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AQUATIC ECOSYSTEM SERVICES

Review Paper

Aquatic ecosystem services: an overview of the Special Issue

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Introduction to ecosystem services

Millennium Ecosystem Assessment

The dependency of human wellbeing from ecological systems has been long recognized. At the same time, ecosystems' integrity and their capacity to sustain human wellbeing have been threatened (Vörösmarty et al., 2010; Steffen et al., 2015; Culhane et al., 2019). One way of raising public awareness about ecosystems' value and the need for their protection is to recognize and value the services they provide to society (Bull et al., 2016); an approach that is not without criticism (Bekessy et al., 2018).

The seminal study by Costanza et al. (1997) was the first attempt to call the attention of policymakers

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Table 1 Ecosystem services framework proposed by the MEA (2005)

Category of ecosystem service	Definition	Examples
Supporting services	Services needed for the production of all other ecosystem services	Water cycling; Nutrient cycling; Primary production; Oxygen production; Soil formation and retention; Provisioning of habitat
Regulating services	The benefits obtained from the regulation of ecosystem processes	Storm protection; Erosion control; Climate regulation; Air quality maintenance; Water regulation; Water purification and waste treatment; Regulation of human diseases; Biological control; Pollination
Provisioning services	The products obtained from ecosystems	Fresh water; Food; Ornamental resources; Fuel; Genetic resources; Fiber; Biochemicals, natural medicines and pharmaceuticals
Cultural services	The non-material benefits obtained from ecosystems	Aesthetic values; Inspiration; Spiritual and religious values; Sense of place; Ecotourism; Recreation; Educational values; Cultural diversity; Knowledge systems; Social relations; Cultural heritage values

and the general society to the economic value of ecosystems. In a conservative approach considering only 17 ecosystem services and 16 biomes, they suggested that the global ecosystem services annual average economic value was twice (US$ 33 trillion) that of the annual global gross national product in 1995 (Costanza et al., 1997); this value is greatly underestimated mainly due to our poor knowledge about the complexity of ecosystems. However, the lack of a global ecosystems' assessment prompted the United Nations to launch the Millennium Ecosystem Assessment (MEA) in 2000 (formal public launch in June 2001), which ran for 5 years (MEA, 2003, 2005). This was an international assessment program aiming at evaluating the effects of ecosystem change for human wellbeing and to provide scientific evidence to support ecosystems' conservation and sustainable use so that they can continue to support human wellbeing (MEA, 2005). The MEA focused on the relation between ecosystems and ecosystem services, which refer to the "benefits people obtain from ecosystems" (MEA, 2005). According to the MEA framework, ecosystem services include both direct and indirect benefits taken from ecosystems and can be grouped into four categories: supporting, regulating, provisioning and cultural services (Table 1).

Although the ecosystem services approach may be considered utilitarian and anthropocentric (e.g., McAfee, 2012; Silvertown, 2015), it reflects human dependence on nature and contributes to increasing environmental awareness (MEA, 2005). In addition, valuation of the services provided by ecosystems should ideally consider values other than economic, such as ecological, social and cultural values, as they are all essential for human wellbeing. Surely, the intrinsic value of nature should never be disregarded in ecosystem conservation and restoration efforts, but approaches based on both economic and human wellbeing values are complementary tools to address the world's environmental crisis (see Rea & Munns, 2017). Also, the ecosystem services approach is flexible and works at different scales; for instance, ecosystem services can be derived from ecosystems but also from individual taxa or guilds.

The ecosystem services approach has provided background and motivated international legislation and agreements aiming to halt and reverse ecosystem degradation and biodiversity loss, such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), the UN Decade on Ecosystem Restoration, and the EU Nature Restoration Law. Identifying ecosystem services provided by aquatic ecosystems and organisms is, therefore, of paramount importance to help draw attention towards their protection. Given people's strong dependence on aquatic ecosystems and organisms, their protection will contribute to achieving the UN Sustainable Developments Goals.

