frontiers in Marine Science

REVIEW
published: 07 February 2020
doi: 10.3389/fmars.2020.00037

Moving Toward an Agenda on Ocean Health and Human Health in Europe

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Specialty section:
This article was submitted to Marine Ecosystem Ecology, a section of the journal Frontiers in Marine Science

Received: 06 October 2019
Accepted: 20 January 2020
Published: 07 February 2020

Citation:
Borja A, White MP, Berdalet E, Bock N, Eatock C, Kristensen P, Leonard A, Lloret J, Pahl S, Parga M, Prieto JV, Wuijts S and Fleming LE (2020) Moving Toward an Agenda on Ocean Health and Human Health in Europe. Front. Mar. Sci. 7:37. doi: 10.3389/fmars.2020.00037

The integrated study of ocean health and human health is an emerging area of increasing global importance. Growing evidences demonstrate that the health of the ocean and the health of humans have always been and will continue to be, inextricably linked. Our actions toward the oceans will significantly influence the future of the whole planet and, in turn, our own health. The current review of these issues arose from a summer school in San Sebastian (Spain), from 5th to 7th June, 2019. An interdisciplinary group of researchers discussed key risks (e.g., microbial pollution, pharmaceuticals, harmful algal blooms, plastic pollution) and benefits (e.g., bathing waters, recreation, tourism) of the seas and global ocean for humanity; and debated the future priorities and potential actions for a joint Oceans and Human Health research and governance programme in Europe. The aim of this review is to contribute to the emerging scientific agenda on ocean health and human health, as well as coordinate efforts with stakeholders, policy makers and the general public. This agenda operates within the larger context of the upcoming United Nations Decade of Ocean Science for Sustainable Development: 2021–2030, which strives to achieve the Sustainable Development Goals (SDG), including healthy (human) lives and well-being (SDG3) and conserving and sustainably using the oceans (SDG14), among others. In addition to summarizing some of the key risks and benefits, therefore, we describe the governance of oceans and health interactions (especially in Europe), and we finish by proposing a list of elements for potential future research priorities on oceans and human health.

Keywords: ocean health, human health, well-being, ecosystem services, harmful algal blooms, marine pollution, seafood provision

INTRODUCTION

The health of the environment has been, and always will be, critical for human health (Whitmee et al., 2015). Our seas and global ocean are no different (Inniss et al., 2016; Gascón et al., 2017; Elliott et al., 2018; Gollan et al., 2019). However, despite the direct importance of ocean health on the health of billions of people globally, the interaction between the two is still relatively under-studied (European Marine Board, 2013; Depledge et al., 2017, 2019; Fleming et al., 2019; World Health Organization [WHO], 2019). The current review of these issues draws on a summer school that took place in San Sebastian (Spain), from 5th to 7th June, 2019[1]. With a primarily European focus, an interdisciplinary group of researchers discussed key risks and benefits that the seas and global ocean provide humanity; and debated the future priorities and potential actions for the joint Oceans and Human Health (OHH) research and governance. Below we outline the background to both the topic and the workshop, and summarize some of the key issues that emerged. Our aim then, and now, was to put these issues firmly on the agenda and highlight the vital importance of the oceans to the medical, and in particular the public health, communities.

Oceans have historically provided livelihoods, trade, food, and other resources, known as "ecosystem goods and services," recently valued at $24 trillion (Barbier et al., 2012; Hattam et al., 2015; WWF, 2015). However, rapidly increasing and aging human populations globally, and the resulting anthropogenically driven environmental changes are increasing pressure on coastal waters, the seas and global ocean, and the ecosystem services they provide (Pecl et al., 2017). In particular, human activities increasingly involve continued and cumulative pressures, producing negative impacts (e.g., pollution, habitat destruction and overfishing), which affect not only ecosystem health, but also human health (Depledge et al., 2019). Human interactions with the ocean and seas can be inherently risky (as shown in section "Yes, Oceans are Risky. . ."). Conversely, human health and well-being may be promoted through positive interactions with the coasts and oceans (as shown in section ". . .But Humans Can Benefit From Blue Spaces!"), with the sustainable use of the natural resources and through the restoration and preservation of coastal and marine ecosystems (De Groot et al., 2013; Pueyo-Ros et al., 2018; Pouso et al., 2019).

In this context, human health and well-being are considered a physical, social and mental state, dependent, at least in part, upon marine and other ecosystems services, provided by the natural world (Alexandrova, 2012). Ecosystem services include material (food, transport, economic benefits) and non-material outputs those consisting on cultural services promoting physical and mental health and having positive effects on social relationships (Ghermandi et al., 2012; Ghermandi and Nunes, 2013; Bullock et al., 2018).

Marine and coastal ecosystems are part of a wider network of aquatic environments, including freshwater systems, which are generically referred to as "blue spaces" (White et al., 2010; Gascón et al., 2017). Despite the acknowledged interactions between healthy blue spaces and human health and well-being (Völker and Kistemann, 2011; Wheeler et al., 2012; Nutsford et al., 2016; Bullock et al., 2018), systematic research on this topic is relatively recent, and important knowledge gaps have been identified (Grellier et al., 2017; Fleming et al., 2019). These research gaps imply a weaker understanding of how marine blue spaces produce cultural and other relevant ecosystem services, how these are used, and their implications for human health and well-being.

These gaps are probably due to the fact that the study of ocean health and human health needs to be inherently interdisciplinary and *trans*-sectoral (Knap et al., 2002; European Marine Board, 2013; World Health Organization [WHO], 2019), requiring joint collaboration between the medical and public health fields with economic, ecological, marine, social and behavioral sciences, as well as diverse stakeholder communities. Reviewing the history, policies, and both known and possible risks and the benefits of these interactions, provides insights into new avenues of global cooperation. This will allow for potential collaborations to address the local and global challenges of the interactions of humans with the Ocean. These interactions are occurring now and will increase in the future, with the expansion of the human population living in the coastal zones (Barragán and de Andrés, 2015) and the increasing use of the oceans, due to the increasing promotion of "blue growth" or "blue economy" (Eikeset et al., 2018).

This review initially arose from a summer school delivered in San Sebastian (Spain), from 5th to 7th June, 2019[2]. With a primarily European focus, but a global interest as well, an interdisciplinary group of researchers discussed key risks and benefits that the seas and global ocean provide humanity; and debated the future priorities and potential actions for the joint Oceans and Human Health (OHH) research and governance programme. The aim of this paper is to contribute to the emerging agenda on ocean health and human health scientific research and coordination with stakeholders, policy makers and the general public. This agenda operates within the larger context of the upcoming United Nations (UN) Decade of Ocean Science for Sustainable Development - 2021–2030 - (UNESCO, 2018), which strive to achieve the Sustainable Development Goals (SDG), including healthy lives and well-being (SDG3) and conserving and sustainably using the oceans (SDG14), among others (United Nations, 2016; Ryabinin et al., 2019).

YES, OCEANS ARE RISKY. . .

Elliott et al. (2014) identified a typology of 14 natural and anthropogenic marine hazards, including: hydrological (floods), physiographic removal by natural processes or human actions, climatological (sea-level rise), tectonic (seismic, tsunamis), anthropogenic microbial and macrobial, anthropogenic-introduced and extractive technological, and anthropogenic chemicals. These hazards can be acute or chronic, and their respective degree of risk relates to the amount of assets, natural or societal, which may be affected. Some hazards can cause locally-derived problems producing risks at small-scale, and/or have large-scale effects (e.g., climate change, sea-level rise and isostatic rebound), which cause risks at the global level.

For millennia, humans have used the oceans to dispose of wastes, including organic matter, nutrients, chemicals, litter, etc., in part based on an erroneous belief that the seas and global ocean have the capacity of absorbing and recycling all those contaminants. In addition, oil tanker accidents, atomic weapon tests and other human activities have impacted the oceans,

[1]https://www.azti.es/en/eventos/azti-sophie-project-summer-school-2019-does-human-health-and-wellbeing-depend-on-a-healthy-ocean/

[2]https://www.azti.es/en/eventos/azti-sophie-project-summer-school-2019-does-human-health-and-wellbeing-depend-on-a-healthy-ocean/

producing increasing risks both for the environment and human health. To date, the results of these activities have informed recommended management approaches, and reduced the effects of some contaminants (e.g., metals, TBTs, microbial). The major topics have been oil spills, pollution (including anthropogenic chemicals and microbial wastes), and eutrophication (**Figure 1**). However, in recent years, there has been a dramatic increase in research on macro-, micro- and nano-plastics and other forms of marine litter (e.g.,Science Advice for Policy by European Academies [SAPEA], 2019; **Figure 1**).

