleptus obtusus* in the visceral cavity (color figure available online).

matic index were analyzed as measurements of energy reserves. The large hepatic reserves in sharks (in sharks the liver is the largest organ by weight, varying between 2 and 24% of the body weight) seem to be mobilized during vitellogenesis and oocyte maturation (Winner, 1990). No significant relationship was found between the intensity of parasitization and the condition of *S. canicula* after considering the effect of length. The lesser-spotted dogfish being the definitive host of the parasites, the intensity of parasitization could be more related to the feeding intensity and prey availability (i.e., intermediate hosts of the parasite) rather than the condition, age, or length of the host.

European Hake (Merluccius merluccius)

Recently, several studies carried out in Spanish and French Mediterranean waters have analyzed morphometric and physiological indicators of hake as well as biochemical analysis of the total lipids in the liver and the gonads (Lloret et al., 2002, 2008; Ferraton et al., 2007; Hidalgo et al., 2008). There were geographic and bathymetric differences in the condition of hake in the northwest Mediterranean, which were partly attributed to the different environmental characteristics and food availability of the different locations and depths (Lloret et al., 2002; Ferraton et al., 2007; Hidalgo et al., 2008). Overall, the condition of juvenile hake was found to be poorer in deep waters and in areas where the food supply is low. Furthermore, Lloret et al. (2008) indicated that female pre-spawners expend a considerable amount of energy on reproductive activities and that maternal condition (i.e., spawner quality) may affect the reproductive potential of hake. In the Cantabrian Sea, Murua et al. (2006) also found that the condition factor could be considered as a reliable indicator of the European hake's reproductive condition.

Recently, a study was carried out in northwest Mediterranean waters to evaluate, for the first time, the possible link between parasitism and condition in European hake (Ferrer-Maza and Vila, 2011). In this study, 94 mature females were caught during 2010 by the longline fishery in the Gulf of Lions, at 45–510 m depth. Macroscopic analyses of female skin, perivisceral cavity, digestive system, gonads, liver, and gills were performed to evaluate the prevalence and intensity of the different types of parasites. Several indicators of fish health such as the Le Cren relative condition index, the hepatosomatic index, and the lipid content in the liver were also evaluated. To evaluate the sexual maturity of the females, the gonads were macroscopically classified following staging and terminology proposed by Brown-Peterson et al. (2011). A gonadosomatic or gonad index was also evaluated. The macroparasites were classified as nematodes, cestodes, copepods, monogeneans, digeneans, and acanthocephalans. Results showed that infection by one or more of these parasites was discovered in all samples, with an average intensity of between 1.50 and 8.28 parasites per individual hake. The prevalence of nematode (88%) and cestode (80%) infections were higher than that of copepods (32%), monogeneans

(26%), digeneans (5%), and acanthocephalans (2%). Moreover, the intensity of infection by nematodes increased linearly with the length of the hake. No statistically significant relationship was detected between condition (Le Cren condition index, hepatosomatic index, and lipid content in the liver) and either prevalence or intensity or number of parasite groups. However, female hake parasitized by copepods (Figure 4) had a lower gonadosomatic index (GSI) than that of non-parasitized ones (Figure 5). Furthermore, a negative and significant ($p < 0.05$) linear relationship between copepod infection and the GSI of developing females was observed. These results suggest that the reproductive potential of infected females is lower than that of uninfected ones.



Figure 4 Copepod parasite of the gill of European hake (*Merluccius merluccius*) in the northwest Mediterranean (color figure available online).