Motivation and organization of the Special Issue

Aquatic ecosystems are among the most threatened ecosystems on Earth (Dudgeon, 2019) and their ecosystem services are among the least studied (Vári et al., 2022). The aim of this Special Issue is to raise awareness about the importance of aquatic ecosystems and organisms to human wellbeing by providing overviews of the ecosystem services they provide to human societies. This is done following the ecosystem services framework proposed by the MEA (2005). The Special Issue starts with an assessment of the trends in the study of ecosystem services provided by freshwaters (Nabout et al., 2022). This is followed by 6 reviews addressing ecosystem services provided by specific aquatic ecosystems and 12 reviews addressing ecosystem services provided by different groups of aquatic organisms (Table 2). The Special Issue then ends with an assessment of inequality in aquatic ecosystem services (Kovalenko et al., 2023). The papers included in this Special Issue, together with reviews on ecosystem services provided by other aquatic ecosystems and organisms (e.g., Barbier et al., 2011; Macadam & Stockan, 2015; Hilt et al., 2017; Riis et al., 2020; Janssen et al., 2021), contribute to highlighting the relevance of these ecosystems and organisms to human wellbeing, and emphasizing the need for their conservation and restoration.

Ecosystem services provided by aquatic organisms and ecosystems

Supporting services

Different lines of research in ecology are taxonomically biased, so much so that even certain groups (e.g., fungi) that are well-known to provide important supporting ecosystem services (e.g., nutrient cycling) are neglected. In this context, the call of Seena et al. (2022) to consider the different ecosystem services provided by aquatic hyphomycetes is most timely. Supporting ecosystem services provided

Table 2 Aquatic ecosystems and organisms addressed in this Special Issue

Ecosystem/organism	References
Aquatic ecosystems	
Freshwater ecosystems	Nabout et al. (2022)
Small streams	Ferreira et al. (2022)
Stream restoration	Verdonschot & Verdonschot (2022)
River–floodplain ecosystems	Petsch et al. (2022)
Dry rivers	Vidal-Abarca Gutiérrez et al. (2022)
Coastal lagoons	Rodrigues-Fillho et al. (2023)
Seagrass ecosystems	Lima et al. (2023)
Aquatic organisms	
Bacteria, archaea, and viruses	Llames et al. (2022)
Marine and freshwater phytoplankton	Naselli-Flores & Padisák (2022)
Freshwater and marine diatoms	B-Béres et al. (2022)
Silica-scaled chrysophytes	Lengyel et al. (2022)
Freshwater macrophytes	Thomaz (2021)
Freshwater fungi	Seena et al. (2022)
Freshwater metazooplankton	Declerck & Senerpont Domis (2022)
Freshwater invasive bivalves	Burlakova et al. (2022)
Jellyfish	Lee et al. (2022)
Marine forage fish	Nissar et al. (2022)
Neotropical freshwater fishes	Pelicice et al. (2022)
Anadromous fish	Almeida et al. (2023)
Inequality in aquatic ecosystem services	Kovalenko et al. (2023)

by other often neglected groups (e.g., exotic bivalves, chrysophytes, and viruses) were also reviewed in this Special Issue (Burlakova et al., 2022; Lengyel et al., 2022; Llames et al., 2022). As reviewed by Pelicice et al. (2022), Neotropical freshwater fishes are directly involved in nutrient cycling and habitat provisioning, and indirectly in soil formation owing to the deposition of fish remains on riparian areas by traditional populations in the Amazon. Anadromous fish are important in maintaining the productivity of food-webs and biological cycles, for instance (Almeida et al., 2023). The key role of marine forage fish as prey for larger-bodied fish, aquatic mammals, and birds, was highlighted by Nissar et al. (2022). Even though supporting ecosystem services provided by emblematic groups (e.g., phytoplankton, as reviewed by Naselli-Flores & Padisák, 2022) are generally better known, B-Béres et al. (2022) describe a noteworthy parallel between soil formation and sedimentary deposits formed by diatom remains (in this context, see also Naselli-Flores & Padisák, 2022). Critical supporting ecosystem services of freshwater macrophytes (e.g., habitat provisioning) and metazooplankton (e.g., food source for larvae and juveniles of most freshwater fish species, in nature and in aquaculture) were discussed by Thomaz (2021) and Declerck & Senerpont Domis (2022), respectively. In general, Nabout et al. (2022) suggested that macroinvertebrates, microorganisms, and aquatic macrophytes were the main groups evaluated when it comes to the analysis of supporting services provided by freshwater organisms.