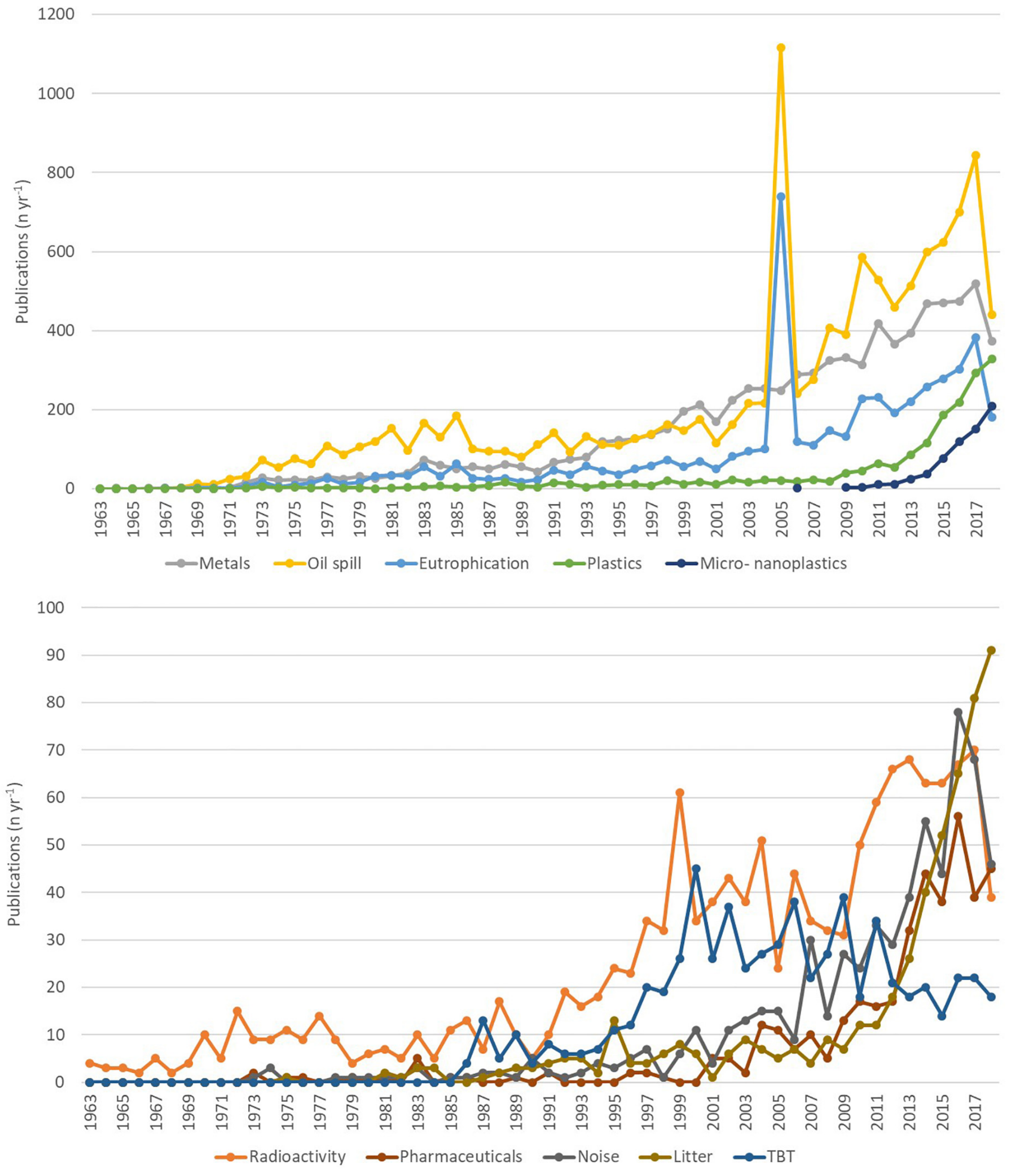

FIGURE 1 | Evolution of the number of papers published in one of the indicated pollution topics in a year. Search in SCOPUS, for the period 1963–2018, and following terms: radioact* OR radiact* OR metal* OR oil-spill OR oil spill OR eutroph* OR plastic* OR microplast* OR nanoplast* OR pharmaceut* OR noise OR litter* OR TBT AND pollut* AND marine. For details, see Borja and Elliott (2019). TBT: tributyltin. Note that the vertical scales are different in both figures.

The following section explores just some of the risky effects of important pollutants and biotoxins found in the oceans on human and ocean health, for illustrative purposes.

Traditional and Emerging Risks: Microbial Pollution, Pharmaceuticals, and Antimicrobial Resistance

Sewage spills and discharge of insufficiently treated waste containing microbes, nutrients (e.g., nitrates and phosphates), and non-nutrient pollutants (e.g., pharmaceutical residues) can have multiple adverse impacts on both ocean health and human health. The introduction of these pollutants to coastal areas results in eutrophication, impacts on the biology of marine life by chemicals, and various illnesses acquired from exposure to seawater containing pathogenic microorganisms (Wade et al., 2003; Agardy et al., 2005; Yau et al., 2009; Iwamoto et al., 2010; Gaw et al., 2014; Arnold et al., 2016; Leonard et al., 2018a). Despite the known harms of microbial pollution on ocean and human health, this type of pollution regularly affects surface waters worldwide, whether from untreated human waste, wastewater treatment plant effluents, sewer overflows, or from diffuse sources of pollution, such as land runoff.

Recently, there is increasing concern about the introduction into the environment of bacteria that are resistant to anti-microbials, alongside substances with anti-microbial properties that select for and maintain genes conferring resistance to clinically important antibiotics among human-associated bacteria (Gullberg et al., 2011, 2014; Rutgersson et al., 2014; Singer et al., 2016; Murray et al., 2018). Unlike many other pollutants, which degrade in the environment, bacteria reproduce and can amplify these antibiotic resistance genes (ARGs) and pass them to other members of the microbial community via various horizontal gene transfer mechanisms (Pruden et al., 2006).

Coastal environments are an important site where people can be exposed to both pathogenic microorganisms and antibiotic resistant bacteria. Recreational use of coastal waters and water sports expose water users (bathers, surfers, etc.) to antibiotic resistant bacteria in the water column. Research in the United Kingdom has shown that levels of the bacteria, *Escherichia coli*, resistant to a group of critically important antibiotics are high enough to be an exposure risk to recreational water users. This exposure risk is particularly high among those who participate in high-contact water sports, such as surfing and swimming, which tend to involve ingesting large volumes of water (Leonard et al., 2015). Analysis of *E. coli* metagenomes revealed that exposure to *E. coli* harboring various ARGs is possible even during low-contact water sports in bathing waters categorized as being of good microbiological quality (Leonard et al., 2018b). Furthermore, frequent bathing in coastal waters has been shown to be associated with gut colonization by (for example) cefotaxime-resistant *E. coli* harboring the plasmid-borne ARGs, blaCTX-M, which are easily mobilized among bacteria via horizontal gene transfer, and which confer resistance to clinically important antibiotics (Leonard et al., 2018c). Many of these resistant *E. coli* colonizing participant guts were characterized as *E. coli* sequence type 131, which can cause urinary tract infections that are difficult to treat.

Contaminants carried by sewage to marine waters can also reach the food chain. Pharmaceuticals compounds, from pharmaceuticals that have been ingested but not fully metabolized in the human gut, have been detected in seafood, including finfish and mollusks (Alvarez-Muñoz et al., 2015) along with pathogenic microorganisms (Iwamoto et al., 2010). Seafood harvested from microbially polluted seawater can expose consumers to these harmful agents, commonly causing gastrointestinal illness, as well as life-threatening conditions. Bivalve mollusks, like mussels and oysters, are particularly risky because as filter feeders, they bioconcentrate environmental pollutants, including antibiotic resistant bacteria in their tissues (Bighiu et al., 2019). Many such filter feeders are often consumed raw or lightly cooked; and consumers might be exposed to pathogenic resistant bacteria, like *E. coli* and *Vibrio parahaemolyticus* (Heuer et al., 2009).

It is useful to detect, prevent and remediate microbial pollution in order to protect ocean and human health. It is recommended that sensitive marine waters, such as those used for bathing and shellfish production, are monitored for the indicators of water quality, including microbial pollution (World Health Organization [WHO], 2003; European Union [EU], 2006a,b). This helps to detect elevated levels of pollution that might be harmful for bathers, workers and consumers. However, these monitoring activities are not performed worldwide; and data on bacteria resistant to antibiotics in these waters are not routinely collected. Further work needs to be done to select appropriate indicators, and to develop methods for their measurement before environmental levels of antibiotic resistant bacteria can be regulated.

