Ecological Indicators 129 (2021) 107867

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Review

The key role of zooplankton in ecosystem services: A perspective of interaction between zooplankton and fish recruitment

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ARTICLE INFO

Keywords:
Ecosystem services
Zooplankton
Fish stock
Aquaculture
Trophic interactions

ABSTRACT

Marine biota is a great source of ecosystem services. Recently, the involvement of marine organisms in biotechnological applications has been discovered and become useful for the development of alternative and healthy food, natural medicine and cosmetics. The most known ecosystem service is the provision of seafood; however, fishery management has to be implemented in order to avoid fishing exploitation, depletion of the sea and assure the recruitment by fish larva. This review put in relation the role of zooplankton in the ecosystem and its importance in fish recruitment. Zooplankton and fish are close connected; indeed, their prey-predator relation is an important factor for fish recruitment. Understanding the dynamic and trophic relation among different groups (phytoplankton – zooplankton – fish) and the ecosystem services they give to us, may increase the awareness of the importance to preserve marine environments. Furthermore, this relation is also important for fish aquaculture practices, as it is discussed in the present review. Further researches on potential zooplankton species that may be involved in fish farms may also ameliorate aquaculture services.

To preserve the seas from fish depletion and to assure seafood provision, it is fundamental to have deep knowledge about the ecological connections in the marine environment and to obtain fishery management respectful for the environment.

1. Introduction

Marine ecosystems are among the most populated habitats in the world; their richness is given by an incredible number of marine organisms that provide us ecosystem services. The Millennium Ecosystem Assessment defined “ecosystem services” as “the benefits that people obtain from ecosystems”. Ecosystem services are divided into four categories: supporting, provisioning, regulating and cultural services (Millennium Ecosystem Assessment, 2005).

Ecosystem services are dependent from natural ecosystem functions, thus it is important to preserve our planet and its habitats. For example, provision of seafood is the most exploited ecosystem service, which is result of a combination of primary and secondary production, biogeochemical cycling, food web dynamics, etc (Austen et al., 2011). The economic part is also encouraging: it has been estimated that marine ecosystem services are valued at $50 trillion per year (Costanza et al., 2014).

Marine species mostly used for human benefits are principally known in the food industry (Fradique et al., 2010), but they can also assure several benefits in different biotechnological applications, such as nutraceutical, pharmaceutical or cosmetic industry, as it happens recently with further studies on seaweeds (Lee et al., 2020; Miyashita et al., 2020) and microalgae (Galasso et al., 2019; Matos, 2019). Among benthonic organisms, mussels are also used in different sectors, for example the anti-inflammatory agent contained in Lyprinol may be extracted from a green-lipped mussel originated from New Zeland (Benkendorff, 2009). Moreover, sponges and coral are also rich in bioactive compounds that could be useful for forward studies and development of new human services (Leal et al., 2013; Munro et al., 1999).

Ecosystem services offered by marine resources are diverse. For example, mangrove ecosystems are important to ensure nursery and breeding habitat for many important fish species that can be exploited for aquaculture, providing other important services associated with habitat functions and protection (Barbier, 2017).

Activities related to tourism, religion and culture are also strictly

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https://doi.org/10.1016/j.ecolind.2021.107867
Received 11 February 2021; Received in revised form 31 May 2021; Accepted 1 June 2021
Available online 5 June 2021

connected with extraction and harvesting of natural marine resources. Commercial fishing and marine tourism are both highly dependent on ecosystems, but marine tourism has been identified as having lower impact on the environment and higher monetary value (Bryhn et al., 2020). Cultural ecosystems services provided by marine resources are included in different categories: (1) aesthetic experience, which relates with the vision of natural beauties; (2) recreation, as it is noticed sea and beaches are considered a holiday location where is possible to practice different activities such as swimming, snorkelling or diving; (3) inspiration for art and culture, as many artists use the sea as source of inspiration; (4) cultural heritage and identity, such as the identification of local connection or family link (Fletcher et al., 2014).

Unfortunately, anthropogenic impact affects our ecosystems, bringing up habitat degradation, pollution, overfishing etc. Due to the unsustainable human exploitation of natural resources, ecosystem services are limited (Gentry et al., 2020).

Thus, to avoid the complete depletion of marine environments and to have functional ecosystem services along time, it is necessary to preserve and to adopt sustainable uses of the environment. The Marine Strategy Framework Directive suggests the use of biological indicators to recognize stressed ecosystems, in order to facilitate the process of restoration (Hattam et al., 2015).

In the following sections, the importance of zooplankton groups and their contribution in ecosystem services is mentioned through the description of zooplankton ecological roles and its impact on fish recruitment and fishery management.

2. Zooplankton contribution in marine ecosystems and aquaculture

The term "plankton" was attributed in 1884 by Hensen to indicate organisms randomly disposed in the space (Hensen, 1884); further, the plankton distribution was assumed as uniformly distributed in space (Lussenhop, 1974). Studying the physical structure of lakes, expert limnologists noticed a vertical and horizontal distribution for the zooplankton that is appliable on every environment, and Hutchinson in the 50 s developed different patterns of distribution: clumps, swarms or aggregates (Hutchinson, 1953). Zooplankton is directly connected to higher trophic levels, thus knowing how its distribution influences the entire ecosystem and the interactions with other planktonic organisms (Pinel-Alloul et al., 1988) may be helpful to understand ecological models related to other planktonic groups (Pinel-Alloul et al., 1988). Perissinotto and McQuaid (1992) found a connection between diurnal vertical migration of zooplankton and fish feeding habits. The stomach content of *Kreffrichthys anderssoni*, local fish of the Prince Edward Archipelago (South Africa), showed the presence of the euphausiid *Euphausia vallentini*, *Microcalanus pygmaeus* and the copepod *Rhincalanus gigas*. *Kreffrichthys anderssoni* spend the daytime 300–400 m below the surface, shifting to the upper 50–100 m at nigh time, when zooplankton is in surface water (Perissinotto and McQuaid, 1992). It is clear that the vertical migration of zooplankton influences fish migration and food availability.

Zooplankton presence affects the ecosystem dynamics (Bruce et al., 2006). Zooplankton have a position as grazers for algae and bacteria, influencing their community population (Lehman and Sandgren, 1985; Sterner, 2009), but they also provide phytoplankton with nitrogen and phosphorous (Hudson et al., 1999; Hudson and Taylor, 1996; Lehman and Sandgren, 1985; Sterner, 2009; Urabe et al., 1995) having a perfect cycle of nutrient recycling.

Furthermore, zooplankton have a crucial role in the efficiency of the Biological Carbon Pump (BCP) that regulates the atmospheric carbon dioxide levels (Kwon et al., 2009; Parekh et al., 2006). Cavan et al. (2017) underline the roles of zooplankton in improving the effectiveness of the BCP through the control of particles export by grazing, by fractioning large and fast sinking particles in slower ones and moving Particulate Organic Carbon (POC) to depth via diel vertical migration (Cavan et al., 2017).

Zooplankton has also a strong effect on biomass stocks of other planktonic groups, in fact zooplankton can alter the concentration of prey populations (by consumption) and predator populations (by being consumed), consequently having effects on fish biomass (Vanni, 2002).

The predominant anthropogenic disturbance for fish is the bottom trawling practice. However, it has also strong impact on the biogeochemical cycling of carbon and nutrient. Dissolved and particulate nutrients may be transferred from benthic to pelagic systems, favouring the occurrence of algal blooms (Pilskaln et al., 1998). This increase of primary productivity could have significant effects for eutrophication of the water column, causing stress for the marine communities, such as zooplankton (Dounas et al., 2007).

Zooplankton species are widely used as live feed for farmed fish. Fish feed is one the main expensive cost in aquaculture (Lupatsch et al., 2001), but the most important as well: quality and quantity of feed directly affect growth and, indirectly, maturation and mortality in fish (Wotton, 1990). Therefore, it is possible to alleviate this cost by utilizing live-feed. Traditional live-feed products are rotifers (e.g., *Brachionus* spp.) and brine shrimp (*Artemia* spp.), both with non-marine origins, thus they sometimes need added enrichment before use (Hansen, 2017).

Copepods represent an important alternative live-feed in marine fish production, as they improve survival, growth and development of fish larvae (Hansen, 2017). Biochemical profile of copepods and their size range make them appropriate feed for fish farm larvae (Hansen, 2017). It has been demonstrated that in lakes zooplankton is fundamental as food for young fish, which represents an important element in human diet (Mavuti, 1990). This is a suitable example of ecosystem service and how the ecological role is related to the ecosystem service.

2.1. Main contributions of zooplankton long time series

Oceans are unpredictable environments and their physical and chemical conditions are continuously changing. To collect reliable data about these variables, it is important to follow a long time-series approach and to have replicates of physical, biological and chemical measurements collected during the years and perform statistical analysis (Valdés et al., 2007).

Long-term series is the best way to have reliable information (Beaugrand et al., 2003; Omori et al., 1994; Perry et al., 2004) about the status of an ecosystem, considering the combined effect of anthropogenic pressure on biota (Serranito et al., 2016).

