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Review

Climate Change Implications for Metal and Metalloid Dynamics in Aquatic Ecosystems and its Context within the Decade of Ocean Sciences

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Abstract: Anthropogenic activities are affecting marine ecosystems, notably coastal ones, in multiple ways and at increasing rates, leading to habitat degradation, loss of biodiversity, and greater exposure of flora and fauna to chemical contaminants, with serious effects on ocean health. Chemical pollution, in particular, is a significant negative stressor for aquatic ecosystems, both oceanic and coastal, and has recently been identified as a priority for conservation efforts. Metals and metalloids, in particular, present environmental persistence, bioavailability, tendency to bioaccumulate along the trophic chain, and potential toxic effects. However, the current scenario of climate change is increasingly affecting the aquatic environment, altering water mass flows and the transport of pollutants, aggravating toxic effects and ecological risks. Moreover, although traditional sources of contamination have been studied for decades, many knowledge gaps persist, in addition to the emerging effects of climate change that are still poorly studied. In this regard, this review aims to discuss climate change implications for metal and metalloid dynamics in aquatic ecosystems and its context within the Decade of Ocean Sciences. We also discuss how an increasing interest in plastic pollution has led to contamination by metals and metalloids being neglected, requiring mutual efforts to move forward in the understating of the negative and often lethal impacts of this type of pollutants, thus aiming at prioritizing contamination by metals and metalloids not just in the oceans, but in all water bodies.

Keywords: United Nations; ocean conservancy; pollution; physiology; policy

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1. Introduction: Drivers of Climate Change and Pollutant Dynamics in Aquatic Ecosystems

Climate change now permeates every aspect of life on Earth. This term refers to long-term shifts in average temperatures and weather patterns that define local, regional, and global climates on Earth [1,2]. These shifts take place through both natural processes, such as internal variabilities (e.g., normal cyclical ocean patterns such as El Niño, La Niña, and the Pacific Decadal Oscillation) and external forcings (e.g., volcanic activity, solar cycles, variations in Earth's orbit), and, of course, anthropogenic activities, which have, without a doubt, played a major role in this process [1]. Key climate change indicators comprise several factors, including but not limited to global land and ocean temperature increases, ocean acidification, rising sea levels, ice deposit losses, and extreme weather frequency and severity alterations (i.e., hurricanes, heatwaves, wildfires, droughts, floods, and altered precipitation rates). All these dynamics, both alone and grouped, have important global repercussions on both the environment and human society [1,2].

Under this new scenario, the dynamics and toxic effects of many environmental contaminants will be significantly altered in different water bodies worldwide [3,4], resulting in modified distribution, bioavailability, toxicity, and trophic transfer [5,6], leading to increased associated ecological and human risks [7–11].

Increasingly frequent extreme climate events are expected as a result of climate change, which will directly and indirectly affect contaminant dynamics in aquatic ecosystems. One example in this regard comprises alterations in physical and geochemical soil–contaminant–water system properties [12]. For instance, groundwater levels and flows have been reported as directly affected by altered frequencies and intensities of rainfall events [13,14], modifying associated contaminant leaching and waterborne transport [15,16]. Runoff variations are also reported, in many instances resulting in the higher release of topsoil contaminants influenced by elevated groundwater levels and longer low flow periods [17,18]. Higher runoff of these contaminants due to higher fluvial discharges to coastal environments and, consequently, the oceans, are thus also expected [10].

Other concerns regarding climate change outcomes on contaminant dynamics effects include higher sediment and nutrient load transports to water bodies [19–25]. For example, Ockenden et al [4] evidenced that high flow events, which are expected to increase under a climate change scenario, transported >90% of sediment loads from two rural headwater catchments in the UK. This is extremely worrying, as many contaminants exhibit significant sediment and particle-binding behavior [26], increasing ecological risks. Furthermore, some authors indicate increased nutrient loads under a climate change scenario, such as high phosphorus load transport during high flow events and higher rainfall volume and intensity [4]. This results in eutrophication and higher organic matter (OM) loads in aquatic ecosystems. This will, in turn, become a significant concern regarding chemical contamination, as many contaminants exhibit a high affinity for OM in aquatic environments, and several studies have reported significant positive correlations between OM and certain contaminant classes, such as polycyclic aromatic hydrocarbons [27] and metals and metalloids [28].