Approximately 77% of pollutants in coastal waters come from terrestrial sources, e.g., via rivers, and atmospheric deposition (Agardy et al., 2005). Preventing and managing the risks associated with fecal pollution and antimicrobial resistance will require identifying important land-based processes introducing microorganisms and selective agents to marine environments which can be targeted for intervention. These processes and the factors determining their relative contribution will vary spatially. They may be affected in the future by changes in local human and animal populations (increased urbanization, migration), as well as by changes to the hydrological cycle and increases in global ocean temperatures induced by climate change (Vezzulli et al., 2016). Therefore, an integrated approach involving environmentally sound and economically viable solutions will be needed to reduce risk to human and ocean health posed by sewage in the oceans.

Harmful Algal Blooms as a Paradigm of the Interconnection Between Human Health and Oceans Health

A "Harmful Algal Bloom" (HAB) is a discrete event associated with a proliferation of microalgae, cyanobacteria or macroalgae that is perceived by humans as harmful to their health or ecosystem services. "Bloom" is defined as an increase in abundance of a particular organism relative to its normal background level (which may be "low" or "high" depending on the species). For instance, excessive algal biomass accumulation can cause harm to aquatic organisms due to decreased sunlight and to oxygen decrease in the water when the bloom degrades. High biomass blooms of microalgae that synthesize ichthyotoxins or physically damage fish gills can cause massive fish kills (in aquaculture or natural fisheries). Other microalgae produce potent toxic compounds that cause harm to humans by direct contact, inhalation or consumption of contaminated seafood. Food borne poisonings (most commonly Paralytic Shellfish Poisoning (PSP), Diarrheic Shellfish Poisoning (DSP), Amnesic Shellfish Poisoning (ASP), and Ciguatera Fish Poisoning (CFP); see e.g., Berdalet et al., 2015) constitute the main threat to human beings.

The HAB toxins (thermostable and chemically very diverse) are transferred and bio-concentrated through marine food webs up to humans (**Figure 2**) who can experience acute or chronic symptoms, and in severe cases, death. The presence of toxic organisms and/or their toxins in the water result in bans on finfish and shellfish collection and commercialization, resulting in important economic losses in different sectors including tourism (e.g., Adams et al., 2018).

Socio-cultural impacts (e.g., change on dietary patterns and traditional seafood - professional and recreational - collection activities) are particularly relevant in the case of CFP, endemic in tropical areas (Friedman et al., 2017), or due to exceptional blooms such as those of the domoic-acid (ASP) producer, *Pseudo-nitzschia* in 2015 in the Pacific coasts of America (Ritzman et al., 2018). Estimating the total cost of HABs is difficult and complex. A conservative total annual direct cost of HABs could account for about 100 billion US$, excluding costs for human health care (Bernard et al., 2014; Trainer and Yoshida, 2014).

Harmful Algal Blooms are a particular example of phytoplankton (and phytobenthos) dynamics controlled by complex combination of physical (temperature, wind, waves, atmosphere-ocean interactions), chemical (inorganic and organic nutrients), and biological (predation, competition, allelochemistry, parasitism) processes that operate at different spatio-temporal scales (GEOHAB, 2001). Climate change may also influence HAB events, intensity and impacts. In particular, ocean warming can favor the biogeographic extension of tropical and subtropical organisms, such as *Gambierdiscus* species, to more temperate latitudes, increasing the threat of CFP. Nevertheless, future trends are uncertain (e.g., Wells et al., 2019), while the identification of new toxins can complicate the risks to human health (see e.g., revision in Berdalet et al., 2015).

Harmful Algal Blooms occur in all aquatic environments and latitudes and because they are essentially natural phenomena, their occurrence cannot be completely avoided or eliminated. However, certain anthropogenic forcings (e.g., eutrophication, alteration of the water circulation patterns by harbor construction, habitat destruction, spread of harmful organisms through ballast waters, or transport of cultured organisms), especially in the coastal zone, can benefit some HABs (Masó and Garcés, 2006). Technically, in the 21st Century, it is possible to minimize those activities, and to address the sustainable use of natural resources, which in turn will decrease in part the probabilities of HAB occurrence.

In the last 50 years, the protection of human health and well-being from HAB impacts has been achieved through intensive and improved monitoring of harmful organisms and their toxins coordinated with European food safety[3] regulations (O'Mahony, 2018); and by significant investment in the understanding of blooms dynamics, which can in some cases help to predict their occurrence and design mitigation strategies (Bricker et al., 2008). Due to the complexity of HAB dynamics, major advances have been achieved through interdisciplinary regional, and national and international coordination.

One example of this type of coordination includes the multi-agency and multi-institutional interdisciplinary collaboration over many years to investigate the recurrent massive blooms of the neurotoxin and fish-killing HAB, *Karenia brevis* (Florida red tide), in the Gulf of Mexico and Florida (e.g., Fleming et al., 2011). Progresses concerned toxin detection in water and air, and human health prevention protocols and medication approaches. Another example is the Accord RAMOGE[4] that coordinates the strategies of Monaco, Italy, France, and Spain for monitoring *Ostreopsis* blooms in some beaches where the proliferation of this benthic dinoflagellate is associated to mild respiratory distress in humans. RAMOGE also facilitates communication between scientists, stakeholders and general public.

At global international scale, the SCOR and IOC UNESCO programs GEOHAB (2000–2013) and GlobalHAB (2016–2025) foster coordination on interdisciplinary, international and interinstitutional research of HABs. Among the 12 Themes of GlobalHAB[5], that of "HABs and Human Health" aims to increase collaborations among scientists with medical, veterinary, public health, economic, and other social science expertise to help understand and minimize the risk of HAB impacts to human health and animal health, with a particular global change perspective. These GlobalHAB scientific objectives are implemented through interactions with other international programs and projects. The overall approach followed by the research on HABs, can inspire analogous strategies to address other challenges posed to oceans and human health.

Marine Plastic Pollution: Changing Behavior and Engaging Communities

Plastic pollution on the coast and in the ocean is another example of anthropogenic activities posing considerable risk to the environment and also, potentially, to human health and well-being. Plastic pollution is entirely caused by the human production of plastic materials, use and disposal (Pahl et al., 2017). Plastic is a relatively new material; it has only been used widely since the 1960s, so the amount and the trend of this material escaping into the natural environment globally are astonishing (Jambeck et al., 2015), producing different impacts (Galgani et al., 2019).

[3]www.efsa.europa.eu

[4]www.ramoge.org The name comes from the cities involved in the agreement: Saint-Raphaël, MOnaco and GEnoa

[5]www.globalhab.info

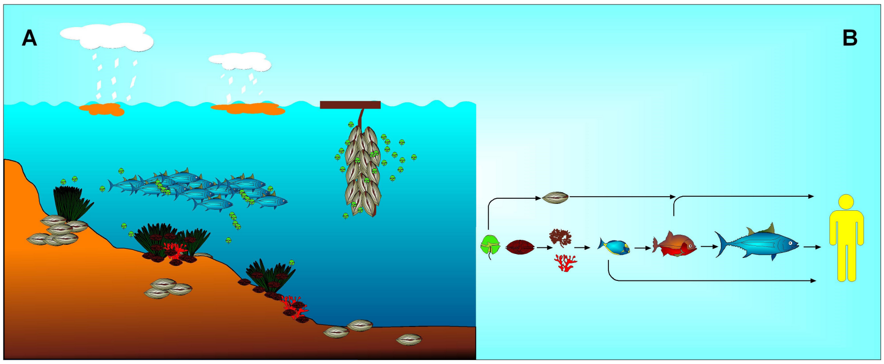

FIGURE 2 | Microalgal blooms may have different impacts on the environment and human health. **(A)** Some microalgae are ichthyotoxic (e.g., *Pseudo-chattonella, Chrysochromulina*), causing massive fish kills in aquaculture sites or natural fish populations. High microalgae cell concentrations can aggregate at the water surface and form floating foams that decrease water bath quality and light availability for other aquatic organisms. In some cases, from the (floating or not) aggregates compounds causing respiratory irritation are aerosolized by wind and waves (as in the case of *Karenia* and *Ostreopsis*). In general, when the blooms decay, bacterial decomposition of the high microalgal biomass can decrease oxygen availability to the other organisms in the ecosystems. Some planktonic microalgae (e.g., *Alexandrium, Pseudo-nitzschia*) are ingested by filter feeders such as cultured or naturally growing shellfish. Toxic benthic microalgae grow attached to corals of macroalgae. **(B)** Biotoxins bioaccumulate and are transferred through the food webs causing seafood borne poisonings in human. PSP, DSP,and ASP can occur from consumption of contaminated shellfish, while different fish species can cause CFP.