Valdés et al. (2007) showed that long repeated time-series samplings of zooplankton increase the likelihood to detect changes in the environment (Valdés et al., 2007). The time-series from 1992 to 2007 in the Northern and Western coast of Spain studied the responses of zooplankton to environmental conditions, such as temperature, distribution and water column stratification. Through the years, the seasonal cycle of zooplankton populations has been observed to change with temperature (Edwards and Richardson, 2004; Greve et al., 1996). Indeed, zooplankton species distribution also have been affected by global warming (Southward et al., 1995).

Long time-series study can be utilized in fishery management to assess or to predict the presence of fish stocks in relation with the presence of zooplankton. Mackas et al. (2013) analysed zooplankton data between 1990 and 2010. The sampling points are in the Strait of Georgia, sites rich in salmon and herring. The community composition of zooplankton included abundance of large copepods, euphausiids and amphipods, and non-crustacean gelatinous predators such as chaetognaths, hydromedusae, and siphonophores. From this time-series analysis, Mackas et al. (2013) discovered a big fluctuation in zooplankton biomass during the 20 years: in the very early 1990s and 1999–2002 the biomass of zooplankton was at the maximum, while minimum biomass was showed in 1994–1995 and 2004–2007 with a following recovery of the average biomass in 2008–2010. In the years 2005 and 2007 the effect of lower zooplankton biomass affected largely an impoverished growth and survival of juvenile salmon and herring (Mackas et al., 2013). The abundance of fish stocks is not only dependent on zooplankton abundance, but it is also a potential factor.

Specific zooplankton species are indicated as bioindicators sensitive to disturbances within the natural environments. For this reason they are also called "sentinels of environmental changes and pressures" (Beaugrand et al., 2010; Legendre and Rivkin, 2005; Richardson, 2008). The Marine Strategy Framework Directive assumes that zooplankton can identify environmental changes and anthropogenic invasion in the nature, such as addition of chemicals (Serranito et al., 2016). Since zooplankton is very sensitive to changes, the response to the disturbance will appear in a short-time respect for the higher trophic level. The short response and their ubiquity make them potential bioindicators for different wet areas all over the world (Serranito et al., 2016). A case study conducted in Toulon Bay in the Mediterranean presents a times-series approach from 2002 to 2013. The aim of the study was to quantify the biomass abundance of copepods and to evaluate the possibility to use them as bioindicators for chemicals in the environment. Results showed a great abundance of species from fam. Oithonidae was present in the bay, and these organisms possess characteristics to be considered as bioindicators of anthropogenic pollution present in the Bay (Serranito et al., 2016).

2.2. Impacts of gelatinous zooplankton on ecosystem services

Zooplankton include also gelatinous organisms, which is represented by the phyla Cnidaria, Ctenophora and Chordata. Jellyfish (Cnidaria) have positive impacts for the ecosystems services: they are widely used in Asian food industry but also in other continents (Graham et al., 2014) and in pharmaceutical industry. The extraction of collagen is already used for the production of cosmetic products (Patwa et al., 2015).

From the ecological side, gelatinous zooplankton are key species for particular fish, such as blue fin tuna in Mediterranean (Cardona et al., 2012). Moreover, they also contribute to the nutrient recycling transferring nutrients to the benthic organisms through release of faecal pellets or decomposition of the entire body (Henschke et al., 2016; Sweetman and Chapman, 2015). Nevertheless, gelatinous zooplankton are well-known for the formation of dense species gathering called "bloom" that could be repetitive during the years and could have consequences for human health, as it happened in South Italy (Salento seacoast) where jellyfish blooms caused skin burnt and the total cost for emergency medical aid was around 400,000€/5 years services (De Donno et al., 2014). Consequently, blooms provoke damages in tourism and economy (Boero, 2013; Kim et al., 2012; Kontogianni and Emmanouilides, 2014).

Jellyfish and ctenophores (Ctenophora) are both predators for zooplankton and juvenile fish stage (Boero, 2013; Purcell and Arai, 2001). The presence of blooms indicates a fall in the good ecosystem status or anthropogenic pressure due to overfishing and depletion of predators of gelatinous zooplankton. This can bring up an overpopulation of gelatinous zooplankton which will impact drastically the fish recruitment (Lynam et al., 2004, 2005; Schneider et al., 1998). One of the most harmful species is the invasive species *Mnemiopsis leidyi* (Shiganova et al., 2006) which disrupted the Black Sea ecosystem at all trophic levels and affected fisheries. *Mnemiopsis leidyi* is native to estuaries and bays along temperate and subtropical coastal waters of North and South America. Since the early 1980s *Mnemiopsis leidyi* has penetrated in new areas such as Black Sea Caspian Sea North and Baltic Sea trough ballast waters contained in commercial ships (Shiganova et al., 2019).

The abundance of gelatinous zooplankton can affect also the clog up of fishery nets, aquaculture fish mortality, or obstruction of cooling systems of coastal desalination, nuclear and coalfired power plants (Graham et al., 2014). It happened during blooms of the jellyfish *Aurelia* spp., which provoked clogging cooling water intakes at coastal power plants, causing mortality of aquaculture species, and interfering with fisheries and tourism (Dong et al., 2010; Purcell, 2012; Richardson et al., 2009).

Pelagia noctiluca blooms, usually present in the Eastern Atlantic and the Mediterranean Sea, are very large and they interfere with several marine human activities, such as tourism and fishing (Canepa et al., 2014). This species is one of the most common stinging jellyfish, as also one of the primary cause of fish mortality in fishing farms. Similar cases of gill disorders and caged fish mortality events have been reported in Northern Europe (Rodger et al., 2011).

3. Influence of the zooplankton on fish stocks

The fishery management processes must be sustainable and ecological, to avoid the depletion of fish abundance due to overfishing and wrong fishery policy.

It is important to consider the effects of environmental changes and stressors on stock recruitment. To provide future stocks may be useful combining the use of biological indicators and recruitment models (Pershing et al., 2005). Zooplankton are used as indicators of environmental conditions, which reflect on the ecosystem status and also in the living component, giving us information about the abundance of predators like fish (Sherman et al., 2002). Zooplankton organisms occupy a crucial position in the food chain, thus they have effects also on fish stocks and fish recruitment (Fig. 1). Variation of the biomass abundance of zooplankton could trigger a cascade effect that reflect also on the fish stock.

3.1. Interactions between zooplankton and fish recruitment

Commercial fisheries are dependent on fish stocks, which are supported by the bottom of the food chain (Nixon et al., 1986): primary production assures the carbon production which will provide abundance in zooplankton biomass, the prey-resource for larval stages of fish (Sherman et al., 2002).

The correlation between zooplankton and fish recruitment was already discussed in the 80s. Studying the biomass abundance of zooplankton in the North Sea, it appeared to have a huge decline during the same period in which the abundance of commercial fish was diminishing (Reid, 1984). The decline of zooplankton which occurred due to climate change, could be also a suitable explanation for reduction in stocks, since low food availability may be critical for fishery (Reid, 1984). Additionally, detailed studies showed that the decrease in stocks for herring and mackerel was also due to a period of overfishing and a consequential impoverished recruitment (Reid, 1984). Pershing et al. (2005) studied zooplankton community patterns in the Gulf of Maine (Atlantic Ocean - east coast of North America) and their relation with the recruitment of determined fish stocks. Researches suggested that changes in those patterns could influenced on a large-scale the ecosystems, with consequentially changes on the services they can provide to humans (Pershing et al., 2005). Further investigations identified strong physical changes in the Gulf of Maine that could be stressors for the fish stocks.

Besides, shifts in zooplankton community abundance co-occurred with lower fish recruitment abundance. It is not conclusive saying that fish recruitment is only influenced by zooplankton biomass, but among the varieties of factors, high prey abundance present in the timing of fish spawning will increase the recruitment (Beaugrand et al., 2003; Cushing, 1990; Hjort, 1914; Platt et al., 2003).

The Barents Sea is another important area to find commercial fish stocks. In the mid-1980s and mid-1990s the stock of *Mallotus villosus*, known as capelin, faced a severe decline in recruitment, due to the strong predation exert by young herring on capelin larvae. Since capelin are a key species of the Barents Sea ecosystem, their decrease influences the higher trophic level which include cod, harp seals, and guillemots (Dalpadado et al., 2002).