Supporting services provided by specific ecosystem types, such as river–floodplain systems, dry rivers, small streams, coastal lagoons, and seagrass ecosystems, were also minutely summarized in papers published in this Special Issue (Ferreira et al., 2022; Petsch et al., 2022; Verdonschot & Verdonschot, 2022; Vidal-Abarca Gutiérrez et al., 2022; Lima et al., 2023; Rodrigues-Filho et al., 2023). The general importance of ecosystem services to poverty alleviation was a pivotal theme discussed in the MEA (2005). In this context, Kovalenko et al. (2023) discuss how different services provided by aquatic ecosystems are unevenly distributed among people and emphasize that fostering equitable access to these services is most needed to increase public support for the protection and restoration of aquatic ecosystems.

Regulating services

Regulating services are the most studied ecosystem service category in aquatic ecosystems to date (Nabout et al., 2022). Aquatic primary producers play a key role in air quality and climate regulation via photosynthesis, as reviewed in this Special Issue (Thomaz, 2021; B-Béres et al., 2022; Lengyel et al., 2022; Naselli-Flores & Padisák, 2022), but they also contribute to climate regulation via silicified carbon sequestration and emissions of dimethylsulphide (B-Béres et al., 2022; Lengyel et al., 2022). Less commonly recognized is the climate regulating role of metazooplankton, the latter affecting biogeochemical cycling of carbon by grazing and sequestration (Declerck & Senerpont Domis, 2022).

Mussels, including invasive species such as *Dreissena* spp., filter large volumes of water and can be used in bioremediation (Burlakova et al., 2022). Metazooplankton likewise plays an important filtrating role (Declerck & Senerpont Domis, 2022). The role of some aquatic organisms in water purification is more specialized; for instance, phagotrophic chrysophytes contribute to biodegradation of crude oil (Lengyel et al., 2022). Macrophytes purify water *via* nutrient retention and pollutant sequestration and are used in phytoremediation (Thomaz, 2021), and macrophytes and benthic algae also contribute to sediment stabilization (Thomaz, 2021; B-Béres et al., 2022).

Organic matter decomposition is one of the most studied ecosystem services provided by microorganisms (Llames et al., 2022; Seena et al., 2022), although viruses and bacteria also play a significant role in biological control of all aquatic biota. Other detritivores, such as several fish families, contribute to organic matter decomposition by breaking up larger particles (Pelicice et al., 2022), thereby increasing the surface area available for microorganism colonization. Neotropical fish also play a role in seed dispersal (Pelicice et al., 2022), likely driving community dynamics of riparian forests. Anadromous fish are greatly involved in the redistribution of nutrients, particularly by carrying marine-derived nutrients into freshwaters (Almeida et al., 2023).

Different types of aquatic ecosystems provide a different balance of the various ecosystem services. For instance, small streams are more likely to provide regulating and supporting services, whereas larger rivers are more important in terms of provisioning services (Ferreira et al., 2022), floodplains play a critical role in water level regulation, aquifer recharge, and erosion control (Petsch et al., 2022), and seagrass ecosystems are recognized for their important role in climate regulation (carbon sequestration), storm protection, erosion control, and water purification (Lima et al., 2023).

Provisioning services

The most obvious provisioning service provided by aquatic organisms is fisheries, a topic reviewed by Nissar et al. (2022), Pelicice et al. (2022), and Almeida et al. (2023). Indeed, Nabout et al. (2022) showed that studies on provisioning services mostly consider fish as the focal organism group. Although fish are recognized as an important food source in most ecosystems, it is interesting that the role of small forage fish is often undervalued, a topic addressed in this Special Issue by Nissar et al. (2022), and goes in line with the recent discussion about the importance and conservation needs of non-game fish (Rypel et al., 2021).

In addition to fish, other groups of aquatic organisms are also consumed directly by humans, including some invertebrates (e.g., Burlakova et al., 2022; Rodrigues-Filho et al., 2023) and aquatic macrophytes (Thomaz, 2021). Indeed, one of the most consumed foods in the world derives from an aquatic macrophyte: rice (*Oryza sativa* L.) (Thomaz, 2021). Also, food production was recognized as a major provisioning ecosystem service of several ecosystems addressed in this Special Issue, such as coastal lagoons (Rodrigues-Filho et al., 2023), floodplains (Pestch et al., 2022), seagrass ecosystems (Lima et al., 2023), and even dry rivers (Vidal-Abarca Gutiérrez et al., 2022). It is, therefore, not surprising that provisioning services are the second most studied ecosystem service provided by freshwaters, after regulating services (Nabout et al., 2022).