It is useful to think about plastic use as a system where plastic moves from the economy to the environment, with many stakeholders and sectors involved making decisions on materials and use. For example, a manufacturer might decide to use plastic as packaging because it is durable, cheap and protects against moisture. However, consumers might decide *against* this product because it is using plastic packaging, having seen media reporting of harm to wildlife. Increased reporting of harm to wildlife has been documented in scientific articles and in the wider media (Science Advice for Policy by European Academies [SAPEA], 2019). In fact, the European public report high concern about this wildlife impact, but lower concern about economic costs or human health impacts (e.g., Hartley et al., 2018). Beaumont et al. (2019) have recently provided the first global assessment of marine plastic pollution, using an ecosystem services approach that takes into consideration social (including health) impacts, in addition to ecological and economic impacts.

Moreover, while some media reports have recently discussed potential human health impacts, particularly of microplastics, there is currently not enough scientific evidence to establish risks conclusively, whether it is via ingestion or inhalation (Science Advice for Policy by European Academies [SAPEA], 2019). It seems that in public discourse the *presence of microplastics* in the environment (which has been established conclusively) is sometimes conflated with the *presence of risk* (for which assessment is missing). This conclusion does not indicate an absence of risk. Future research is needed on effects of exposure to different size ranges (also compared to natural particles) and the role of plastic carrying additives and microorganisms and pathogens (compared to such concentrations in the absence of plastic; Science Advice for Policy by European Academies [SAPEA], 2019; Vethaak and Leslie, 2016).

Newman et al. (2015) have observed that, in most cases, the price of plastic is disconnected from the true cost of disposal, and that the costs of recycling and disposal are currently borne by society. This encourages the production and consumption of plastic at low prices, while waste management after household collection is typically hidden from the consumer, posing another disconnect between the experienced benefits of the material and the end-of-line costs and impacts. While such a complex system dependent on many different actors might seem difficult to change, at the same time it poses a range of opportunities. Top-down and bottom-up pressures can work together, combining, for example, policy change and NGO campaigns with self-organized community activities and individual leadership. Right now, there appears to be high "problem awareness" (e.g., Dilkes-Hoffman et al., 2019) and consensus that together form the momentum for change unprecedented in the context of other environmental challenges (e.g., compared to climate change).

So, how can we build on this momentum to maximize change? In research terms, we need to apply interdisciplinary perspectives to both the issue itself and to potential solutions. We need to understand the perceptions, motivations and intentions of different stakeholders to design solutions and alternative systems that will be acceptable and effective. These candidate solutions then require systematic small-scale trials and evaluation to avoid unwanted side effects (e.g., increased carbon footprint) before they are rolled out more widely. Such evidence-based approaches require social and behavioral science methods (see Pahl and Wyles, 2017), alongside economic, technical and lifecycle analyses and environmental science assessments of harm.

Behavioral science research, in particular, has demonstrated the limited effect of just increasing knowledge in motivating behavior change. While better knowledge can help facilitate change, other factors have been shown to be more powerful [see Pahl and Wyles (2017) for a summary]. Social norms and a sense of efficacy or control over actions are among the most important predictors of behavior change; while emotions, values and social identity can help or hinder action above and beyond the presence of knowledge. Future activities should go beyond solely communicating facts and targeting knowledge to apply more comprehensive models of behavior change and community engagement.

In sum, plastic pollution is very much the center of attention in terms of the current public discourse, research and policy action, but it is less clear whether this attention is entirely justified, compared with other existing risks to ocean and human health. On the flipside, this attention could be used to engage individuals and communities with wider environmental issues that go beyond plastic pollution. Finally, and despite these wide-ranging concerns, it is also important to remember that plastic remains a useful material in many aspects of modern life, from healthcare to transport (Thompson et al., 2009). Arguably the key problem is not the material itself, but how we use and manage it.

. . .BUT HUMANS CAN BENEFIT FROM BLUE SPACES!

Bathing in coastal areas explicitly for health and well-being has been practiced with "Sea Bathing" hospitals and clinics popular around Europe from the mid-18th Century onward (Wheeler et al., 2014). In the early days, many of the "treatments" focused on skin complaints and intestinal issues, whereas nowadays the focus is more on mental health and well-being; and how spending time in and around marine environments can help reduce stress, anxiety, and depression related disorders which are fast becoming the main leading causes of disability in middle to high income countries (Kassebaum et al., 2016).

The quality of these places matters and the benefits depend on accessible, clean, and safe coastal settings for the benefits to accrue. In addition, to good water quality for bathing, clean unpolluted water is required for healthy ecosystems sustaining biodiversity and functioning, and to support economic activities such as tourism and sustainable aquaculture.

Use and Evolution of Bathing Waters in Europe

Bathing water quality is a cause for concern for public health, as swimming at beaches contaminated with chemicals, fecal bacteria and other organisms (viruses, parasites, etc.), or even playing in the sediments and sands where fecal matter can accumulate, can result in illness, as discussed in section "Traditional and Emerging Risks: Microbial Pollution, Pharmaceuticals, and Antimicrobial Resistance." The major sources of pollution responsible for microbial pollution are urban sewage and water draining from farms and farmland, while chemical contamination can result from improper treatment and disposal of waste from production plants. Such pollution increases during heavy rain and floods, when contaminants are washed into rivers and seas, and as a result of overflowing sewerage networks and farm run-off.

Development of Bathing Water Legislation

As recently as 40 years ago, large quantities of mostly uncontrolled, untreated or partially treated municipal wastewater were discharged into many of Europe's surface waters (a practice that still continues in many undeveloped places around the world). At the same time, an increasing number of beach visitors, along with the dirty and degraded state of many beaches, raised concerns about the health of beach users and environmental awareness, which paved the way for the first European Union (EU) Bathing Water Directive (European Union [EU], 1976).

The Directive defined bathing waters as "*those fresh or sea waters where bathing is either explicitly authorized or is not prohibited, and is traditionally practiced by large numbers of bathers*." The Directive listed 19 physical, chemical and microbiological parameters for which limit values had to be defined. Some of them were "imperative" values, whilst others were "guideline" values. Member States had to set values for bathing water that were no less than the imperative values, whilst the guideline values were seen as desirable targets. The Directive also stipulated minimum sampling frequencies and reference methods of analysis. Member States were obliged to take all necessary measures to ensure that, within 10 years of the publication of the Directive, the quality of bathing water would conform to the limit values.

However, that Directive reflected the state of our knowledge and behavior in the early 1970s. Patterns of bathing water use have changed subsequently, as has the state of scientific and technical knowledge. Hence, the revised Bathing Water Directive (European Union [EU], 2006a), used scientific evidence from the most reliable indicators to predict microbiological health risk and achieve a higher level of protection. This Directive is implemented in coordination with other Community legislation on water, such as directives on urban wastewater treatment (European Union [EU], 1991a), protection of waters against pollution caused by nitrates from agricultural sources (European Union [EU], 1991b), and joint actions with the Water Framework Directive (European Union [EU], 2000). The revised Bathing Water Directive puts greater emphasis on the integrated management of bathing waters, which, if implemented in an effective way, should lead to appropriate bathing water quality.

Bathing Waters Quality and Trends

As a result of the EU's Bathing Water Directives, Europe's bathing water quality has improved markedly over the last 40 years. Effective monitoring and management (e.g., investment in the sewerage system, better wastewater treatment and the reduction in pollution from farms), introduced under the Directives, led to a drastic reduction in pollutants released through untreated or partially treated urban and rural wastewaters. The implementation of the Urban Wastewater Treatment Directive (European Union [EU], 1991a) and a focus on reducing overflow from sewers, have been instrumental in reducing pollution and in improving the quality of several low-quality bathing waters (Europena Environment Agency [EEA], 2019). As a result, more and more bathing sites are not only meeting the minimum "sufficient" quality standards, but have reached "excellent" quality (**Figure 3**).

However, there are still poor-quality bathing waters (**Figure 3**). The major sources of pollution responsible for microbial pollution in bathing waters today are still insufficiently treated or untreated wastewater.

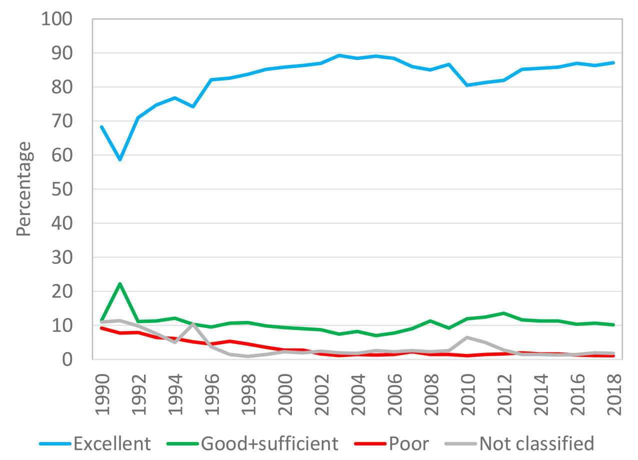

FIGURE 3 | Evolution of the quality in >15,000 European beaches, under the Bathing Water Directive. Source: https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/state-of-bathing-water/state-of-bathing-water-3.