2. Metal and Metalloid Dynamics in Aquatic Ecosystems under A Climate Change Scenario

In contrast to organic chemical compounds, metals are non-degradable and cannot be easily metabolized in less toxic compounds [29], comprising a significant concern for aquatic ecosystems. These compounds, whose general biogeochemical cycling is displayed in Figure 1, in particular, are of significant concern under a climate change scenario, as these elements display certain features, such as high persistence, non-degradability, trophic transfer capability, and potentially toxic effects, that will be exacerbated following the environmental equilibria disturbances we are now suffering [3–7].

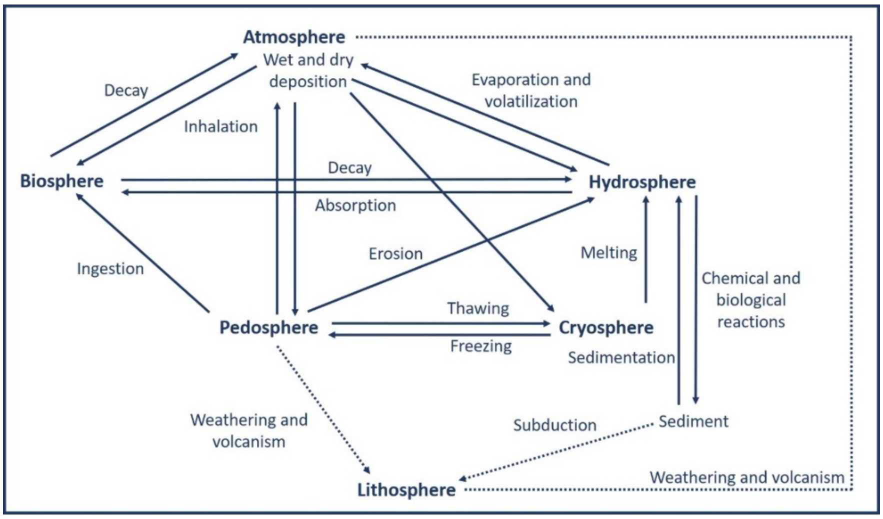

Figure 1. General biogeochemical metal and metalloid cycling throughout environmental and biological compartments (Adapted from [30]).

Metal and metalloid transfers into water bodies are governed by hydrodynamics, biogeochemical and physicochemical factors [31,32]. Following their input into the aquatic compartment, these compounds may suffer different fates, mainly water column redistribution, sediment accumulation and/or trophic web incorporation, mostly through the dietary route [33]. However, geochemical equilibria in different aquatic ecosystems are significantly affected by climate change-driven pressures [33,34], due to significant metal and metalloid remobilization and transfer under hydroclimatic extremes [35] caused by altered physicochemical water parameters. This affects metal speciation and adsorption/desorption and remobilization processes, such as sediment compound precipitation, particulate matter binding, association with organic molecules and co-precipitation with certain oxides or carbonates [36,37].

In general, metal and metalloid deposition rates in aquatic environments are directly influenced by altered precipitation levels, affecting continental runoff to oceans, as well as mixing and stratification processes and physicochemical water parameters [38,39]. These altered processes also directly affect metal-associated carbonate and sulfide dissolutions, which may result in increased release of these contaminants to the water column [40]. However, it is important to note that these dynamics all depend on the type of water body, as pH, salinity, and temperature, among other water properties, are paramount in metal and metalloid speciation, sediment and water column abundance, and bioavailability. The pH, in fact, is one of the main metal mobility drivers in sediment [41], strongly affected by more frequent flooding events. Because of this, metal and metalloid dynamics assessments become paramount under a climate change scenario considering type of water body (i.e., freshwater, estuarine, and marine ecosystems).