Another key provisioning service addressed in the papers of this Special Issue is the provisioning of high-quality water, a service that is highlighted in small streams (Ferreira et al., 2022) and worthy of restoration (Verdonschot & Verdonschot, 2022). Access to safe water—an ecosystem service central for human wellbeing (highlighted by being at the core of UN's Sustainable Development Goal 6; https://www.un.org/sustainabledevelopment/water-and-sanitation/)—is considered highly unequally distributed (Kovalenko et al., 2023). This service is frequently threatened by human activities not only by direct pollution and eutrophication but also through changes to microbiota (Llames et al., 2022).

Less commonly recognized aquatic provisioning services include the role of macrophytes and algae as biofuel (Thomaz, 2021; B-Béres et al., 2022), use of fungal metabolites in plant disease management (Seena et al., 2022), and ornamental uses of macrophytes and fish (Thomaz, 2021; Pelicice et al., 2022; Petsch et al., 2022). Provisioning services of aquatic organisms also include genetic and biotechnology resources, discussed in this issue for aquatic prokaryotes, viruses (Llames et al., 2022), and phytoplankton (Lengyel et al., 2022; Naselli-Flores & Padisák, 2022). Several groups of aquatic organisms are sources of bioactive compounds and metabolites, which can be used in the pharmaceutical industry and as health supplements (Thomaz, 2021; Lengyel et al., 2022; Naselli-Flores & Padisák, 2022; Seena et al., 2022). Chrysophytes also have applications in materials science (Lengyel et al., 2022). Finally, this Special Issue also covers often underappreciated ecosystems, including small headwater streams that provide high-quality drinking water and hydropower (Ferreira et al., 2022), and dry rivers that are a major source of building materials (Vidal-Abarca Gutiérrez et al., 2022).

Cultural services

Few elements have as many symbolic values as water. In mythology and religion, water is always present as a sacred element and symbol par excellence of life, rebirth, and purification. Not surprisingly, aquatic ecosystems and their plants and animals, and even microorganisms, have given rise to myths, legends and stories and have become essential elements in art and education. To what extent different groups of aquatic organisms contribute to different types of cultural services has been largely a function of their size (visibility to the naked eye), complexity or special features of their morphology, beauty, and importance for supporting human life. For instance, Nissar et al. (2022) list a number of examples of how herring, a major forage fish, was incorporated into social systems of different peoples. In contrast, Llames et al. (2022) found no mention of cultural services for aquatic viruses, archaea and bacteria. Seena et al. (2022) mentioned the potential of conidial morphology of aquatic hyphomycetes as an inspiration for decorative arts but without popular examples, while Naselli-Flores & Padisák (2022) suggest that Art Nouveau design and architecture are likely paying a tribute to the drawings of microalgae (and other aquatic organisms) published in the early twentieth century by the German biologist Ernst Haeckel in his work *Kunstformen der Natur* (Artforms in Nature; Haeckel, 1904). Cultural ecosystem services are the most difficult to assess and evaluate, because most are highly subjective, and therefore they are often not recognized (e.g., Hirons et al., 2016). However, they make important contributions to the physical and mental health of populations (e.g., Kosanic & Petzold, 2020) and therefore deserve special attention.

Traditionally, *aesthetic values* are closely linked to species' beauty and size. As microscopic organisms remained largely invisible before microscopy was invented and became popular (eighteenth century), they are generally missing from traditional artworks. Aesthetics of lakesides with macrophytes, the associated wildlife and the proximity of recreation activities explain why many people prefer living near such places (Thomaz, 2021). The diversity and beauty of Neotropical freshwater fishes made them preferred species in aquaria worldwide (Pelicice et al., 2022), which is not without threats (Patoka et al., 2018) as they can become invasive or can carry non-target, potentially invasive species.

Countless painters, writers and musicians over the centuries have drawn their inspiration from aquatic ecosystems and their biota (Thomaz, 2021; Ferreira et al., 2022). The visual arts extensively used the beauty of macrophytes: e.g., the lotus (*Nelumbo nucifera* Gaertn.) and the water lily (*Nymphaea alba* L.) appear in many artworks of Eastern countries (Thomaz, 2021). The sardine, a major marine forage fish, is one of the symbols of Lisbon (Portugal), particularly during the month-long Festas Populares when sardine images decorate the city and are the center of gastronomic activities that attract locals and tourists (Nissar et al., 2022). Inspiring values generally depend on life experience gained through observing the world under different perspectives, even with the help of technology. Artists are increasingly inspired by visual images that light-, transmission- or scanning electron-microscopy offers. The amazing diversity of diatom frustules was discovered very early and artistically arranged assortments ("Typenplatten" or "Salonpreparat") were very popular in the nineteenth century. Recently the huge morphological diversity of algae has appeared on many types of artworks including paintings, statues, T-shirts, mugs, jewelry, face-masks, stamps, puzzles, etc. (B-Béres et al., 2022; Naselli-Flores & Padisák, 2022). Scales covering silica-scaled flagellates are only visible in transmission electron-microscopy, but they inspired an artist to use these scales to cover a dragon in a storybook (Lengyel et al., 2022).