Weather is an additional factor that affects bathing water quality. In wet summers, large amounts of rainwater cause storm water overflow, resulting in the release of diluted sewage into bathing waters or streams that discharge close to or onto beaches. This is not simply *force majeure*, however, since the failure also lies within what the sewage systems are designed to accommodate and with increasing weather extremes predicted under future climate change, engineering systems need to be prepared for shorter, heavier rainfall events (McMichael et al., 2006). In years with below average sunshine, water quality is also affected, as the sun's ultraviolet rays can kill fecal bacteria found in the water (Aragonés et al., 2016).

In order to further improve cases of poor bathing water quality, it is imperative that the sources of pollution be assessed. The bathing water profiles prepared under the Bathing Water Directive should provide an indication of pollution sources in the catchment area of the bathing water; and, together with historical data on rainfall, stream flow and sea currents, provide information on the upstream sources of pollution to be targeted with measures. Management measures are primarily implemented for sufficient or poor-quality bathing waters.

Water samples are collected at bathing sites throughout the bathing season (generally end of May to end September). The samples are then analyzed for two types of bacteria, namely intestinal enterococci and *E. coli*, indicators of pollution from sewage. Depending on the levels of bacteria detected, the bathing water quality is classified. After the end of the bathing season, and based on 4 years of data, bathing waters are classified into one of the bathing water quality classes ("excellent," "good," "sufficient" or "poor"). Some bathing waters have not been classified because there were insufficient samples, or because they are new or have undergone changes potentially affecting water quality.

At the end of the bathing water season EU Member States report the observations at their bathing water sites to the Commission and the European Environment Agency. Before the start of the next bathing season an annual report on the quality of bathing areas is prepared, being the main messages from the most recent (Europena Environment Agency [EEA], 2019):

- More than 22,000 bathing waters were monitored throughout Europe (28 EU Member States, plus Albania and Switzerland). Two thirds of all sites were coastal bathing waters, while one third were situated at rivers and lakes.
- Globally, 95.4% of EU bathing sites met the minimum "sufficient" quality requirement and 85.1% of bathing water sites met the Bathing Water Directive's most stringent "excellent" quality standards. This gives a good indication of where to find good quality bathing water during the coming summer.
- Only 290 (1.3%) EU bathing water sites were rated as having "poor" water quality, which is slightly lower than in 2017. Such poor quality, polluted water can have impacts on human health, causing gastroenteritis, respiratory, skin, ear, and eye infections.
- All reported bathing water sites in Austria, Cyprus, Greece, Latvia, Luxembourg, Malta, Romania, and Slovenia achieved at least "sufficient" quality in 2018 – i.e., thus no bathing waters with poor quality. In four countries, 95% or more of bathing waters were assessed as being of "excellent" quality: Cyprus (99.1%), Malta (98.9%), Austria (97.3%), and Greece (97%).

Of note, with the development of cheap, effective wetsuits, bathing seasons are effectively extending way beyond the traditional May-September time period, with certain groups such as surfers spending time in bathing waters across the entire year. Thus, there is an increasingly strong argument that bathing waters should be monitored all year round.

Assessing the Links Between Seas, Ocean, and, Human Health and Well-Being in Europe in the 21st Century

Although there is a long history of research into the risks to health and well-being from our seas and global ocean (see section "Yes, Oceans are Risky. . ."), the systematic study of potential benefits is more recent. In order to look at possible associations it is useful to utilize a range of approaches, to account for the strengths and weaknesses inherit with each in isolation (**Table 1**).

Analyses of population-based surveys such as the United Kingdom Census suggest the closer people live to the coast, the more likely they were to self-report good health, especially among more socio-economically deprived communities (Wheeler et al., 2012, 2015). Such analyses are limited, however, in that they use area aggregates of both exposure and outcomes and are open to the critique of "ecological fallacy," i.e., the mistake of making assumptions about individuals from group-based data. Consequently, other research has used repeat-cross sectional surveys such as the Heath Survey for England (HSE) that are able to compare individual level exposures with individual level outcomes. These data have not only replicated the basic pattern that people who

TABLE 1 | Overview of strengths and limitations of different research approaches to exploring health and well-being from blue environments.

Method	Pros	Cons	Studies (Examples)
Census data	Population level sample	Cross sectional Ecological fallacy	English Census (N = 48 million) (Wheeler et al., 2012, 2015)
Repeat cross-sectional surveys	Large annual representative samples	Cross sectional Multiple confounders	Health Survey for England (N = 12,000 per year) (Garrett et al., 2019b; Pasanen et al., 2019)
Cohort studies	Longitudinal data; Toward understanding causality	Selection effects Multiple confounders	BHPS (N = 12,000 × 18 years) (White et al., 2013) 1958 Birth Cohort (N > 17,000 x > 50 years) (Cherrie et al., 2015)
Visitor surveys	Large samples; multiple environments	Memory biases Selection effects	MENE (N = 280,000 visits) (Elliott et al., 2015, 2018; Wyles et al., 2019)
Field experiments	Realistic exposure; some control; toward causality	Difficult to randomize/blind to condition	Marine Aquarium (Cracknell et al., 2017) Dental surgeries (Tanja-Dijkstra et al., 2018)
Lab experiments	Reduced confounders and selection effects Increased understanding of underlying processes	Small numbers; non-ecological	Videos/photos/sounds (White et al., 2010) Delay of gratification Jenkin et al., 2018)
Qualitative interviews	In-depth understand of people's motives and beliefs	Small unrepresentative samples	Adult interviews (Bell et al., 2015) Parent/Child interviews (Ashbullby et al., 2013)
Systematic reviews	Systematic overview; Meta-analyze data	Exclusion of important studies; Non-weighting of quality criterion	Neighborhood proximity (Gascón et al., 2017) Water-based interventions (Britton et al., 2018)

MENE: Monitor of Engagement with the Natural Environment. BHPS: British Household Panel Survey.

live on the coast, especially those on lower incomes, have better mental health (Garrett et al., 2019a), they have also been used to investigate the mechanisms through which these effects emerge, e.g., greater physical activity (Pasanen et al., 2019).

However, the cross-sectional nature of even these data mean that it is not possible to assume causality since people with better health may choose to live on the coast, a "selection effect." Analysis of longitudinal cohorts is thus required to explore how people's mental and physical health changes as they move home between inland and coastal settings. Analysis of the longitudinal "British Household Panel Survey," for instance, has shown that, after controlling for a number of individual and area-level factors, participants report significantly better general health and mental health in years when they lived closer to the coast (White et al., 2013). This is stronger evidence of a causal pathway but still relies on self-report data.

Cross-sectional analyses of the English 1958 birth cohort (>17,000 over >50 years) have also been used, therefore, to explore the long-term effects of exposure to the coast on physiological biomarkers of health. In one study, individual's vitamin D status (derived from synthesis of UV light and considered protective for many chronic diseases), was explored in relation to proximity of living near the coast. After controlling for a number of potential confounding factors (e.g., diet, outdoor activity), coastal residence was associated with greater solar irradiance; and individuals living closer to the coast had higher vitamin D levels than those inland, particularly in autumn (Cherrie et al., 2015).

However, living near the coast is often only a proxy for direct contact, under the assumption that people who live near it, spend more time in and around it (White et al., 2014). More interesting, is how people spend their time in marine environments, and how the activities engaged in affect their mental and physical health. To explore these questions researchers have used the English "Monitor of Engagement with the Natural Environment" (MENE) survey which asks around 40,000 adults a year about their interactions with the natural world, including the seas and coasts. Not only are coastal visits reported as being better than other settings for stress reduction (White et al., 2013), they are also the locations where most energy is expended (Elliott et al., 2015); in other words, they provide two important health-related functions. Coastal settings such as beaches also attract a far broader spectrum of the population than inland sites such as woodlands and this may explain why coastal areas are lower in health inequalities (Elliott et al., 2018). More recent research using MENE data has found that feelings of connectedness to coastal/marine sites is also higher when they have a designated status (e.g., due to high levels of biodiversity), suggesting that management and quality of such sites matter directly for people's concerns about them (Wyles et al., 2019).