Concerning freshwater, groundwater variations due to climate change are of significant concern, directly affecting groundwater contamination, as events that lead to high groundwater levels result in topsoil contaminant removal and groundwater inputs, such as diffuse iron and other elements [42,43]. Extreme climate events also result in more frequent river discharges, resulting in differential freshwater metal and metalloid inputs and consequent accumulation in overlying waters [44]. These contaminants have also been frequently associated with higher temperatures caused by climate change in several freshwater systems. For example, significant associations between sediment Pb, As, Cd, and Hg contents and temperature were noted in one study carried out in Romania assessing freshwater water bodies [44]. In another assessment carried out on three lakes in China, several metals and metalloids (i.e., Al, As, Ca, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Ni, Pb, Ti, V, Zn) were determined, and their associations to nutrients (i.e., total organic carbon and total phosphorus) in bottom sediments while also considering meteorological factors (temperature and precipitation) were investigated to reveal contributions of climate change to the deposition of these pollutants [45]. The determined metals were significantly correlated with nutrient concentrations, implying geochemical associations during transport and/or similar anthropogenic sources (such as fertilizers), or both. Furthermore, all elements except Al, Ca, Fe and Mg were directly associated with annual average temperature and annual precipitation rates, two factors expected to increase under a climate change scenario. In another study, fluoride and arsenic concentrations in urban lakes in Beijing exhibited significant positive correlations with temperature/precipitation, suggesting that water quality associated with fluoride and arsenic concentrations in the investigated lakes is becoming worse under this climate change trend [3].

Estuarine systems, such as mangroves, also suffer direct effects from several key climate change effects, such as sea level rises, increased CO_2 and increased atmosphere and seawater temperatures, as well as altered precipitation rates and ocean currents [46]. However, studies on this subject are still scarce [34]. In this regard, some climate change pressures have been associated specifically with metal and metalloid dynamics, chemical speciation, mobility, and bioavailability in mangroves. These include the residence time of waters in estuaries, sedimentation rates and redox state of surface and pore waters, all major controllers of trace metal chemical speciation, mobility, and bioavailability, which have been recently discussed in depth by [34]. Briefly, these authors indicate that increased erosion processes due to sea level rises dissociate deposited sulfides in these environments, remobilizing these contaminants to the water column, which may then adsorb onto suspended particles and become re-deposit within the same estuary or exported to continental shelf sediments, reaching the ocean. They also discuss that saline mangrove intrusion is also capable of oxidizing deeper sediment layers releasing metals and metalloids to porewaters and potentially adsorbing to organic matter, increasing their bioavailability to local biota. Furthermore, some studies discussed by these authors also indicate that altered annual rainfall rates alter material flows to mangroves, estuaries, and, finally, the ocean.

Concerning marine ecosystems, changes in seawater temperature, salinity, pH, and other marine environmental parameters are the main drivers concerning the fate and global cycling, bioaccumulation, bioavailability and toxicity of chemical pollutants, including metals and metalloids, to marine organisms [47]. These parameters are significantly altered in several climate change endpoints, such as global warming, ocean acidification, and higher rainfall rates, resulting in both biological and chemical changes. Concerning the former, for example, one of the main climate change effects, global warming, takes place unevenly around the globe, strongly influencing ocean current behavior [48], consequently altering ocean dynamics, local climates, and several biological processes such as reproductive periods and migratory behavior. Oceanic migration climate change effects have, in fact, already been reported for several ocean inhabitants (i.e., elephant seals, [49], and other pelagic marine species [50]). Furthermore, fish growth for certain species has been reported as having slowed under the global warming scenario, resulting in recruitment issues, and spawning and feeding ground changes have also been indicated, both with disastrous ecological and human health consequences [51]. These are, in turn, directly associated with metal and metalloid dynamics in a two-fold manner, as altered ocean currents will of course alter metal transport, but mainly, altered migratory events will expose migratory animals to different environmental contamination levels, due to the aforementioned altered dynamics of these contaminants. In addition to these biological outcomes concerning marine ecosystems, significant physicochemical water column alterations are expected under a climate change scenario. Under normal conditions, dissolved metals are usually present at low concentrations in the water column, as these compounds are relatively insoluble in seawater, and most become adsorbed to the sediment at significantly higher concentrations compared to the water column, although this process depends on the metal and sediment organic carbon content, particle size and crystal structure, among others [52]. Thus, the sediment–water interface is one of the most affected in this regard, as metal speciation, solubility, and concentration gradients, as well as oxidation–reduction interface potentials, will become altered. For example, Hg, one of the most toxic elements, suffers extensive biomethylation processes mostly at the water–sediment interface, where partly alkylated (ionic) metal and metalloid species, such as Hg, remain in the aqueous phase and comprise highly bioavailable contaminants to local biota, while fully alkylated species are volatilized to the atmosphere, where they may be transported via wind currents to other areas or be degraded to inorganic forms, returning to soil/sediment systems via precipitation [53]. Climate change is thus expected to alter these processes, as well as many others for this and other elements exhibiting different valence states in aquatic environments, such as As, Cr, and Se [54], to name but a few. Of course, each element is unique concerning chemical properties, water environmental bioavailability, and toxicity, all of which directly affect bioaccumulation and biomagnification processes.