Among those years the zooplankton biomass has also showed

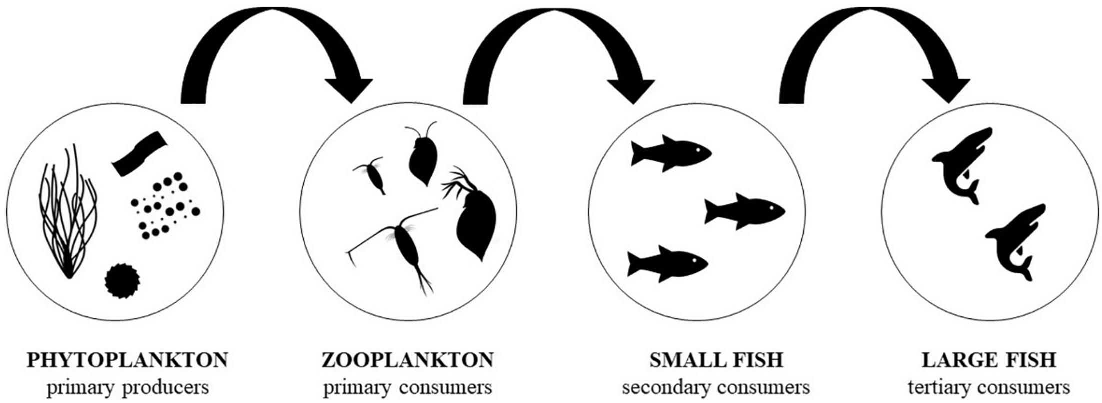

Fig. 1. Illustration of the aquatic food chain.

variations (Skjoldal and Rey, 1989) possible due to differences in horizontal transportation and big predation pressures. These variations may be signals for further changes in the ecosystem, as studies demonstrated some interactions among cod (*Gadus morhua*), herring (*Clupea harengus*), and capelin and between fish and zooplankton (Bogstad and Mehl, 1997; Dalpadado and Skjoldal, 1996; Gjøsæter, 1998; Ponomarenko and Yaragina, 1979). Zooplankton is the major nutriment in capelin and herring diets (Dalpadado et al., 2002), while cod consume krill, amphipods, shrimps (*Pandalus borealis*), capelin, herring, polar cod (*Boreogadus saida*), redfish (*Sebastes* spp.), cod, and haddock (*Melanogrammus aeglefinus*) (Bogstad and Mehl, 1997; Ponomarenko and Yaragina, 1979).

The Barents Sea food chain is characterized by few dominant species, they could be resumed such as: diatom → krill → capelin → cod. Shifts among different trophic levels are the proof of the strength of these biological interactions and how they can easily change the ecosystem status (Dalpadado et al., 2002).

An interesting example of the negative influence of gelatinous zooplankton on fish recruitment is given by the case study conducted in the Black Sea. In the time-series observations during 1960–2001 the Black Sea faced significant changes that affected the ecosystem health that appeared weak and less stable (Grishin et al., 2007).

These conditions favoured the outburst of gelatinous zooplankton *Mnemiopsis leidyi* and jellyfish *Aurelia aurita*. Since 1988 until the late 1990s, *Mnemiopsis leidyi* has the control on the zooplankton biomass, its favourite prey, affecting also the stocks of some abundant commercial fish species (Grishin et al., 2007).

The decrease of fish stocks in the early 1990s was mainly affected by overfishing due to unregulated fisheries, even though the presence of the invasive non-indigenous species *Mnemiopsis leidyi* negatively contributed as food competitor of planktivorous fish (Daskalov, 2003, 2002). The outburst of gelatinous zooplankton also produces indirect effect on the ecosystem, leading to the increase in phytoplankton and detritus with a consequential reduced water quality, hypoxia and negative effects on fishes and other organisms (Grishin et al., 2007).

In order to avoid further increases in mortality rates for juveniles and to substantially reduce the number of juveniles by overfishing vessels, the European Union provides the Council Regulation (EC) N. 1967/2006 of 21 December 2006. This regulation determines the minimum landing sizes of certain marine organisms (Annex III) (European Commission, 2006). In this way, the selectivity of fishing gear should correspond as closely as possible to the minimum landing size established for a certain species or group of species caught by that gear. Gears should be adapted base on the fishing zone: for example, part of the coastal zone should be reserved for selective fishing gears used by small-scale fishermen, in order to protect nursery areas and sensitive habitats and enhance the social sustainability of Mediterranean fisheries. Management plans may also include measures to monitor the fishing effort, in order to safeguard the sustainability fisheries in the Mediterranean Sea (European Commission, 2006). In light of this close relation between zooplankton communities and fish stocks, it is important to apply an approach in fishery management that recognize and include the knowledge of the status of the ecosystem.

4. Zooplankton as primary fish feed source

Fish, like other animals, need a nutritional diet rich in protein content for optimizing growth and reproduction (Weatherley and Gill, 1983); they cannot synthesize essential amino acids (EAAs) (Ketola, 1982), thus they need to keep it from external sources (Taipale et al., 2018).

For example, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are required in the juvenile stage of fish – as well as mammals and birds – for growth, eye and brain tissue development and immunity function (Tocher, 2010). The omega-3 fatty acids EPA and DHA are synthesized only by few phytoplankton taxa such as dinoflagellates, golden algae, diatoms, and cryptomonads (Galloway and Winder, 2015; Taipale et al., 2016), thus fish assimilates those biomolecules through the consumption of zooplankton which feed on phytoplankton or converting the precursor of fatty acid, the α-linolenic acid (Taipale et al., 2018).

Zooplankton groups are characterized by different feeding preferences and metabolism; cladocerans prefer phytoplankton species abundant in EPA (e.g., *Daphnia magna*) whereas copepods prefer phytoplankton species rich in DHA, indeed copepods present abundance of DHA, such as *Eudiaptomus* (Taipale et al., 2018). DHA is highly present in many aquatic food webs (Strandberg et al., 2015) because of the great assumption by copepods and the predation of copepods by fish.

A common procedure in fish aquaculture is to add microalgae to culture system of zooplankton prey for fish larvae (Tamaru et al., 1994). The most popular microalgae used for feeding zooplankton for aquaculture purposes are *Nannochloropsis oculate*, *Tetraselmis suecica*, *Pavlova lutheri* and *Isochrysis* sp., which are PUFAs-rich and they enrich zooplankton in DHA (Nichols et al., 1989).

Nutritional quality of phytoplankton has a cascade effect along the food chain, influencing through zooplankton all the trophic web (Brett and Müller-Navarra, 1997; Elser et al., 2000; Müller-Navarra et al., 2000). Thus, in fishery management it should be mandatory to consider always the trophic relation between phytoplankton, zooplankton and fish, in order to have an efficient stock and make a better use of fishery resources (Waya et al., 2017).

4.1. Use of zooplankton in fish farming

Aquaculture is nowadays one of the most exploited sectors around the world (FAO, 2018) and this phenomenon is co-occurring with dramatical decrease of functionality of our ecosystems and habitat changes due to anthropogenic exploitation of natural resources, environmental pollution and spread of invasive species (Naeem et al., 2012).

Feed used for aquaculture releases an amount of organic matter, nutrients and suspended solids (Edwards, 2015) which may have negative impact on the aquaculture but also on the environment, due to the discharge of nutrients from the aquaculture implants (Naylor et al., 2000). Nitrogen and phosphorus are often released in high concentration causing eutrophication, oxygen depletion and siltation in the environment (Burford et al., 2003). To minimize the impacts of nutrients, several countries are developing Integrated Multi-Trophic Aquaculture (IMTA) systems, which imply the wastewaters for cultivation of macro- and microalgae. In this way, aquaculture wastewater will provide the right amount of nutrients (ammonia, nitrite, nitrate, dissolved organic nitrogen and phosphate) discharged (Abe et al., 2002; Converti et al., 2006; Soletto et al., 2005).

Studies demonstrate that it is possible to employ microalgae to remove nutrients from aquaculture wastewaters (Gao et al., 2016; Lefebvre et al., 2004). Bioremediation with microalgae is ecological and low-cost (Mulbry et al., 2008). The most valid candidates to utilize for aquaculture bioremediation wastewater are *Tetraselmis suecica* and *Dunaliella tertiolecta* (Borges et al., 2005; Michels et al., 2014).

Due to the high market demand, is emerging the need to have the highest yields achieved with the least nutrient loading. In semi-intensive fishpond systems, cereals are often replaced by complex fertilizers that increase the natural productivity of fish (Kaushik, 1995; Pechar, 2000; Potužák et al., 2007; Tacon, 1996) without compromising fish flesh quality (Dickson et al., 2016). Unfortunately, traditional fish feeds are often made from fishmeal and oil, and the use of such ingredients is unsustainable (Welker et al., 2014), thus their use has been reduced in the last decade (Tacon and Metian, 2015).

There are many alternative sources available, which are not only comparatively cheaper but are nutritionally enriched. For example, poultry by-product meal (Bureau et al., 1999; Rawles et al., 2006) may be included in the feed of carnivorous fish species such as rainbow trout because of its relatively high protein content and lower price compared to fishmeal (Shapawi et al., 2007). Therefore, some microalgae (e.g., *Spirulina*) are rich in amino acids and omega-3 and omega-6 fatty acids, which make them potential natural replacement of fishmeal, adding nutritional value and benefits to animal health (Hodar et al., 2020). Zooplankton organisms can contribute to the growth of fish economically important: they support the nutrient flows between phytoplankton and fish (Howick and Wilhm, 1984), are source of amino acids, protein, fatty acids, lipids, enzymes and minerals (Watanabe et al., 1983) and they are rich in protein and carbohydrate-poor, while using cereal feed the uptake of protein is lower (Tóth et al., 2020).