Surveys can never fully unpack causality which is why different types of experiment have also been conducted, including both naturalistic field-experiments and even more controlled laboratory studies. An example of the former was conducted at the United Kingdom's National Marine Aquarium (Cracknell et al., 2017). During a restocking, individuals were asked to sit and watch the aquarium's largest tank for 10 min at periods when the tank had different levels of biodiversity. Broadly speaking, higher levels of biodiversity were associated with better physiological (e.g., heart rate) and psychological (e.g., mood) outcomes. A second study tested how "walking" along a virtual reality (VR) beach (using a headset and hand controller) affected experienced pain during real dental treatment. Patients were randomized to nature (coastal) VR, urban VR, and usual dental care. Those randomized to either type of VR reported reduced experienced and recollected pain compared with no VR. Furthermore, the content of the VR mattered: coastal nature VR was reportedly better for pain reduction than urban VR (Tanja-Dijkstra et al., 2018).

In two laboratory studies the preferences (e.g., attractiveness), affect and perceived restorativeness ratings of views from the same hypothetical "hotel room" were explored for participants looking at photographs of 120 different views (White et al., 2010). Both natural and built scenes containing water were associated with higher preferences, with greater positive affect and higher perceived restorativeness than those without water. In a similarly controlled study using videos and children aged 8–11, researchers found that children showed better self-regulation (e.g., the ability to delay gratification) after watching a video of a local beach than a local urban setting (Jenkin et al., 2018).

Qualitative studies can go beyond large surveys and experiments by having in-depth conversations with a smaller number of individuals. In one, both parents and children reported that the coast encourages families to play actively together, compared to inland places (Ashbullby et al., 2013). In another, in-depth interviews were undertaken about specific trips to coastal settings for recreational purposes using innovative geo-location techniques (Bell et al., 2015). Specifically, people's locations during the visits were recorded using a satellite geo-locator and then a map of their activity recorded and presented back to them after the visit to be discussed in-depth. This technique enabled people to enjoy the visit without interference at the time, while at the same time being able to reflect on why they stopped at a certain point for several minutes, with responses such as "the light on the water was fascinating and I just had to stop and watch." Although generalizability is difficult from such studies, they offer a far richer picture of people's personalized everyday lived experiences, emotions and thoughts than can achieved from either generic surveys or highly controlled experiments.

Finally, as the number of studies in the area increases, systematic reviews and evidence syntheses of multiple studies can be performed. One recent review of 35 epidemiological studies examined the relationships between coastal residence and various health outcomes and concluded that the balance of evidence supported a positive association between living in areas with more blue space and benefits to both mental health and well-being. However, the evidence for a positive association with general health, and reduced obesity, cardiovascular disease, and related outcomes, was less consistent (Gascón et al., 2017). Another review of 33 intervention studies (e.g., that used watersports among at risk communities for health and wellbeing promotion purposes) concluded that carefully structured interactions with the sea/ocean could help both personal and social wellbeing (Britton et al., 2018).

There is still much research to be done in this area. For example, there are issues around how best to measure "exposure," and further work is needed on the mechanisms of benefit, and whether these beneficial effects are only found in certain countries and not others. The Horizon 2020 BlueHealth Study[6] is examining a many of these issues. In particular, the International BlueHealth Survey[7] has recently been run in 14 European Countries, as well as Hong Kong, Australia, California, and Canada; and will begin to examine whether the beneficial effects can be found in countries beyond United Kingdom. Additional research is also needed about the risks and benefits for coastal populations in developing countries, particularly given the increasing impacts of climate and other environmental change on these potentially vulnerable communities.

Case Study of Collaboration and Engagement to Foster Research and Knowledge Transfer in OHH

Currently, new state-of-the-art tools to study and disseminate the importance of marine ecosystems on human health and well-being are needed. Living marine resources have strong links with human health and well-being that are complex, still not well understood (Lloret et al., 2016). An innovative tool to engage stakeholders and citizens is the "Oceans and Human Health Chair"[8], which was established in 2017, thanks to a pioneering collaboration between the University of Girona, the City of Roses, the Fishers Association of Roses, and the Fishmongers' Guild of Catalonia. The Chair is the first in Spain, and one of only a few in Europe, that focuses on the topic of oceans and human health (OHH). The Chair provides a unique bank of knowledge on the subject, integrating different stakeholders from universities, research centers, health centers, environmental administrations, commercial companies, and society. This combination of knowledge and expertise means that the Chair is in a unique position to contribute in the development of important work, not only from an academic point of view but also for society as a whole.

The OHH Chair promotes and carries out studies on the complex relationships that exist between marine ecosystems and the health of people, as well as the transfer of this knowledge to society. In this way, the Chair not only contributes to a better understanding of the links between marine ecosystems and human health, but also helps informing people about a relatively little-known aspect: how protecting and preserving marine ecosystems can protect and preserve the health and well-being of people. Hence, the Chair organizes lectures, courses, conferences and exhibitions aimed at specific audiences (e.g., fishers, fishmongers, patient associations, tourism companies, environmental and health technicians and university students, among others) as well as the general public – both local and tourist, young and old – to spread information on the links between the sea and people's health and well-being.

The Chair is based in Roses in the north-western Mediterranean, which is part of the "Cap de Creus Natural

[6]https://bluehealth2020.eu
[7]https://bluehealth2020.eu/?s=survey
[8]http://www.oceanshealth.udg.edu/en/what-is-it.html

Park"[9], one of the most emblematic marine reserves on the Catalan coast. This marine protected area (MPA) is an excellent testing ground for the Chair for studying how marine reserves, through an active management to preserve marine habitats and resources, can contribute to human health and well-being. Furthermore, the fact that the Chair is situated in a Mediterranean area affected over many years by human activities constitutes another testing ground to study the impacts of tourism and fishing in the Mediterranean on human health and well-being (Lloret and Riera, 2008; Lloret, 2010; Lloret et al., 2019).

The Chair shares the 17 SDGs of the UN 2030 Agenda for Sustainable Development (United Nations, 2016). Among the goals are the conservation of the seas and oceans and the sustainable use of the marine resources, the promotion of a healthy life, and the preservation of people's well-being. The Chair also endorses the "One Health Initiative"[10], which is a worldwide strategy for expanding interdisciplinary collaborations and communications in all aspects of health care for humans, animals and the environment. In this way, the OHH Chair is contributing to forge inclusive collaborations between marine and fisheries biologists, oceanographers, physicians from difference disciplines (oncology, allergology, cardiovascular risk, epidemiologists, etc.) as well as veterinarians, social scientists and marine ecosystems managers.

The future development of chairs such as the OHH Chair in Roses could give way to new collaborations and synergies between universities and research centers studying OHH topics and other non-academic entities including fishers', consumers', and patient's associations, hospitals and primary care centers and tourism industry, among others, to foster sustainable maritime activities and healthy lifestyles. The OHH Chair could serve as an example of efficient tool to build strong relations with all the regional agents operating in the field of OHH, to generate efficient interactions and to create trust between society and the academia.

Weaving Alliances Between Blue Tourism and OHH Research, Through Citizen Science

Coastal tourism is one of the pillars of the Blue Economy, and a key driver of economic development and jobs in Europe (European Union [EU], 2015) and beyond. Every year, millions of tourists visit coasts worldwide. Enjoying time by the beach is still the number one reason for tourists to go on holiday among European citizens (TNS Political & Social, 2015).

The seasonal concentration of tourism in coastal areas can have a negative impact on the environment (Davenport and Davenport, 2006), and, as a consequence, on the health of those living or spending time by the sea (Fleming et al., 2006). However, it also opens a window of opportunity to boost Ocean literacy amongst citizens, and to make them aware of the consequences of poor environmental management (Uyarra and Borja, 2016). Given the educational and interpretational dimension of ecotourism, those operators offering ecotourism activities by the coast or at sea ("blue ecotourism") can support education and awareness on the relationship between the OHH, as well as contributing to advances in research these interactions through citizen science engagement (Pocock et al., 2018).

Citizen science is emerging as a very useful ally of both research and education efforts directed at better understanding our natural environment and managing our relationship with it (Vann-Sander et al., 2016). Within this broad framework, the emerging discipline of OHH can benefit tremendously from the engagement of civil society in data collection efforts, supporting research and decision-making processes. Actually, OHH needs that engagement to facilitate the implementation of measures geared at minimizing the risks and maximizing the benefits of people's interaction with the ocean.

While there are many examples of successful citizen science initiatives that are contributing to gather research data on biological variables (such as those focusing on recording sightings of marine life, amongst others) (Crain et al., 2014), the "blue health" dimension of spending time by the coast or at sea remains largely untapped by citizen science efforts. The H2020 SOPHIE project[11] is seeking to fill in this gap, piloting a Citizen Science Programme to activate tourism operators and their customers as "citizen sensors" that contribute to build knowledge on OHH.