Many aquatic ecosystems and organisms support *spiritual and religious values, myths and legends*. The original biblical verses were written on papyrus (originally obtained from the stems of the marsh plant *Cyperus papyrus* L.), and contain several references to the papyrus itself, and the wild rice (*Zizania palustris* L.) is considered as a sacred resource to the identity of the Ojibwe peoples of North America. At high densities, microorganisms develop macroscopic phenomena (water blooms, red tides) giving rise to many myths and legends (Naselli-Flores & Padisák, 2022). Fish, marine and freshwater, appear in the cosmological systems of many cultures with influence on customs, the sense of belonging and religious beliefs. For instance, the Bible mentions fishes in many sections, one of the most famous being the lesson about whether to teach fishing or to give fish.

Recreational and sport fishing attract anglers everywhere but there are hotspots such as the Brazilian Pantanal region, the lower Paraná River coastal rivers and some tributaries of the Amazon (Pelicice et al., 2022). Snorkeling for observing freshwater fish is less common than snorkeling with marine fish, but it has been an important activity in the highlands surrounding the Pantanal region (Thomaz, 2021; Pelicice et al., 2022). Recreational angling and gastronomic festivals supported by anadromous fish are also important cultural activities in the Iberian Peninsula (Almeida et al., 2023). Crowds of lesser flamingos generate ecotourism at African saline lakes (Naselli-Flores & Padisák, 2022).

There are also well documented *educational values* involving aquatic ecosystems and organisms. Small sized, fast growing aquatic organisms are especially suitable for experimenting in high-school and university courses; e.g., the transparency of metazooplankton species, especially cladocerans and rotifers, makes them suitable for observing functioning of organs and behavioral responses such as predator avoidance (Declerck & Senerpont Domis, 2022). The challenge of making algal models in university courses increases the detail-sensitivity of students (B-Béres et al., 2022), and increasing the presence of aquatic hyphomycetes in university courses and museums is also needed to increase recognition of their importance in stream ecosystem functioning (Seena et al., 2022). Zebra mussels have been a favorite model organism in Europe since the 1970s as they accumulate a wide array of toxic substances (heavy metals, organic pollutants and even radioactive contaminants) in their shells or tissues (Burlakova et al., 2022). Small streams are ideal for whole-ecosystem manipulation of environmental conditions, allowing for the establishment of realistic causal relationships between environmental change and changes in aquatic communities and ecosystem processes (Ferreira et al., 2022).

Aquatic organisms also support *knowledge systems and cultural heritage*. The evolution of writing took advantage of papyrus (*C. papyrus*), which has been used as paper for millennia (Thomaz, 2021). In historical times, local knowledge on the neighboring aquatic ecosystems and their sustainable management were essential for gaining resources such as housing, animal farming, and this knowledge is still invaluable as a source of recent methods for nature conservation (Thomaz, 2021; Almeida et al., 2023). Neotropical freshwater fishes contributed to scientific knowledge in many branches of science such as models to understand physiological issues, comparative anatomy, behavior, vertebrate evolution, intraspecific genetic variability, consequences of environmental degradation and understanding evolutionary processes (Pelicice et al., 2022). Fishes, in general, serve as a common source of traditional ecological knowledge including understanding of ecological relationships and consequences of habitat loss (Nissar et al., 2022; Pelicice et al., 2022; Almeida et al., 2023). For instance, herring is of major importance as the key element of cultural identity and beliefs of Indigenous people. At some places it is still an important food resource, served at cultural events and feasts, and the arrival of herring marked the beginning of the year for some peoples (Nissar et al., 2022). Metazooplankton's contribution to scientific knowledge has been essential in the fields of ecology, evolutionary biology, and toxicology. As many of their species are parthenogenetic, e.g., *Daphnia* species, it is possible to maintain individual genotypes over many generations and to study microevolution, phenotypic plasticity, morphological defenses against predators, and the effect of toxic substances (Declerck & Senerpont Domis, 2022).