Ocean Sunfish (Mola mola)

The ocean sunfish, the world's heaviest bony fish, has no commercial interest in the Mediterranean, but it is caught as by-catch in some fisheries (Froese and Pauly, 2011; Macías et al., 2004). The ocean sunfish is often infected by a high number of parasites, including the larvae of the cestode *Molicola horridus* (Gibson et al., 2011). In a recent study of more than 100 juvenile sunfish caught in Murcia, Spain (western Mediterranean), *M. horridus* was found in more than 95% of individuals of *M. mola*, occupying up to 28% of the liver surface (Ahuir-Baraja, unpublished data). The heavy parasite loads observed in *M. mola* apparently hamper the liver function (up to 14.7% of liver biomass occupied), although the exact degree of damage is difficult to estimate. However, the high parasite load of young

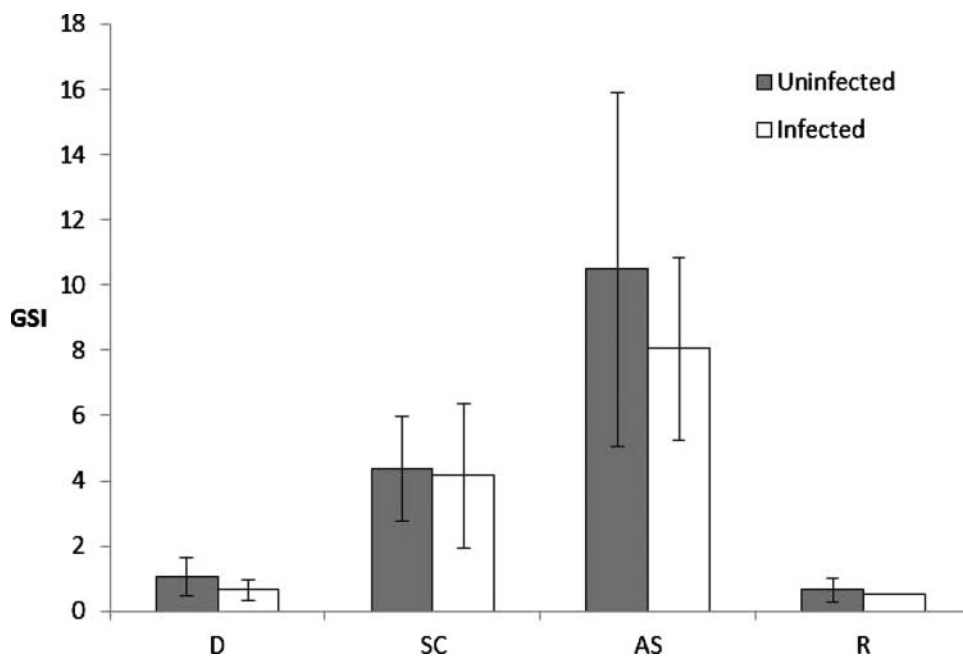


Figure 5 Average gonadosomatic index of female European hake (*Merluccius merluccius*) in different states of maturity, infected and uninfected by copepods (northwest Mediterranean). D: developing, SC: spawning capable, AS: actively spawning; R: regressing.

sunfish (parasite prevalence and abundance are markedly lower in the oldest fish) may be the cause of the higher mortality rates experienced by young individuals (Ahuir-Baraja, unpublished data). Therefore, *M. horridus* could be an important factor in determining the demography of the sunfish, especially when only small specimens are susceptible to being preyed upon by sharks, which are the definitive hosts (Dick and Choudhury, 1995; Pope et al., 2010). The larvae of *M. horridus* also parasitize the muscle and liver of several commercially valuable fish, such as *Brama brama*, *Tetrapturus albidus*, and *Xiphias gladius*, even though the consequences for the individuals of these species are not known.

DISCUSSION

Are Energy Reserves and Parasite Prevalence and Loads Good Indicators of Fish Stock Productivity?

The bluemouth and hake case studies show that the links between condition and reproduction is complex and may be only established in specific reproductive stages, e.g., before spawning, or using particular parameters such as fecundity. Similarly, several studies have found significant relationships between condition and reproductive potential (Kjesbu et al., 1991; Marshall et al., 1999; Lambert and Dutil, 2000; Oskarsson et al., 2002), maturity (Morgan, 2004), and growth (Rätz and Lloret, 2003) of different exploited species in the North Atlantic. Therefore, the evaluation of fish energy reserves during specific life stages of fish, particularly through biochemical analysis, could contribute to understanding changes in the parameters reflecting stock productivity (abundance, biomass, growth, mortality, maturity, and recruitment).