Two SOPHIE citizen science initiatives have been launched in the European Atlantic and Mediterranean basins, namely "Blue spaces and Well-being" –looking at the relationship between exposure to blue spaces through ecotourism activities and mental well-being and environmental awareness- and "Mapping *Ostreopsis* spp." (a HAB) –seeking to work with tourism operators of the WILDSEA Europe network[12] who live and work by the coast all year round, as an early detection system in their areas of blooms of *Ostreopsis* spp. [a harmful microalga with mild effects on beach users, e.g., Vila et al. (2016)]. To date, 96 tourism operators have proactively signed up to contribute to both citizen science initiatives through SOPHIE's Citizen Science Program.

Although the results of the Program will not be demonstrated until late 2020, the successful engagement of tourism operators speaks to the disposition and willingness to contribute to OHH research of tourism stakeholders connected to blue ecotourism. SOPHIE's Pilot program will help to identify barriers and critical success factors to address when rolling-out citizen science initiatives on OHH at a larger scale in Europe.

GOVERNANCE OF OCEANS AND HEALTH INTERACTIONS, IN EUROPE

The inventory of risks and benefits related to oceans and health, as described in the previous sections, highlights the importance of this OHH theme, but to date, it does not have an explicit place in European policy making. The EU maritime policy and legislative framework is designed to regulate human activities in the marine environment and to

[9] http://www.catalunya.com/cap-de-creus-natural-park-17-17001-573533?language=en

[10] http://www.onehealthinitiative.com/

[11] https://sophie2020.eu

[12] www.wildsea.eu

underpin marine environmental protection (Boyes and Elliott, 2014). Only a small number of EU maritime instruments take specific account of human health aspects (e.g., the Bathing Water Directive (European Union [EU], 2006a), the Shellfish Waters Directive (European Union [EU], 2006b), the Water Framework Directive (European Union [EU], 2000), and the EU Maritime Security Strategy (European Commission [EC], 2014); and these are specifically targeted at dealing with risks to health (e.g., due to chemical pollution or waterborne pathogens) rather than health promotion. Most of the EU's maritime legislative instruments, however, do not take explicit account of the connections between marine environmental health and human health, including flagship policy instruments such as the Marine Strategy Framework Directive (MSFD; European Union [EU], 2008), the Maritime Spatial Planning Directive (European Union [EU], 2014) and the Blue Growth Strategy (European Commission [EC], 2012).

European Union health policy aims to protect and improve health of EU citizens and complements national policy since Member States are primary responsible for health services and medical care. However, cross-border health threats may be subject to a European approach. So far, there seems to be little focus on health benefits at the EU level. The EU Third Health Programme (2014–2020) (European Union [EU], 2014) addresses the critical link between environment and health, but does not refer to the particular benefits of coastal or blue environments or how these could be realized.

In European water policy, a shift from government to governance can be identified in the last decades (European Commission [EC], 2001). Governance approaches, with the involvement of multiple actors at multiple levels, and particularly bottom-up approaches, are often regarded as more effective in dealing with complex urban water issues, compared to conventional legal frameworks with top-down central steering mechanisms (Lee, 2009; Howarth, 2017). In 2016, the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy launched an agenda for international ocean governance (JOIN, 2016) and is part of the EU's response to the UN SDGs, in particular SDG 14 "*to conserve and sustainably use the oceans, seas and marine resources*."

The agenda aims to strengthen international ocean governance in order to manage and use the world's oceans and their resources in ways that keep our oceans healthy, productive, safe, secure and resilient. The agenda calls for a cross-sectoral, rules-based international approach. Although some (indirect) linkages to health risks can be found in agenda, the potential benefits of oceans to human health and well-being are lacking.

To bring the oceans and health theme to EU policy table, might need specific conditions of governance. Conditions of governance are defined as the elements and activities that are necessary in a governance approach to realize the objectives aimed for. So far, administrative bodies on oceans and health operate at parallel tracks that do not necessarily interact, both at national and European levels. To improve effectiveness, interactions need to be established, both from national and European communities. An incentive, potential benefit or shared vision could be a vehicle to get this started. Understanding the oceans as part of the global hydrological cycle; how it is influenced by various drivers and pressures; the benefits and risks to human health; and the potential effects of interventions, all contribute to capacity building for those who have the authority and means to act. So far, the distribution of knowledge among authorities, other stakeholders and citizens is fragmented. Citizen awareness of the benefits of oceans and health would support policy debates (e.g., "right to water" initiative[13]), as well as data and evidence to support the debate and to monitor the effects of any interventions agreed upon.

IMPACTS OF FUTURE TRENDS ON OHH

The intricate relationship between the health of both the oceans and humans is further complicated because the marine environment is under increasing pressure from human activities, e.g., maritime transport, industrial processes, fishing, maritime tourism and agricultural and waste practices as well as the growing impacts of global change. Other trends that could impact the relationship between oceans and health concern demography, economy, social-cultural aspects, migration across the sea (e.g., the actual refugee crisis in the Mediterranean), technological developments, and policy development. Examples are the increasing human life expectancy, the increasing percentage of chronically ill, yet active people, the increase of tourism worldwide, and the use of technology for awareness raising and healthy behavior.

So far, the assessment of the resultant impacts, on both marine ecosystems themselves and on human health and well-being, have largely been undertaken as separate activities, under the auspices of different disciplines with no obvious interactions (Fleming et al., 2015; Depledge et al., 2019). Furthermore, the impacts of these trends have been studied at a continental or national level; and policy development is often based on these high-level studies. The implications of global trends on a local level are barely understood so far. However, local authorities need to take action now to anticipate the impacts of future trends to keep their citizens healthy and safe.

To identify challenges at a local level arising from global trends, a participatory approach has been developed to discuss the relevancy of different trends for different European sea basins with local stakeholders, their perspectives on how to deal with these trends and potential research gaps. **Box 1** shows the results of such a discussion during the AZTI's Summer School 2019, focusing on the Atlantic Ocean and especially the Basque coastline. Although these workshop results are influenced by the issue of participant representation and should therefore be treated with care, the interactive and integral approach resulted in viewpoints on local relevant issues, trends, impacts and research gaps, that are distinct from the more generic observations regarding oceans and human health.

[13]https://www.right2water.eu/

BOX 1 | Global trends, local impacts for oceans and health and research gaps focusing on the Basque coastline of the Atlantic Ocean.
The San Sebastián area is part of the Basque Autonomous Region (northern Spain), and it can be characterized as a region with a relatively high economic growth. Employment is mainly in the services sector [tourism (beach/surf/gastronomy), congresses and festivals], with an ongoing effort to welcome visitors but avoid mass tourism. The fishing sector is declining. Strong currents, waves, temperature and hydrographic conditions limit the possibilities for aquaculture. Population in the region is slightly growing and is progressively ageing. Due to climate change, the risk of flooding and "explosive cyclogenesis" (strong storms generating very high waves) are expected to increase, potentially causing damage to infrastructure, beaches and the old town.

With regard to future outlooks, participants of the AZTI's 2019 summer school identified: the further loss of biodiversity and other ecological impacts; the development towards a circular economy; transitions in healthcare and energy; and the increasing use of blue spaces for recreation, as the most relevant trends for the region. Changes in consumer food preferences, changing institutional and governance structures, and further loss of biodiversity and other ecological impacts were regarded as the most uncertain trends for the region with a potential high impact.

Impacts of these trends on the relationship between oceans and human health and potential research gaps were discussed during the remainder of the workshop. The increasing recreational use of blue spaces for instance was expected to contribute to improved mental and physical health for all, but implies requirements in terms of management (litter, pollution [noise, air, water, impacts on local infrastructure), awareness of risks and local heritage for different groups, and the protection of biodiversity (benthic communities). Research gaps identified for this trend focused on behavioral change ("cleaner" habits, perception of risks), integrative implementation strategies, inclusiveness in the use of blue spaces, assessment of the sustainable recreation capacity, and research on the negative aspects of recreation on the environment. Other relevant trends were discussed in a similar way.

CONCLUSION/PRIORITIES FOR FUTURE RESEARCH

In the present paper we posit that there is increasing evidence that healthy oceans are providing crucial ecosystem services, which benefit humans in different ways, including better physical and mental health, as well as a general well-being. Hence, achieving "good environmental status," *sensu* the Marine Strategy Framework Directive (MSFD) in Europe (Borja et al., 2013), and conserving and sustainably using the oceans (*sensu* the SDG14; United Nations, 2016), will result in an increasing and sustainable provision of ecosystem services, which can contribute also to achieve human healthy lives and well-being (as required by SDG3).

However, this would need a research and policy agenda on OHH, understanding the complex relationships existing between oceans and human health, in multiple knowledge areas and across sectors. Because human health is intrinsically linked to the health of the oceans, some of the present priorities on the ocean, and by extension, the planet's health determines the priorities on the OHH agenda. Eventually, this agenda could be used in the discussions for the upcoming United Nations (UN) Decade of Ocean Science for Sustainable Development - 2021–2030 - (UNESCO, 2018), contributing to a better knowledge of the complex relationships between oceans health and human health. **Table 2** arose from the 3-day summer school in San Sebastián and could serve as an initial list of elements for discussion among the scientific community and other stakeholders, regarding the research gaps on OHH, based in several topics of importance identified by the participants.