The implication of live feed in aquaculture may be risky considering mortality probability of specimen, but it is also one of the most profitable venture (Khan et al., 2020). Moreover, due to their nutritional properties, zooplankton organisms are the feeding source more appreciated by fish larvae (Rønnestad et al., 1999). Due to their high nutritional value, zooplankton has been exploited in fish farms. Hassan et al. (2020) evaluated the growth performance of European sea bass (*Dicentrarchus labrax*) in relation with replacement of zooplankton biomass in fish diet. The experiment was carried out replacing zooplankton biomass in commercial fishmeal with five different concentrations (from 25% to 100%). Results showed that fish feed by 100% replaced meal gained higher body length, body weight and showed the major feed intake (Hassan et al., 2020).

The assumption of proteins from live food assures a better growth, efficient breeding and survival (Mandal et al., 2009). Live food is available in the market but it is quite expensive, thus to reduce the production costs a good alternative is to cultivate zooplankton species at low-costs venture (Khan et al., 2020). *Artemia nauplii* has been used for aquaculture implants for a long time (Agadjihouèdé et al., 2011), but the high cost of *Artemia nauplii* cysts led to search for other species (Bhaskaran and Imelda, 2020; Khan et al., 2020).

Live food that is also recommended for aquaculture is *Daphnia magna* which can be easily cultured with low-cost expenses. *Daphnia magna* is considered a natural source of proteins, vitamins, carbohydrates and lipids (Jorge et al., 2016) and with the 45–70% protein content and 11–27% lipid content (Macedo and Pinto-Coelho, 2001), it represents a nutritional food for fish (Khan et al., 2020). Cladocerans in general have the advantage of high reproduction rates, wide temperature tolerance and the ability to regulate the presence of phytoplankton and organic wastes (Khan et al., 2020) and they meet the nutritional requirement of fish larvae (Evjemo et al., 2003). Among other species, *Brachionus plicatilis, Brachionus rotundiformis, Pseudodiaptomus annendeli, Pseudodiaptomus serricaudatus and Moina* sp. have been discovered as the most successfully species to cultivate in small and large scale in the mariculture hatchery, as they possess high reproductive rate, short generation time, and the ability to live and grow in crowded culture conditions (Bhaskaran and Imelda, 2020).

In Taiwan, the calanoid copepod *Pseudodiaptomus annandalei* is commonly used as live feed for commercially important species such as grouper larvae (Chen et al., 2006; Lee et al., 2010). This copepod has been cultivated successfully in Taiwan in ponds for several decades at relatively high densities, in order to have huge disposal of live-feed for feeding fish larvae (Blanda et al., 2015). Kar et al. (2017) carried out the cultivation of the species *Moina micrura*, *Scapholeberis kingi* and *Brachionus calyciflorus*; the growth and the reproduction of the three species were satisfactory to sustain the mass culture and the supply as live feed fish (Kar et al., 2017). Moreover, zooplankton organisms are often considered as bioindicators to assess the ecosystem quality of fishponds (Marbà et al., 2013) and fishery health (Ejsmont-Karabin, 2012; Ersoy et al., 2019; Pociecha et al., 2018).

5. Conclusion

The present review underlines the importance of ecosystem services provided by marine systems. The provision of seafood has crucial importance; fish add nutritional value to our daily diet, moreover, fishing and aquaculture farms represent economic entrances in different countries. Therefore, fishery management has to consider all the ecological roles of marine organisms and their trophic connections, in order to preserve the environment but also assure fish stocks. The present review discusses about the roles of zooplankton in marine systems, showing how its presence is essential for the good functioning of the ecosystem and fish recruitment. Zooplankton has a pivotal role in the food chain since it allows income of nutrient to the lower level and guaranteeing food to the upper levels. Malfunctions of each trophic level affect even the predator–prey interaction, leading a severe degradation of the ecosystem. To avoid the collapse of the food web, it is important to preserve zooplankton as it is fundamental for the existence of ecosystem services, such as fishery and aquaculture.

Fish preferred feed items are zooplankton organisms, thus a long-time series monitoring of zooplankton is useful to know not only the environmental status since zooplankton is also implied as bioindicator, but also if the relation predator–prey is efficient to assure fish recruitment. In light of this assumption, it is fundamental to develop public policies in fishery management aimed to guarantee sustainable fishing, recruitment of fish and the preservation of the environment as well as the fishing stock.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is financed by national funds through FCT - Foundation for Science and Technology, I.P., within the scope of the projects UIDB/04292/2020 – MARE – Marine and Environmental Sciences Centre and UIDP/50017/2020 + UIDB/50017/2020 (by FCT/MTCES) granted to CESAM – Centre for Environmental and Marine Studies. Silvia Lomartire thanks to the project PORBIOTA, E-Infrastructure Portuguese Information and Research in Biodiversity (POCI-01-0145-FEDER-022127), which co-financed this research supported by Competitiveness and Internationalization Operational Programme and Regional Operational Programme of Lisbon, through FEDER, and by the Portuguese Foundation for Science and Technology (FCT), through national funds (OE). Ana M. M. Gonçalves acknowledges University of Coimbra for the contract IT057-18-7253.

Conflict of Interest Statement.

The authors declare that they have no conflict of interest.

References

Abe, K., Imamaki, A., Hirano, M., 2002. Removal of nitrate, nitrite, ammonium and phosphate ions from water by the aerial microalga Trentepohlia aurea. J. Appl. Phycol. 14, 129–134. https://doi.org/10.1023/A:1019599216554.

Agadjihouèdé, H., Bonou, A.C., Montchowui, E., Laleye, P., 2011. Recherche de la dose optimale de fiente de volaille pour la production spécifique de zooplancton à des fins piscicoles. Cah. Agric. 20, 247–260. https://doi.org/10.16194/j.cnki.31-1059/g4.2011.07.016.

Austen, M.C., Malcolm, S.J., Frost, M., Hattam, C., Mangi, S., Stentford, G., Benjamins, S., Burrows, M., Butenschön, M., Duck, C., Johns, D., Merino, G., Mieszkowska, N., Miles, A., Mitchell, I., Smyth, T., 2011. The UK National Ecosystem Assessment Technical Report, UK National Ecosystem Assessment. UNEP- WCMC, Cambridge, 459 – 498. Marine 459–498.

Barbier, E.B., 2017. Marine ecosystem services. Curr. Biol. 27 (11), R507–R510. https://doi.org/10.1016/j.cub.2017.03.020.

Beaugrand, G., Brander, K.M., Lindley, J.A., Souissi, S., Reid, P.C., 2003. Plankton effect on cod recruitment in the North Sea. Nature 426, 661–664. https://doi.org/10.1093/plankt/19.10.1405.

Beaugrand, G., Edwards, M., Legendre, L., 2010. Marine biodiversity, ecosystem functioning, and carbon cycles. Proc. Natl. Acad. Sci. U. S. A. 107 (22), 10120–10124. https://doi.org/10.1073/pnas.0913855107.

Benkendorff, K., 2009. Aquaculture and the production of pharmaceuticals and nutraceuticals, New Technologies in Aquaculture: Improving Production Efficiency, Quality and Environmental Management. Woodhead Publishing Limited. https://doi.org/10.1533/9781845696474.5.866.

Bhaskaran, B., Imelda, J., 2020. Zooplankton Culture for Mariculture. Blue Bonanza A Man. job Train. Program. VHSE students Adv. Fish. Aquac. Tech. ICAR-Central Mar. Fish. Res. Institute, Kochi.

Blanda, E., Drillet, G., Huang, C.C., Hwang, J.S., Jakobsen, H.H., Rayner, T.A., Su, H.M., Wu, C.H., Hansen, B.W., 2015. Trophic interactions and productivity of copepods as live feed from tropical Taiwanese outdoor aquaculture ponds. Aquaculture 445, 11–21. https://doi.org/10.1016/j.aquaculture.2015.04.003.

Boero, F., 2013. Review of jellyfish blooms in the Mediterranean and Black Sea. Food Agric. Organ, United Nations.

Bogstad, B., Mehl, S., 1997. Interactions between Atlantic cod (Gadus morhua) and its prey species in the Barents Sea. Ecosyst. Alaska Sea Grant Coll. program, Forage Fishes Mar.

Borges, M.-T., Silva, P., Moreira, L., Soares, R., 2005. Integration of consumer-targeted microalgal production with marine fish effluent biofiltration - a strategy for mariculture sustainability. J. Appl. Phycol. 17 (3), 187–197. https://doi.org/10.1007/s10811-005-4842-y.

Brett, Michael, Müller-Navarra, Dörthe, 1997. The role of highly unsaturated fatty acids in aquatic foodweb processes. Freshw. Biol. 38 (3), 483–499.