On the contrary, the case studies presented in this article reveal that the effects of parasitism on life traits of fish, such as condition, mortality, and recruitment, of marine fish are not always clearly evident, and, when these effects do exist, they are difficult to quantify. The case studies of European eel, European hake, and lesser-spotted catshark indicate that parasites found in these species do not affect their energy reserves, even in the case of the highly parasitized lesser-spotted catshark or in a fish affected by an introduced parasite (as in the case of eel). However, parasites were found to have a significant effect on the condition of anchovy and on the gonadosomatic index of hake, whereas in the greater amberjack and ocean sunfish, there were only indirect indications that parasitism could cause higher mortalities. Although, by definition, parasites take an amount of the energy from their host, it is difficult to identify the direct effects of parasites on the condition (i.e., energy reserves) of marine fish species. Despite this, there are some examples revealing negative relationships between high parasite loads and growth or condition of marine fish (Adlard and Lester, 1994; Faliex and Morand, 1994; Williams and Jones, 1994; Durieux et al., 2007; Fogelman et al., 2009; Sala-Bozano et al., 2012). These examples mostly concern specific stages of hosts (juveniles) or

castrating parasites (i.e., parasites that cause the reproductive death of the host) and remain anecdotal, as almost all fish are naturally infected with parasites and, therefore, are expected to exhibit some effects of being parasitized. Even in the case of a new host–parasite association (as in the case of eel), simple condition indices are not able to highlight the negative effects of parasites on the energy reserves of fish. There are several reasons that could explain the failure to demonstrate the negative effects of parasites on fish condition. The first, and most pragmatic, is that wild fish hosts are able to compensate for the energy drawn by the parasites. Indeed, parasites are generally small compared to the size of the host, and therefore, the amount of energy taken by the parasite (both directly and indirectly) is probably negligible compared to that required for the host to live. On the other hand, condition indices often used in the literature, such as the relative condition index and the hepatosomatic index, are proxies of the energy reserves of fish, and so they can miss the underlying effects, which will become apparent if biochemical indicators, such as total lipid content, are used. Another argument is the theory of “the prudent parasite,” arguing that adult parasites aim to reproduce in their definitive host and spread a maximum of eggs and larvae and would therefore avoid weakening their host. This argument is usually supported by the more marked effects of larval stages of parasites on the intermediate hosts (either invertebrates or vertebrates). The reason for these parasitic effects on the intermediate hosts is to reach their definitive host by whatever means possible (behavior modification, castration, condition effects, etc.). The intermediate host will then be easily preyed upon by the definitive host. Finally, the lack of detectable negative effect on the condition of the final host can be also explained by higher mortality rates for the heavily infected individuals, but this obviously makes them impossible to sample.

In fact, host–parasite relationships are systems that result from a stable balance over time between resistance and virulence and in which each partner thwarts attacks from the other. As a consequence, parasitism will generally not induce drastic changes in host energetic reserves but will have limited and reversible effects on lipid reserves (Durieux et al., 2007), physiology and metabolism (Ösflund-Nilsson et al., 2005), and gene expression (Faliex et al., 2008), which will be more difficult to detect. Moreover, very few cases exist where parasites have sublethal or lethal effects on fish in the wild. Ill or moribund fish normally go unnoticed in the sea as they die and quickly decompose, or, when fished, they are usually rejected before they reach fishing markets or the consumers. Evidences of parasite-dependent fish mortalities usually come from indirect observations. For example, Ogawa (2002) and Shirakashi et al. (2006) reported a palpable decrease of the commercial captures of the olive flounder (*Paralichthys olivaceus*) in Japan, apparently related to outbreaks of the monogenean *Neoheterobothrium hirame* (Platyhelminthes). Nevertheless, many fish parasites (e.g., larval cestodes) are not commonly associated with important pathologies, as they are usually latent, “waiting” to be ingested by the definitive host (Dick et al., 2006). Overall, it

is clear that more sophisticated and comprehensive approaches are needed to fully understand the real effects of parasites on life history traits of marine wild fish populations, such as natural mortality, growth, and reproductive potential. These new approaches should take into account not just the presence or absence of the parasites but also the number and diversity of parasites.