- Climate change: Climate change is already having tangible effects and will pose increasing risks and impacts to the coasts, seas, and global ocean in different ways; and these risks and impacts will increasingly affect human lives and health (**Table 2**). There is a need to know today's baseline and future projections to define adaptive and mitigation strategies to guarantee good ocean and human health.
- Sustainable use of ecosystem services: The provision of ecosystem services is directly linked with human well-being in different ways (**Table 2**). There is a need to objectively identify the level of ecosystem services available nowadays at local and global scales and explore future scenarios differently affecting OHH.
- Pollution: Progress has been made in addressing some pollutants and pathways and impacts of certain pollutants have been reduced, but other pollutants, specifically plastics and pharmaceuticals still need attention and new risks are emerging as well as complex combinations of substances and pathways (**Table 2**).
- Ecosystem conservation: In a planet under change, with rapidly decreasing biodiversity, there is a need to conserve not only the species, but the habitats and the whole ecosystem (**Table 2**). Science, stakeholders and end users should work together for the preservation of natural habitats as an essential condition of good OHH.
- Cross-cutting issues: To make progress in addressing the complex system of inputs, pathways and impacts a cross-cutting approach is needed that can integrate expertise across sectors and disciplines, and encourage working in partnership between private and public organizations (**Table 2**).
- Solution focus: Problems should always be well described, by collecting information, assessing risks and impacts. But the field should also consider researching interventions and solutions more than it has traditionally been done (Borja and Elliott, 2019).

From the discussions in the summer school, the idea emerged that the OHH agenda should include more interdisciplinary research and training, which could be integrated in national and international research priorities, but also in the context of the UN Decade of Ocean Science for Sustainable Development - 2021–2030 - (UNESCO, 2018; Ryabinin et al., 2019). In particular, the research agenda should be co-created and connected to the society, stakeholder and policymaker concerns at both local and global levels. We hope that this review can contribute to achieving those objectives.

TABLE 2 | List of priorities for research in Oceans Health and Human Health, as identified by the authors of this review, for a series of topics and trends.

Topic	Trend	Research gap
Climate change	More extreme events: floods, heatwaves, heavy storms, higher waves, etc.	Threats to human life in coastal areas, impacts on mental health after coastal ecosystem destruction
	Sea-level rise: Migration from coastal areas to safer regions	Human physical and mental impacts after migration
	Ocean acidification, affecting sensitive organisms	Impacts on human health yet unknown, but probably affecting health through decreased nutrition well-being
	Increasing temperatures and changes in precipitation, humidity, etc.	Effects on infectious diseases and parasites, both to fish and shellfish species, and directly to humans (e.g., tropical diseases in temperate regions)
	Shift of species and the introduction of exotic species	Effects on human health, through the relationships between biodiversity and well-being
Use of ecosystem services	Healthy and sustainable seafood is a key aspect for a healthy diet, to have a good human health	Contribution of the marine omega 3 fatty acids to the decrease of not only cardiovascular risk but also to the prevention of certain cancer and possibly dementia
	Recreation (bathing, water sports, blue tourism, eco-tourism, nature experiences, etc.) is increasingly important for our well-being and our physical and mental health	How excessive tourism is threatening the benefits derived from these marine based activities
	Renewable energy technologies must substitute carbon-based energies; and the increase of marine renewables (i.e., offshore wind, waves, tides, etc.) is playing an important role in the provision of such energy	Impacts on human health yet unknown. The impacts of these energy platforms at sea on marine organisms should be well assessed.
	Specially in the last centuries humanity has exploited marine species and habitats in an unsustainable way, leading to a degradation from estuaries and coasts to deep waters	There is an increasing need to restore those degraded ecosystems and recover the lost services they provided (i.e., food, recreation, natural products, etc.) investigating how this recover is benefiting human health and well-being. Also, certain fish gears (non-industrial) used by small communities should be reconsidered as a tool for the sustainable use of natural resources. Marine Protected Areas should be maintained and increased.
	Livelihoods, economy. For many coastal nations, particularly the developing ones, seafood extraction and tourism play a key role in the local economy and the livelihoods of local people	Investigate how this affects well-being and analyze future economic activities.
Pollution	From the "traditional" pollutants (i.e., metals, some organic contaminants) with in general their concentrations being reduced, the planet faces new emergent pollutants (i.e., pharmaceuticals, AMR, etc.) and complex mixtures	How these emerging pollutants and mixtures of pollutants can produce harm both to the environment and human health, exploring the needs of monitoring, assessment and solutions.
	The amount of litter, plastics and micro/nanoplastics has increased in last decades, leading to an unsustainable situation, needing urgent solutions	Investigate the effects of micro and nanoplastics in human health, introduced by seafood and drinking water. Foster reduction of plastic use and waste.
	HABs and eutrophication, although "traditional" phenomena and problems, which are being reduced in developed countries, are matter of concern in many developing countries and possibly can be exacerbated with climate change	Investigate the health risks of these phenomena, including the expansion of toxins such as ciguatoxins linked to changes in distribution of the biota due to sea warming and global trade of seafood, which are matter of concern too for seafood consumers, and develop prevention plans.

(Continued)

TABLE 2 | Continued

Topic	Trend	Research gap
Ecosystem conservation	Increasing use of marine ecosystems	The links between better ocean status and better human health (both physical and mental) should be better understood
	Increasing protection of oceans	The links between Marine Protected Areas and human health should be explored in depth particularly in developing countries
Cross-cutting issues	Multiple uses of the oceans	Methodologies (i.e., surveys; inclusion of environmental, socio-economic, and public health and medical data; etc.) need to develop new, diverse and mixed approaches, especially related to big data in environmental and human health studies (artificial intelligence)
	Changing institutional and governance structures, more healthy living in international and national policies and strategies	How to improve enforcement of environmental laws (fishing, maritime recreational activities, etc.), and involvement of medical, veterinary and patient associations, with inclusion of OHH in the legislation agenda, including the global level (e.g., SDGs), studying what is there and what to be enhanced
	Complexity of the oceans	OHH studies require interdisciplinarity-transdisciplinarity (i.e., medicine, ecology, biology, chemistry, sociology, etc.) and *trans*-sector collaboration and co-creation (i.e., researchers, business, government, NGOs, citizens) as well as interdisciplinarity-transdisciplinarity training and practice
	Rising income and social inequalities	Explore social (health and environmental) inequality (i.e., increasing the most at risk places are where the most vulnerable people live and decreasing access to the benefits of ocean interactions for those of lower socio-economic class)
	Increasing use of the oceans	Raising awareness about the ocean problems, particularly among young people and people from countries with weak environmental awareness (e.g., in many developing countries), looking for achievable solutions to have healthy oceans and, as such, better human health, is necessary through education and Ocean Literacy, targeting the right actors and stakeholders, to change attitudes and behavior in our daily lives
	Changing institutional and governance structures	Better governance of the oceans, including stakeholders' participation and co-creation in decisions, as well as involving society through citizen science in monitoring and surveillance, will benefit the ocean and human health
	More healthy living in international and national policies and strategies	Unified policies and other governance agendas and mechanisms which take both ocean and human health into account locally, regionally, nationally and internationally
Solutions	After identifying the multiple problems at oceans, we need to start implementing solutions to revert the impacts	Multiple fields: from nature-based solutions to technological, changes in human attitudes and behavior, economic and social changes, etc., which all together will serve to increase ocean health and human health

AUTHOR CONTRIBUTIONS

AB developed the idea of the summer school and the manuscript with CE and LF. Each author wrote one of the sections under his/her expertise. AB wrote the first draft of the manuscript. All authors contributed equally to the discussion of the future priorities and in writing the final manuscript.

FUNDING

This manuscript is the result of an AZTI's Summer School, celebrated in San Sebastian (Spain), from 5th to 7th June, 2019, funded by AZTI (www.azti.es), the Aquarium of San Sebastian, European Union's Horizon 2020, Grant/Award Number: 774567 (SOPHIE Project https://sophie2020.eu) and 666773 (BlueHealth Project https://bluehealth2020.eu); SCOR and IOC/UNESCO GlobalHAB program (http://www.globalhab.info); the Oceans and Human Health Chair/University of Girona (www.oceanshealth.udg.edu); and the European Environment Agency (EEA). AB was supported through a convention between AZTI and the Basque Water Agency, for monitoring and assess marine waters.

ACKNOWLEDGMENTS

This is contribution number 954 from AZTI's Marine Research Division.

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Conflict of Interest: JP was employed by the company Travelecoology.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.