Bruce, L.C., Hamilton, D., Imberger, J., Gal, G., Gophen, M., Zohary, T., Hambright, K.D., 2006. A numerical simulation of the role of zooplankton in C, N and P cycling in Lake Kinneret, Israel. Ecol. Modell. 193 (3-4), 412–436. https://doi.org/10.1016/j.ecolmodel.2005.09.008.

Bryhn, A., Kraufvelin, P., Bergström, U., Vretborn, M., Bergström, L., 2020. A model for disentangling dependencies and impacts among human activities and marine ecosystem services. Environ. Manage. 65 (5), 575–586. https://doi.org/10.1007/s00267-020-01260-1.

Bureau, D.P., Harris, A.M., Cho, C.Y., 1999. Apparent digestibility of rendered animal protein ingredients for rainbow trout (Oncorhynchus mykiss). Aquaculture 180 (3-4), 345–358. https://doi.org/10.1016/S0044-8486(99)00210-0.

Burford, M.A., Costanzo, S.D., Dennison, W.C., Jackson, C.J., Jones, A.B., McKinnon, A.D., Preston, N.P., Trott, L.A., 2003. A synthesis of dominant ecological processes in intensive shrimp ponds and adjacent coastal environments in NE Australia. Mar. Pollut. Bull. 46 (11), 1456–1469. https://doi.org/10.1016/S0025-326X(03)00282-0.

Canepa, A., Fuentes, V., Sabatés, A., Piraino, S., Boero, F., Gili, J.M., 2014. Pelagia noctiluca in the Mediterranean Sea. In Jellyfish blooms. Springer, Dordrecht.

Cardona, L., Álvarez de Quevedo, I., Borrell, A., Aguilar, A., Ropert-Coudert, Y., 2012. Massive consumption of gelatinous plankton by mediterranean apex predators. PLoS One 7 (3), e31329. https://doi.org/10.1371/journal.pone.003132910.1371/journal.pone.0031329.g00110.1371/journal.pone.0031329.g00210.1371/journal.pone.0031329.g00310.1371/journal.pone.0031329.g00410.1371/journal.pone.0031329.g00510.1371/journal.pone.0031329.g00610.1371/journal.pone.0031329.g00710.1371/journal.pone.0031329.g00810.1371/journal.pone.0031329.g00910.1371/journal.pone.0031329.t00110.1371/journal.pone.0031329.t00210.1371/journal.pone.0031329.t003.

Cavan, E.L., Henson, S.A., Belcher, A., Sanders, R., 2017. Role of zooplankton in determining the efficiency of the biological carbon pump. Biogeosciences 14 (1), 177–186. https://doi.org/10.5194/bg-14-177-201710.5194/bg-14-177-2017-supplement.

Chen, Q., Sheng, J., Lin, Q., Gao, Y., Lv, J., 2006. Effect of salinity on reproduction and survival of the copepod Pseudodiaptomus annandalei Sewell, 1919. Aquaculture 258 (1-4), 575–582. https://doi.org/10.1016/j.aquaculture.2006.04.032.

Converti, A., Scapazzoni, S., Lodi, A., Carvalho, J.C.M., 2006. Ammonium and urea removal by Spirulina platensis. J. Ind. Microbiol. Biotechnol. 33 (1), 8–16. https://doi.org/10.1007/s10295-005-0025-8.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Cushing, D.H., 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Advances in Marine Biology. https://doi.org/10.1016/S0065-2881(08)60202-3.

Dalpadado, P., Bogstad, B., Gjøster, H., Mehl, S., Skjoldal, H.R., 2002. 9 Zooplankton-fish interactions in the Barents Sea. Large Mar. Ecosyst. 10, 269–291. https://doi.org/10.1016/S1570-0461(02)80061-1.

Dalpadado, P., Skjoldal, H.R., 1996. Abundance, maturity and growth of the krill species Thysanoessa inermis and T. longicaudata in the Barents Sea. Mar. Ecol. Prog. Ser. 144, 175–183. https://doi.org/10.3354/meps144175.

Daskalov, G.M., 2003. Long-term changes in fish abundance and environmental indices in the Black Sea. Mar. Ecol. Prog. Ser. 255, 259–270. https://doi.org/10.3354/meps255259.

Daskalov, G.M., 2002. Overfishing drives atrophic cascade in the Black sea. Mar. Ecol. Prog. Ser. 225, 53–63. https://doi.org/10.3354/meps225053.

De Donno, A., Idolo, A., Bagordo, F., Grassi, T., Leomanni, A., Serio, F., Guido, M., Canitano, M., Zampardi, S., Boero, F., Piraino, S., 2014. Impact of stinging jellyfish proliferations along south Italian coasts: Human health hazards, treatment and social costs. Int. J. Environ. Res. Public Health 11, 2488–2503. https://doi.org/10.3390/ijerph110302488.

Dickson, M., Nasr-Allah, A., Kenawy, D., Kruijssen, F., 2016. Increasing fish farm profitability through aquaculture best management practice training in Egypt. Aquaculture 465, 172–178. https://doi.org/10.1016/j.aquaculture.2016.09.015.

Dong, Z., Liu, D., Keesing, J.K., 2010. Jellyfish blooms in China: dominant species, causes and consequences. Mar. Pollut. Bull. 60 (7), 954–963. https://doi.org/10.1016/j.marpolbul.2010.04.022.

Dounas, C., Davies, I., Triantafyllou, G., Koulouri, P., Petihakis, G., Arvanitidis, C., Sourlatzis, G., Eleftheriou, A., 2007. Large-scale impacts of bottom trawling on shelf primary productivity. Cont. Shelf Res. 27 (17), 2198–2210. https://doi.org/10.1016/j.csr.2007.05.006.

Edwards, M., Richardson, A.J., 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430, 881–884. https://doi.org/10.1386/stap.22.3.145.

Edwards, P., 2015. Aquaculture environment interactions: past, present and likely future trends. Aquaculture 447, 2–14. https://doi.org/10.1016/j.aquaculture.2015.02.001.

Ejsmont-Karabin, J., 2012. The usefulness of zooplankton as lake ecosystem indicators: rotifer trophic state index. Polish J. Ecol. 60, 339–350.

Elser, J.J., Fagan, W.F., Denno, R.F., Dobberfuhl, D.R., Folarin, A., Huberty, A., Interlandi, S., Kilham, S.S., McCauley, E., Schulz, K.L., Siemann, E.H., Sterner, R.W., 2000. Nutritional constraints in terrestrial and freshwater food webs. Nature 408 (6812), 578–580.

Ersoy, Z., Brucet, S., Bartrons, M., Mehner, T., 2019. Short-term fish predation destroys resilience of zooplankton communities and prevents recovery of phytoplankton control by zooplankton grazing. PLoS One 14, 1–15. https://doi.org/10.1371/journal.pone.0212351.

Commission, E., 2006. Council Regulation (EC) No 1967/2006 of 21 December 2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea. Off. J. Eur. Union 11–85.

Evjemo, J.O., Reitan, K.I., Olsen, Y., 2003. Copepods as live food organisms in the larval rearing of halibut larvae (Hippoglossus hippoglossus L.) with special emphasis on the nutritional value. Aquaculture 227 (1-4), 191–210. https://doi.org/10.1016/S0044-8486(03)00503-9.

FAO, 2018. The State of World Fisheries and Aquaculture: Meeting the sustainable development goals. FAO, Rome.

Fletcher, R., Baulcomb, C., Hall, C., Hussain, S., 2014. Revealing marine cultural ecosystem services in the Black Sea. Mar. Policy 50, 151–161. https://doi.org/10.1016/j.marpol.2014.05.001.

Fradique, M., Batista, A.P., Nunes, M.C., Gouveia, L., Bandarra, N.M., Raymundo, A., 2010. Incorporation of Chlorella vulgaris and Spirulina maxima biomass in pasta products. Part 1: Preparation and evaluation. J. Sci. Food Agric. 90 (10), 1656–1664. https://doi.org/10.1002/jsfa.3999.