Stock Assessment and Fisheries Management Implications

Even though the case studies presented show that the links between fish parasitism, condition, and parameters reflecting stock productivity (e.g., growth, natural mortality, abundance, etc.) are not always evident or easily quantified, there are indications that the energy reserves and the rate of parasitism of fish may be an important factor driving natural mortality (M), growth, fecundity, or recruitment of some fish species, in particular life or reproductive stages. It is suggested that stock assessment working groups, fishery agencies, and research centers in the Mediterranean and elsewhere could incorporate simple fish health indicators, such as morphometric and organosomatic (biometrical) indices (e.g., Le Cren, mesenteric fat, and hepatosomatic indices), lipid content, and parasitic infection, into their routine assessment and research programs, at least for the most important target species. Results could be used, for example, to improve M estimates to be used as input variables in the standard stock assessments. Then, given sufficient information on fish health, it may be possible to evaluate more exactly not only M but also spawner quality (and not only quantity) and to forecast temporal changes of these variables. The monitoring of simple fish health indicators could complement the standard population dynamic procedures commonly used by international scientific and management bodies, and it could also act as an indicator of the stock status in data poor situations where standard assessments (e.g., VPA or XSA) cannot be carried out. This approach will therefore provide a method for detecting negative trends in the health of a fish population over time or anomalous poor health status at any given particular time. This should not be a substitute for standard stock assessment methods but can provide additional information to determine the status of a given stock.

Moreover, simple measurements of parasite infection, such as prevalence, intensity, and abundance, could be monitored to provide a further index of fish health. For practical purposes, monitoring could include macroparasites (i.e., parasites that are large enough to be seen with the naked eye, such as cestodes and nematodes) but not microparasites (e.g., protozoans, which are more difficult to detect), despite the fact that they may also have an impact on the condition and reproduction of fish (see, e.g., Kramer-Schadt et al., 2010; Sitjà-Bobadilla, 2009). While no single measurement of fish health uniquely indicates a stress source (Buckley, 1985), all these simple, related fish energy reserve and parasitism indicators taken together could be used as an index of fish health. Furthermore, the study of parasites can help to characterize an ecosystem, e.g., to recognize the

role of fish host in the food web or ecosystem or to determine changes in host diet (Iwanowicz, 2011).

In particular, the analysis of fish health during critical life periods (e.g., prior to spawning or migration or in the early life stages) may be important in detecting the effects on stock productivity and, thus, their availability to fisheries, as shown by the case study on eel and anchovy. For migratory species (e.g., anchovy, eel, and tuna), it may be important to evaluate the health of individuals before seasonal migration because migrations have a substantial energetic cost (Harden Jones, 1984), with the distance being linked to available lipid stores (Nøttestad et al., 1999). Moreover, a comparative analysis of the health of different populations (of the same species) could be used to refine the parameters used in stock assessment, because stocks constituted by individual specimens in good condition can sustain higher fishing mortality rates (Rätz and Lloret, 2003). As shown in this article, the condition of European hake and anchovy in the Mediterranean, Azov, and Black seas varies spatially, with different stocks displaying different levels of condition.

Whenever there are indications of poor health status, such as high parasitic load, low lipid content, or lower than average relative condition index, input values of stock assessment models could be updated accordingly, using slower growth rates and higher natural mortalities values than average. Moreover, managers may be particularly aware of declining trends in the average health status of individuals within certain stock, such as those detected in several groundfish in the Mediterranean, including European hake (*Merluccius merluccius*) in the Gulf of Lions and in the south and central Tyrrhenian Sea, and common sole (*Solea solea*) in the northern Adriatic or sardine (*Sardina pilchardus*) in the Aegean Sea (STECF, 2010). There are also several examples of stocks in the north Atlantic, including cod (*Gadus norhua*) off Newfoundland (Lambert and Dutil, 1997) and bluefin tuna (*Thunnus thynnus*) in the Gulf of Maine (Golet et al., 2007), that also showed a declining trend for a number of years. Similarly, fisheries managers could be aware of the increasing trends in the rates of infection in several species exploited in the western Mediterranean (Agencia de Protección de la Salud, 2006; Valero et al., 2000), as well as in several species in the north Atlantic, including cod (*Gadus morhua*) and American plaice (*Hippoglossoides platessoiedes*) in the 1980s and 1990s (McClelland and Martell, 2001) and pouting (*Trisopterus luscus*; Rello et al., 2008). Although the consequences for the stocks harboring these increasing rates remain unclear, from a public health standpoint, they may pose a major threat to human health because some parasites (e.g., Anisakids) can infect humans when fish is consumed raw, undercooked, or lightly marinated (McClelland, 2002). Furthermore, heavy infections by macroparasites can simply reduce the marketability of fish, as they are easily visible to the naked eye before and after evisceration (McClelland, 2002; Cairn and Reyda, 2005).