Citizen science and actions such as "fish of the year" have been a very successful, recently growing part of environmental education with innovative didactic tools (Rambonnet et al., 2019). Generally, species "easy to observe" are involved. It is fair to mention here the contribution of amateur naturalists to the development of science. For instance, the famous diatomist József Pantocsek was a medical doctor, whose slides are among the most precious collections of the Hungarian Natural History Museum (Buczkó, 2012). Collections of natural history all over the world represent invaluable items of cultural heritage, and they are receiving growing recognition since DNA can be obtained without substantial damage and used for scientific purposes.

Contribution of aquatic biota to knowledge systems such as maintaining or restoring aquatic ecosystems to good ecological status is, unfortunately, not mentioned by the MEA (2003, 2005), as noted in some of the papers included in this Special Issue (B-Béres et al., 2022; Naselli-Flores & Padisák, 2022). This is particularly apparent in the case of metazooplankton, which despite its central role in pelagic food-webs is not included among the biological quality elements of the EU Water Framework Directive (Declerck & Senerpont Domis, 2022).

There are several examples of how aquatic ecosystems and organisms contribute to the existence and income of the local or even wider societies, therefore contributing to *social relations*. Macrophyte-hosting aquatic gardens in Bonito City (Brazil) are estimated to provide for 4,000 direct and indirect jobs and ~ 40% of the municipality's income (Thomaz, 2021). Recreational activities in Neotropical countries (fishing, diving) attract tourists, providing jobs for thousands of people and contributing to economic development of these regions (Pelicice et al., 2022). Another economically important activity in the region is the export of Neotropical freshwater fishes (Pelicice et al., 2022). Marine forage fish are of pivotal importance for societies along the shorelines, both as direct food and as prey for their predators, and declines in their populations may lead to tension in the society (Nissar et al., 2022). Recreational fishing and gastronomic festivals supported by anadromous fish are also important seasonal economic activities for riverine communities in the Iberian Peninsula (Almeida et al., 2023).

Ecosystem disservices

The concept of ecosystem disservices, introduced in 1969 to refer to negative economic aspects of some species or services, varied over time (Campagne et al., 2018). Shackleton et al. (2016) synthesized previous ideas and defined ecosystem disservices as "the ecosystem-generated functions, processes, and attributes that result in perceived or actual negative impacts on human wellbeing". Ecosystem disservices manifest in social–ecological systems (e.g., agricultural, urban, forest, aquatic) (Lyytimäki & Sipilä, 2009).

A proposed classification of ecosystem disservices considers the origin (a biotic or abiotic component of the ecosystem) and the impact on different aspects of human wellbeing: (i) economic, (ii) physical and mental health and safety, and (iii) aesthetic and cultural (Shackleton et al., 2016). The perception of the negative impacts is context-dependent, being unequal across socio-economic groups. Thus, the same function can be valued as an ecosystem service or disservice, depending on the lifestyle, culture, age, and experience (Lyytimäki, 2015). Environmental justice perspectives must be considered when analyzing and responding to ecosystem disservices (Shackleton et al., 2016).

Several papers in this Special Issue recognize different ecosystem disservices that emerge from biotic components (species, functional groups, or communities), impacting mainly human health. In all cases and for each group, ecosystem services surpass disservices by a wide margin. For instance, metazooplankton indirectly contributes to a plethora of ecosystem services (e.g., water filtration, nutrient cycling, supporting fish for human consumption, scientific knowledge), but it can also act as a vector of human pathogens and contribute to trophic transfer and biomagnification of some pollutants (Declerck & Senerpont Domis, 2022). Macrophytes provide multiple benefits for humans; however, they could increase the prevalence of diseases like malaria and schistosomiasis, whose vectors use some plants as their habitats (Thomaz, 2021). Microbial communities play critical roles in biogeochemical processes, providing numerous crucial supporting, regulating, and provisioning services. Unpleasant, unwanted, or economically harmful effects associated with archaea, bacteria, and viruses are mostly related to their role as infectious agents for humans or species of economic value (e.g., contamination and toxin production) (Llames et al., 2022). At the same time, Llames et al. (2022) stress the relevance of accounting jointly for positive and negative aspects of individual and microbial community attributes, exemplified by the duality of *Escherichia coli* (Migula 1895) Castellani and Chalmers 1919 presence in aquatic ecosystems: an indicator of fecal contamination (disservice) and its role in the degradation of pollutants (providing a self-purification service).