Galasso, C., Gentile, A., Orefice, I., Ianora, A., Bruno, A., Noonan, D.M., Sansone, C., Albini, A., Brunet, C., 2019. Microalgal derivatives as potential nutraceutical and

food supplements for human health: a focus on cancer prevention and interception. Nutrients 11, 1–22. https://doi.org/10.3390/nu11061226.
Galloway, A.W.E., Winder, M., 2015. Partitioning the relative importance of phylogeny and environmental conditions on phytoplankton fatty acids. PLoS One 10, 1–23. https://doi.org/10.1371/journal.pone.0130053.
Gao, F., Li, C., Yang, Z.-H., Zeng, G.-M., Feng, L.-J., Liu, J.-Z., Liu, M., Cai, H.-W., 2016. Continuous microalgae cultivation in aquaculture wastewater by a membrane photobioreactor for biomass production and nutrients removal. Ecol. Eng. 92, 55–61. https://doi.org/10.1016/j.ecoleng.2016.03.046.
Gentry, R.R., Alleway, H.K., Bishop, M.J., Gillies, C.L., Waters, T., Jones, R., 2020. Exploring the potential for marine aquaculture to contribute to ecosystem services. Rev. Aquac. 12 (2), 499–512. https://doi.org/10.1111/raq.v12.210.1111/raq.12328.
Gjøsæter, H., 1998. The population biology and exploitation of capelin (Mallotus villosus) in the barents sea. Sarsia 83 (6), 453–496. https://doi.org/10.1080/00364827.1998.10420445.
Graham, W.M., Gelcich, S., Robinson, K.L., Duarte, C.M., Brotz, L., Purcell, J.E., Madin, L.P., Mianzan, H., Sutherland, K.R., Uye, S.-I., Pitt, K.A., Lucas, C.H., Bøgeberg, M., Brodeur, R.D., Condon, R.H., 2014. Linking human well-being and jellyfish: ecosystem services, impacts, and societal responses. Front. Ecol. Environ. 12 (9), 515–523. https://doi.org/10.1890/130298.
Greve, W., Reiners, F., Nast, J., 1996. Biocoenotic changes of the zooplankton in the German Bight: the possible effects of eutrophication and climate. ICES J. Mar. Sci. 53, 951–956. https://doi.org/10.1006/jmsc.1996.0117.
Grishin, A., Daskalov, G., Shlyakhov, V., Mihneva, V., 2007. Influence of gelatinous zooplankton on fish stocks in the black sea: analysis of biological time-series. Mar. Ecol. J. 7, 5–24.
Hansen, B.W., 2017. Advances using copepods in aquaculture. J. Plankton Res. 39, 972–974. https://doi.org/10.1093/plankt/fbx057.
Hassan, S.E., Azab, A.M., Abo-Taleb, H.A., El-Feky, M.M., 2020. Effect of replacing fish meal in fish diet by zooplankton meal on growth performance of dicentrarchus labrax (Linnaeus, 1758). Egypt. J. Aquat. Biol. Fish. 24, 267–280. https://doi.org/10.21608/EJABF.2020.111756.
Hattam, C., Atkins, J.P., Beaumont, N., Börger, T., Böhnke-Henrichs, A., Burdon, D., De Groot, R., Hoefnagel, E., Nunes, P.A.L.D., Piwowarczyk, J., Sastre, S., Austen, M.C., 2015. Marine ecosystem services: linking indicators to their classification. Ecol. Indic. 49, 61–75. https://doi.org/10.1016/j.ecolind.2014.09.026.
Henschke, N., Everett, J.D., Richardson, A.J., Suthers, I.M., 2016. Rethinking the role of Salps in the Ocean. Trends Ecol. Evol. 31 (9), 720–733. https://doi.org/10.1016/j.tree.2016.06.007.
Hensen, V., 1884. Ueber die Bestimmung der Planktons oder des im Meer triebenden Materials an Pflanzen und Tieren. Bericht der Comm. zur Wissenschaftlichen Untersuchungen der Dtsch, Meere, p. 5.
Hjort, J., 1914. Fluctuations in the great fisheries of Norther Europe. Rapp. Procés-Verbaux 20, 1–228.
Hodar, A.R., Vasava, R., Joshi, N.H., 2020. Fish meal and fish oil replacement for aqua feed formulation by using alternative sources: a review. J. Exp. Zool. India 23, 13–21.
Howick, G.L., Wilhm, J., 1984. Zooplankton and Benthic Macroinvertebrates in Lake 65, 63–65.
Hudson, J.J., Taylor, W.D., 1996. Measuring regeneration of dissolved phosphorus in planktonic communities. Limnol. Oceanogr. 41 (7), 1560–1565. https://doi.org/10.4319/lo.1996.41.7.1560.
Hudson, J.J., Taylor, W.D., Schindler, D.W., 1999. Hudson et al. 1999 Planktonic nutrient 461, 1998–2000.
Hutchinson, G.E., 1953. The concept of pattern in ecology. Acad. Nat. Sci. 105, 1–12. https://doi.org/10.5962/bhl.title.123689.
Jorge, C., Antonio, O.J., German, C., Irina, C., del Carmen, M.M., Daniel, B.-C., 2016. Laboratory production of Daphnia magna (Straus 1820) fed with microalgae and active dry yeast. J. Entomol. Zool. Stud. 4, 548–553.
Kar, S., Das, P., Das, U., Bimola, M., Kar, D., Aditya, G., 2017. Culture of the zooplankton as fish food: observations on three freshwater species from Assam, India. AACL Bioflux 10, 1210–1220.
Kaushik, S.J., 1995. Nutrient requirements, supply and utilization in the context of carp culture. Aquaculture 129 (1-4), 225–241. https://doi.org/10.1016/0044-8486(94)00274-R.
Ketola, H.G., 1982. Amino acid nutrition of fishes: requirements and supplementation of diets. Comp. Biochem. Physiol. – Part B Biochem. 73 (1), 17–24. https://doi.org/10.1016/0305-0491(82)90197-3.
Khan, M.A., Hasan, M.M., Sumon, K.A., Rashid, H., 2020. Culture of freshwater zooplankton Daphnia magna fed with different feed combination. Bangladesh J. Fish 32, 55–59.
Kim, D.-H., Seo, J.-N., Yoon, W.-D., Suh, Y.-S., 2012. Estimating the economic damage caused by jellyfish to fisheries in Korea. Fish. Sci. 78 (5), 1147–1152. https://doi.org/10.1007/s12562-012-0533-1.
Kontogianni, A.D., Emmanouilides, C.J., 2014. The cost of a gelatinous future and loss of critical habitats in the Mediterranean. ICES 71, 853–866. https://doi.org/10.1038/278097a0.
Kwon, E.Y., Primeau, F., Sarmiento, J.L., 2009. The impact of remineralization depth on the air-sea carbon balance. Nat. Geosci. 2 (9), 630–635. https://doi.org/10.1038/ngeo612.
Leal, M.C., Calado, R., Sheridan, C., Alimonti, A., Osinga, R., 2013. Coral aquaculture to support drug discovery. Trends Biotechnol. 31 (10), 555–561. https://doi.org/10.1016/j.tibtech.2013.06.004.
Lee, C.-H., Dahms, H.-U., Cheng, S.-H., Souissi, S., Schmitt, F.G., Kumar, R., Hwang, J.-S., 2010. Predation of Pseudodiaptomus annandalei (Copepoda: Calanoida) by the grouper fish fry Epinephelus coioides under different hydrodynamic conditions. J. Exp. Mar. Bio. Ecol. 393 (1-2), 17–22. https://doi.org/10.1016/j.jembe.2010.06.005.
Lee, X.J., Ong, H.C., Gan, Y.Y., Chen, W.-H., Mahlia, T.M.I., 2020. State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production. Energy Convers. Manag. 210, 112707. https://doi.org/10.1016/j.enconman.2020.112707.
Lefebvre, S., Probert, I., Lefrançois, C., Hussenot, J., 2004. Outdoor phytoplankton continuous culture in a marine fish-phytoplankton- bivalve integrated system: combined effects of dilution rate and ambient conditions on growth rate, biomass and nutrient cycling. Aquaculture 240 (1-4), 211–231. https://doi.org/10.1016/j.aquaculture.2004.06.022.
Legendre, L., Rivkin, R.B., 2005. Integrating functional diversity, food web processes, and biogeochemical carbon fluxes into a conceptual approach for modeling the upper ocean in a high-CO2 world. J. Geophys. Res. C Ocean. 110, 1–17. https://doi.org/10.1029/2004JC002530.
Lehman, J.T., Sandgren, C.D., 1985. Species-specific rates of growth and grazing loss among freshwater algae. Limnol. Oceanogr. 30, 34–46. https://doi.org/10.4319/lo.1985.30.1.0034.
Lupatsch, I., Kissil, G.W., Sklan, D., 2001. Optimization of feeding regimes for European sea bass Dicentrarchus labrax: as factorial approach. Aquaculture 202 (3-4), 289–302. https://doi.org/10.1016/S0044-8486(01)00779-7.
Lussenhop, J., 1974. Victor Hensen and the development of sampling methods in ecology. J. Hist. Biol. 7 (2), 319–337. https://doi.org/10.1007/BF00351208.
Lynam, C.P., Hay, S.J., Brierley, A.S., 2004. Interannual variability in abundance of North Sea jellyfish and links to the North Atlantic Oscillation. Limnol. Oceanogr. 49 (3), 637–643. https://doi.org/10.4319/lo.2004.49.3.0637.
Lynam, C.P., Heath, M.R., Hay, S.J., Brierley, A.S., 2005. Evidence for impacts by jellyfish on North Sea herring recruitment. Mar. Ecol. Prog. Ser. 298, 157–167. https://doi.org/10.3354/meps298157.
Macedo, C.F., Pinto-Corlho, R.M., 2001. Nutritional status response of Daphania laevis and Moina micura from a tropical reservoir to different algal diets: scenedesmus quadricauda and Ankistrodesmus gracilis. Brazilian J. Biol. 61 (4), 555–562. https://doi.org/10.1590/S1519-69842001000400005.
Mackas, D., Galbraith, M., Faust, D., Masson, D., Young, K., Shaw, W., Romaine, S., Trudel, M., Dower, J., Campbell, R., Sastri, A., Bornhold Pechter, E.A., Pakhomov, E., El-Sabaawi, R., 2013. Zooplankton time series from the strait of georgia: results from year-round sampling at deep water locations, 1990–2010. Prog. Oceanogr. 115, 129–159. https://doi.org/10.1016/j.pocean.2013.05.019.
Mandal, S.C., Das, P., Singh, S.K., Bhagabati, S.K., 2009. Feeding of aquarium fishes with natural and artificial foods: available options and future needs. Aquac. Int. 3, 20–23.
Marbà, N., Krause-Jensen, D., Alcoverro, T., Birk, S., Pedersen, A., Neto, J.M., Orfanidis, S., Garmendia, J.M., Muxika, I., Borja, A., Dencheva, K., Duarte, C.M., 2013. Diversity of European seagrass indicators: patterns within and across regions. Hydrobiologia 704 (1), 265–278. https://doi.org/10.1007/s10750-012-1403-7.
Matos, Â.P., 2019. In: Proteins: Sustainable Source, Processing and Applications. Elsevier, pp. 63–96. https://doi.org/10.1016/B978-0-12-816695-6.00003-9.
Mavuti, K.M., 1990. Ecology and role of zooplankton in the fishery of Lake Naivasha. Hydrobiologia 208 (1-2), 131–140. https://doi.org/10.1007/BF00008452.
Michels, M.H.A., Vaskoska, M., Vermuë, M.H., Wijffels, R.H., 2014. Growth of Tetraselmis suecica in a tubular photobioreactor on wastewater from a fish farm. Water Res. 65, 290–296. https://doi.org/10.1016/j.watres.2014.07.017.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Current States and Trends. Isl. Press, Washington, D.C., p. 18
Miyashita, K., Beppu, F., Hosokawa, M., Liu, X., Wang, S., 2020. Nutraceutical characteristics of the brown seaweed carotenoid fucoxanthin. Arch. Biochem. Biophys. 686, 108364. https://doi.org/10.1016/j.abb.2020.108364.
Mulbry, W., Kondrad, S., Pizarro, C., Kebede-Westhead, E., 2008. Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresour. Technol. 99 (17), 8137–8142. https://doi.org/10.1016/j.biortech.2008.03.073.
Müller-Navarra, D.C., Brett, M.T., Liston, A.M., Goldman, C.R., 2000. A highly unsaturated fatty acid predicts carbon transfer between primary producers and consumers. Nature 403 (6765), 74–77. https://doi.org/10.1038/47469.
Munro, M.H.G., Blunt, J.W., Dumdei, E.J., Hickford, S.J.H., Lill, R.E., Li, S., Battershill, C.N., Duckworth, A.R., 1999. The discovery and development of marine compounds with pharmaceutical potential. J. Biotechnol. 70 (1-3), 15–25.
Naeem, S., Duffy, J.E., Zavaleta, E., 2012. The functions of biological diversity in an age of extinction. Science (80-.) 336 (6087), 1401–1406. https://doi.org/10.1126/science:1215855.
Naylor, R., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024. https://doi.org/10.1007/s12665-015-5022-2.
Nichols, P.D., Holdsworth, D.G., Volkman, J.K., Daintith, M., Allanson, S., 1989. High incorporation of essential fatty acids by the rotifer brachionus plicatilis fed on the prymnesiophyte alga Pavlova Lutheri. Mar. Freshw. Res. 40, 645–655. https://doi.org/10.1071/MF9890645.
Nixon, S.W., Oviatt, C.A., Frithsen, J., Sullivan, B., 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. J. Limnol. Soc. South. Africa 12 (1-2), 43–71. https://doi.org/10.1080/03779688.1986.9639398.
Omori, M., van der Spoel, S., Norman, C.P., 1994. Impact of human activities on pelagic biogeography. Prog. Oceanogr. 34 (2-3), 211–219. https://doi.org/10.1016/0079-6611(94)90009-4.