The evaluation of seasonal cycles in fish health could be also important, not only to evaluate the health status of fish but also to contribute to achieving the maximum sustainable yield from a given stock. Thus, fishing during peak physiological condition

can result in a decrease in the number of individuals removed from the stock while profiting from maximum yield and better product quality (Mello and Rose, 2005). Therefore, seasonal cycles in fish health could be used to refine management strategies that promote both economic and conservation benefits for fisheries by harvesting fish during periods when biological impacts are minimal and economic returns maximal (Mello and Rose, 2005). However, concentration of the fishing effort in particular seasons may be neither economically feasible nor healthy for the stocks in question (if, for example, the peak in condition coincides with the spawning season, which is, however, rarely the case).

Furthermore, the evaluation of fish health could serve as an indicator of environmental quality. In particular, the health of small pelagic species can be a valuable indicator of anomalous environmental conditions, as the anchovy case study has shown. A recent study of sardine (*Sardina pilchardus*) condition and environmental quality in the north Atlantic supports this hypothesis (Rosa et al., 2010). Moreover, changes affecting marine food webs are ongoing and may accelerate in the future given threats such as climate change, the introduction of exotic species, and overexploitation. Long-term monitoring of stock health as well as the health of their prey can contribute to understanding how exploited fish stocks are responding to these changes. Fish health could be used as an additional ecosystem indicator for fisheries management other than those proposed recently by different authors (see, e.g., Cury and Christensen, 2005) and policy documents (e.g., the Marine Strategy Framework Directive from the European Union). Regarding this directive, fish health could serve as associated indicators that need to be identified so as to guide progress toward achieving good environmental status in the marine environment.

Results of this study also indicate that more detailed and specialized procedures must be applied in order to increase the understanding of the influence that fish health may have on individual and population life history traits, such as natural mortality, growth, and reproductive potential. An understanding of these traits is a central aspect of providing sound scientific advice for fisheries management (Morgan, 2008). Specialized studies should also consider controlled laboratory experiments altering the health of fish in order to illustrate the direct connection between health, growth, and reproduction of fish. All of these studies will need interdisciplinary work among researchers, such as parasitologists, fish physiologists, and fisheries biologists.

Management intervention through commercial fishing practices and other procedures may also be needed to ensure healthy fish stocks (McClelland, 2002). For example, viscera of some Mediterranean groundfish species, such as the catshark *Scyliorhinus canicula* (considered in this article) and *Lophius* spp., are often discarded at sea prior to reaching the fish market. This practice may result in heavier infections in fish that feed on the discarded viscera (McClelland, 2002). The case study of the catshark demonstrates the very high parasitic load of these discarded viscera. Therefore, discards of fish viscera overboard

could be banned. Finally, the potential spread and impact of farm-origin parasites on the survival of coastal wild fish populations must be taken into account (Krkosek et al., 2006).

Overall, and despite the fact that links between fish health and productivity cannot always be clearly demonstrated, implementing long-term monitoring programs of stock health could support stock assessment and sustainable management of profitable fisheries, particularly in stocks where data shortage prevents the carrying out of standard stock assessments, as is the case with the Mediterranean Sea. This could also help in understanding how exploited fish stocks are responding to environmental and anthropogenic impacts.

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