One of the most evident negative economic impacts, ranging from hundreds to thousands of millions of US$ per year worldwide, caused by invasive mussels is due to biofouling of human-made facilities (e.g., power generating, drinking water and other industrial plants, water conveyance structures, and watercraft) (Burlakova et al., 2022). Other negative impacts of invasive mussels are the trophic transfer of bio-concentrated pollutants and the impairment of recreational activities, the later resulting from the proliferation of submerged macrophytes and filamentous algae due to clear water conditions generated by mussels (Burlakova et al., 2022). Excessive growth of macrophytes or algae may result in negative economic impacts on navigation, swimming, tourism, water provisioning and fishing (Thomaz, 2021; B-Béres et al., 2022). Blooms of jellyfish can also cause a disservice by reducing fishery yields (Lee et al., 2022).

Only one paper in the Special Issue recognizes disservices of abiotic origin: in river–floodplain ecosystems, flood pulse may facilitate the dispersion of disease vectors like mosquito larvae or invasive species producing detrimental impacts on these ecosystems and ecosystem services loss (Petsch et al., 2022).

Overall, several papers included in this Special Issue recognize disservices of different origins (biotic or abiotic) impacting distinct aspects of human wellbeing. Negative impacts relate to economics (mainly biofouling of human-made facilities, impairment of fisheries or water provisioning), human health and safety (mainly trophic transfer of pollutants and spread of vectors of diseases or pathogens), or impairing recreational activities. The absence of a reference to ecosystem disservices for some of the aquatic ecosystems or organisms addressed in this Special Issue does not mean that they do not exist under some circumstances. In the ecosystems where these disservices are recognized, a myriad of relevant and crucial ecosystem services are also identified. Despite the subjective qualification of a disservice as such by humans, the evaluation of both ecosystem services and disservices shows that the benefits from nature surpass these negative impacts (e.g., Campagne et al., 2018).

Conclusion

Although this Special Issue does not cover ecosystem services provided by all aquatic ecosystems and organisms, the 20 papers that it includes allow for some general conclusions.

(i) Even aquatic ecosystems that are often disregarded, such as small streams or dry rivers, are important providers of ecosystem services (Ferreira et al., 2022; Vidal-Abarca Gutiérrez et al., 2022). They are, however, highly vulnerable to degradation as a consequence of human activities. Therefore, scientists need to promote public awareness of these ecosystems and their importance for human wellbeing as a first step towards their protection and restoration.

(ii) Similarly, organisms that are not known to the general public, most because they are microscopic, such as aquatic fungi (Seena et al., 2022), or organisms usually perceived in a negative manner, such as viruses and bacteria (Llames et al., 2022), also provide ecosystem services. These services should be recognized to improve the management of the aquatic ecosystems that these organisms inhabit and support biodiversity conservation.

(iii) Invasive species, generally seen by their harmful ecological and economic impacts, can also provide ecosystem services (Burlakova et al., 2022). Although these services likely do not compensate for the ecological damages that invasive species have in the invaded ecosystem, they still need to be taken into consideration in management.

(iv) In most cases, ecosystem services were identified but their quantification was generally not possible (but see Lee et al., 2022; Almeida et al., 2023). This reflects a recognized challenge in ecosystem services research, especially when considering non-marketable ecosystem services or those that have no material benefits for human populations (Small et al., 2017).

(v) Critically, most papers identified ecosystem services that were not included in the MEA (2005), such as the use of certain taxa as bioindicators of environmental conditions (explored in bioassessment programs; Thomaz, 2021), the provisioning of abiotic materials such as sediments by dry rivers (Vidal-Abarca Gutiérrez et al., 2022) or diatomite that results from diatoms' skeletal remains (Naselli-Flores & Padisák, 2022). This raises awareness to the need of not limiting the assessment of ecosystem services to those identified by the MEA (2005).

This Special Issue contributes to raising awareness of aquatic ecosystems and organisms as providers of ecosystem services, upon which human populations rely. This is aimed as a first step towards conservation and the responsible use of aquatic ecosystems and organisms, as only then can they contribute to attaining multiple Sustainable Development Goals.

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