Parekh, P., Dutkiewicz, S., Follows, M.J., Ito, T., 2006. Atmospheric carbon dioxide in a less duty world. Geophys. Res. Lett. 33, 2–5. https://doi.org/10.1029/2005GL025098.

Patwa, A., Thiéry, A., Lombard, F., Lilley, M.K.S., Boisset, C., Bramard, J.F., Bottero, J.Y., Barthélémy, P., 2015. Accumulation of nanoparticles in "jellyfish" mucus: a bio-inspired route to decontamination of nano-waste. Sci. Rep. 5, 1–8. https://doi.org/10.1038/srep11387.

Pechar, L., 2000. Impacts of long-term changes in fishery management on the trophic level water quality in Czech fish ponds. Fish. Manag. Ecol. 7, 23–31. https://doi.org/10.1046/j.1365-2400.2000.00193.x.

Perissinotto, R., McQuaid, C.D., 1992. Land-based predator impact on vertically migrating zooplankton and micronekton advected to a Southern Ocean archipelago. Mar. Ecol. Prog. Ser. 80, 15–27. https://doi.org/10.3354/meps080015.

Perry, R.I., Batchelder, H.P., Mackas, D.L., Chiba, S., Durbin, E., Greve, W., Verheye, H. M., 2004. Identifying global synchronies in marine zooplankton populations: issues and opportunities. ICES J. Mar. Sci. 61, 445–456. https://doi.org/10.1016/j.icesjms.2004.03.022.

Pershing, A.J., Greene, C.H., Jossi, J.W., O'Brien, L., Brodziak, J.K.T., Bailey, B.A., 2005. Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. ICES J. Mar. Sci. 62, 1511–1523. https://doi.org/10.1016/j.icesjms.2005.04.025.

Pilskaln, C.H., Churchill, J.H., Mayer, L.M., 1998. Resuspension of sediment by bottom trawling in the Gulf of Maine and potential geochemical consequences. Conserv. Biol. 12 (6), 1223–1229. https://doi.org/10.1046/j.1523-1739.1998.0120061223.x.

Pinel-Alloul, B., Downing, J.A., Perusse, M., Codin- Blumer, G., 1988. Spatial heterogeneity in freshwater zooplankton: variation with body size, depth and scale. Ecol. Soc. Am. 69, 1393–1400.

Platt, T., Fuentes-Yaco, C., Frank, K.T., 2003. Spring algal bloom and larval fish survival. Nature 423, 398–399. https://doi.org/10.1038/423398a.

Pociecha, A., Bielańska-Grajner, I., Szarek-Gwiazda, E., Wilk-Woźniak, E., Kuciel, H., Walusiak, E., 2018. Rotifer diversity in the acidic pyrite mine pit lakes in the sudety mountains (Poland)波兰苏台德山脉(Sudety Mts.)黄铁矿酸性矿坑湖湖水轮虫多样性 Diversität von Rotifera in sauren Pyritbergbauseen der Sudeten (Polen)Diversidad de rotíferos en los lagos ácidos del hoyo de mina pirítica en las montañas Sudety (Polonia). Mine Water Environ. 37 (3), 518–527. https://doi.org/10.1007/s10230-017-0492-y.

Ponomarenko, I.Y., Yaragina, N.A., 1979. Seasonal and year to year variations in the feeding of the Barents Sea cod on Euphausiacea in 1947–1977. ICES J. Mar. Sci. 91, 17–20.

Potužák, J., Hůda, J., Pechar, L., 2007. Changes in fish production effectivity in eutrophic fishponds - impact of zooplankton structure. Aquac. Int. 15 (3-4), 201–210. https://doi.org/10.1007/s10499-007-9085-2.

Purcell, J.E., 2012. Jellyfish and ctenophore blooms coincide with human proliferations and environmental perturbations. Ann. Rev. Mar. Sci. 4 (1), 209–235. https://doi.org/10.1146/annurev-marine-120709-142751.

Purcell, J.E., Arai, M.N., 2001. Interactions of pelagic cnidarians and ctenophores with fish: a review. Hydrobiologia 451, 27–44. https://doi.org/10.1023/A:1011883905394.

Rawles, S.D., Riche, M., Gaylord, T.G., Webb, J., Freeman, D.W., Davis, M., 2006. Evaluation of poultry by-product meal in commercial diets for hybrid striped bass (Morone chrysops ♀ × M. saxatilis ♂) in recirculated tank production. Aquaculture 259 (1-4), 377–389. https://doi.org/10.1016/j.aquaculture.2006.05.053.

Reid, P.C., 1984. Yera-to-year changes in zooplaknton biomass, fish yield and fish stock in the North Sea. Int. Counc. Explor. Sea.

Richardson, A.J., 2008. In hot water: zooplankton and climate change. ICES J. Mar. Sci. 65, 279–295. https://doi.org/10.1093/icesjms/fsn028.

Richardson, A.J., Bakun, A., Hays, G.C., Gibbons, M.J., 2009. The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. Trends Ecol. Evol. 24 (6), 312–322. https://doi.org/10.1016/j.tree.2009.01.010.

Rodger, H.D., Henry, L., Mitchell, S.O., 2011. Non-infectious gill disorders of marine salmonid fish. Rev. Fish Biol. Fish. 21 (3), 423–440. https://doi.org/10.1007/s11160-010-9182-6.

Rønnestad, I., Thorsen, A., Finn, R.N., 1999. Fish larval nutrition: a review of recent advances in the roles of amino acids. Aquaculture 177 (1-4), 201–216. https://doi.org/10.1016/S0044-8486(99)00082-4.

Schneider, G., Schneider, G., Behrends, G., 1998. Top-down control in a neritic plankton system by aurelia aurita medusae — a summary. Ophelia 48, 71–82. https://doi.org/10.1080/00785236.1998.10428677.

Serranito, B., Aubert, A., Stemmann, L., Rossi, N., Jamet, J.L., 2016. Proposition of indicators of anthropogenic pressure in the Bay of Toulon (Mediterranean Sea) based on zooplankton time-series. Cont. Shelf Res. 121, 3–12. https://doi.org/10.1016/j.csr.2016.01.016.

Shapawi, R., Ng, W.-K., Mustafa, S., 2007. Replacement of fish meal with poultry by-product meal in diets formulated for the humpback grouper, Cromileptes altivelis. Aquaculture 273 (1), 118–126. https://doi.org/10.1016/j.aquaculture.2007.09.014.

Sherman, K., Kane, J., Murawski, S., Overholtz, W., Solow, A., 2002. 6 The U.S. Northeast shelf large marine ecosystem: zooplankton trends in fish biomass recovery. Large Mar. Ecosyst. 10, 195–215. https://doi.org/10.1016/S1570-0461(02)80058-1.

Shiganova, T.A., Dumont, H.J., Mikaelyan, A., Glazov, D.M., Bulgakova, Y. V., Musaeva, E.I., Sorokin, P.Y., Pautova, L.A., Mirzoyan, Z.A., Studenikina, E.I., 2006. Interactions between the invading ctenophores Mnemiopsis leidyi (A. Agassiz) and Beroe ovata Mayer 1912, and their influence on the Pelagic ecosystem of the Northeastern Black Sea. Aquat. Invasions Black, Caspian, Mediterr. Seas 33–70. https://doi.org/10.1007/1-4020-2152-6_2.

Shiganova, T.A., Sommer, U., Javidpour, J., Molinero, J.C., Malej, A., Kazmin, A.S., Isinibilir, M., Christou, E., Siokou- Frangou, I., Marambio, M., Fuentes, V., Mirsoyan, Z.A., Gülsahin, N., Lombard, F., Lilley, M.K.S., Angel, D.L., Galil, B.S., Bonnet, D., Delpy, F., 2019. Patterns of invasive ctenophore Mnemiopsis leidyi distribution and variability in different recipient environments of the Eurasian seas: a review. Mar. Environ. Res. 152, 104791. https://doi.org/10.1016/j.marenvres.2019.104791.

Skjoldal, H.R., Rey, F., 1989. Pelagic production and variability of the Barents Sea Ecosystem. AAAS Sel, Symp.

Soletto, D., Binaghi, L., Lodi, A., Carvalho, J.C.M., Converti, A., 2005. Batch and fed-batch cultivations of Spirulina platensis using ammonium sulphate and urea as nitrogen sources. Aquaculture 243 (1-4), 217–224. https://doi.org/10.1016/j.aquaculture.2004.10.005.

Southward, A.J., Hawkins, S.J., Burrows, M.T., 1995. Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. J. Therm. Biol. 20 (1-2), 127–155. https://doi.org/10.1016/0306-4565(94)00043-I.

Sterner, R.W., 2009. Encyclopedia of Inland Waters. Encycl. Inl. Waters 678–688.

Strandberg, U., Hiltunen, M., Jelkänen, E., Taipale, S.J., Kainz, M.J., Brett, M.T., Kankaala, P., 2015. Selective transfer of polyunsaturated fatty acids from phytoplankton to planktivorous fish in large boreal lakes. Sci. Total Environ. 536, 858–865. https://doi.org/10.1016/j.scitotenv.2015.07.010.

Sweetman, A.K., Chapman, A., 2015. First assessment of flux rates of jellyfish carcasses (jelly-falls) to the benthos reveals the importance of gelatinous material for biological C-cycling in jellyfish-dominated ecosystems. Front. Mar. Sci. 2, 1–7. https://doi.org/10.3389/fmars.2015.00047.

Tacon, A.G.J., 1996. Feed formulation and evaluation for semi-intensive culture of fishes and shrimps in the tropics fishes and shrimps in the tropics. Santiago CB, Coloso RM, Millamena OM, Borlongan EG Feed. Small-Scale Aquac. Proc. Natl. Semin. Fish Nutr. Feed. SEAFDEC Aquac. Dep. Iloilo, Philipp. 29–43.

Tacon, A.G.J., Metian, M., 2015. Feed matters: satisfying the feed demand of aquaculture. Rev. Fish. Sci. Aquac. 23 (1), 1–10. https://doi.org/10.1080/23308249.2014.987209.

Taipale, S.J., Galloway, A.W.E., Aalto, S.L., Kahilainen, K.K., Strandberg, U., Kankaala, P., 2016. Terrestrial carbohydrates support freshwater zooplankton during phytoplankton deficiency. Sci. Rep. 6, 1–15. https://doi.org/10.1038/srep30897.

Taipale, S.J., Kahilainen, K.K., Holtgrieve, G.W., Peltomaa, E.T., 2018. Simulated eutrophication and browning alters zooplankton nutritional quality and determines juvenile fish growth and survival. Ecol. Evol. 8 (5), 2671–2687. https://doi.org/10.1002/ece3.2018.8.issue-510.1002/ece3.3832.

Tamaru, C.S., Murashige, R., Lee, C.-S., 1994. The paradox of using background phytoplankton during the larval culture of striped mullet, Mugil cephalus L. Aquaculture 119 (2-3), 167–174. https://doi.org/10.1016/0044-8486(94)90173-2.

Tocher, D.R., 2010. Fatty acid requirements in ontogeny of marine and freshwater fish. Aquac. Res. 41, 717–732. https://doi.org/10.1111/j.1365-2109.2008.02150.x.

Tóth, F., Zsuga, K., Kerepeczki, É., Berzi-Nagy, L., Sándor, Z.J., Körmöczi, L., 2020. The effect of feed composition on the structure of zooplankton communities in fishponds. Water Res. 12, 1–14.

Urabe, J., Nakanishi, M., Kawabata, K., 1995. Contribution of metazoan plankton to the cycling of nitrogen and phosphorus in Lake Biwa. Limnol. Oceanogr. 40 (2), 232–241. https://doi.org/10.4319/lo.1995.40.2.0232.

Valdés, L., López-Urrutia, A., Cabal, J., Alvarez-Ossorio, M., Bode, A., Miranda, A., Cabanas, M., Huskin, I., Anadón, R., Alvarez-Marqués, F., Llope, M., Rodríguez, N., 2007. A decade of sampling in the Bay of Biscay: what are the zooplankton time series telling us? Prog. Oceanogr. 74 (2-3), 98–114. https://doi.org/10.1016/j.pocean.2007.04.016.

Vanni, M.J., 2002. Nutrient cycling by animals in freshwater ecosystems. Annu. Rev. Ecol. Syst. 33 (1), 341–370. https://doi.org/10.1146/annurev.ecolsys.33.010802.150519.

Watanabe, T., Kitajima, C., Fujita, S., 1983. Nutritional values of live organisms used in Japan for mass propagation of fish: a review. Aquaculture 34 (1-2), 115–143. https://doi.org/10.1016/0044-8486(83)90296-X.

Waya, R.K., Limbu, S.M., Ngupula, G.W., Mwita, C.J., Mgaya, Y.D., 2017. Temporal patterns in phytoplankton, zooplankton and fish composition, abundance and biomass in Shirati Bay, Lake Victoria. Tanzania. Lakes Reserv. Res. Manag. 22 (1), 19–42. https://doi.org/10.1111/lre.2017.22.issue-110.1111/lre.12161.

Weatherley, A.H., Gill, H.S., 1983. Relative growth of tissues at different somatic growth rates in rainbow trout Salmo gairdneri Richardson. J. Fish Biol. 22 (1), 43–60. https://doi.org/10.1111/jfb.1983.22.issue-110.1111/j.1095-8649.1983.tb04725.x.

Welker, T.L., Lim, C., Barrows, F.T., Liu, K., 2014. Use of distiller's dried grains with solubles (DDGS) in rainbow trout feeds. Anim. Feed Sci. Technol. 195, 47–57. https://doi.org/10.1016/j.anifeedsci.2014.05.011.

Wotton, R., 1990. Fishes. Ecology of teleost. Chapman & HaHall, London.