Another climate change endpoint, increasing rainfall periods in different global areas, is noted as being the responsible for increased continental runoff, a major transfer mechanism for metals from the continent to the sea [55,56], resulting in pulses of high trace metal fluxes to the ocean, predominantly composed of particulate fractions of trace metals [57]. Finally, ocean acidification due to climate change is a significant driver concerning contaminant flux alterations. For example, this effect is responsible for carbonate dissolution in sediments, increasing metal solubility [58]. In turn, altered hydrogen ion, carbonate, and hydroxide water column concentrations directly affect metal and metalloid speciation, both concerning inorganic metal complexes, metal-free ion concentrations, and metal-OM complexes [59]. All these processes significantly increase metal and metalloid bioavailability [58]. One of the major factors that control metal and metalloid assimilation in aquatic environments is the chemical form of these compounds [60]. In this regard, metal and metalloid trophic transfer processes and biota contamination are expected to be significantly affected due to climate change effects.

Irrespective of the type of water body, it is important to note that coastal zones, in particular, comprise some of the main areas significantly affected by climate change. These regions are the most densely populated areas in the world [61], due to their privileged location and the provision of abundant ecosystem services. However, almost all coastal ecosystems are now under significant threat due to climate change [62–64]. Deleterious climate change effects are further exacerbated by the fact that, due to their high human occupation and resulting anthropogenic activities, these ecosystems are extremely affected by environmental contamination, resulting in significant climate change and chemical pollutant interactions [65], which can be categorized as climate change-dominant, where climate change leads to increased contaminant exposure or enhances organism susceptibility to chemical toxicity, or contaminant-dominant, where chemical exposure leads to increased climate change susceptibility [6]. In this regard, several effects are expected in these regions, including loss of coastal biota, sea level rises and coastal erosion, which will, in turn, lead to land losses and human population migration [66], among many other consequences. Eutrophication events in coastal zones, in particular, will increase under a climate change scenario, due to increased runoff from agricultural activities and urbanization following extreme climate events [67].

A summary of expected climate change effects per type of water body is exhibited in Table 1.

Table 1. Summary of expected climate change effects per type of water body.

Type of Water Body	Expected Climate Change Effects
Freshwater systems	Groundwater variations, directly affecting groundwater contamination; High groundwater levels, resulting in topsoil contaminant removal; More frequent river discharges, resulting in differential freshwater metal and metalloid inputs.
Estuaries and mangroves	Increased erosion processes due to sea level rises, resulting in the dissociation of deposited sulfides; Saline mangrove intrusion oxidizing deeper sediment layers, releasing metals and metalloids and increasing their bioavailability to local biota; Altered annual rainfall rates altering material flows.
Marine environment	Altered ocean currents leading to changes in metal transport; Changes in the sediment–water interface due to alterations in metal speciation, solubility, and concentration gradients, as well as oxidation–reduction interface potentials; Increased rainfall periods resulting in pulses of high trace metal fluxes to the ocean; Ocean acidification resulting in increasing metal and metalloid bioavailability.

As noted previously, in contrast to organic chemical compounds, metals are non-degradable and cannot be easily metabolized in less toxic compounds [29]. Thus, they are relatively easily transferred from abiotic environmental compartments (water, sediments) to living organisms, potentially bioaccumulating and, in some cases, biomagnifying throughout trophic chains, albeit significantly dependent on different factors, such as sex, life stage, trophic niche, coastal habits (or not) and, mainly, the chemical form of the accumulated detoxified metal in prey [60]. All these processes result in significant ecological and human health implications [68] and must, thus, also be discussed.

In this regard, in addition to chemical speciation and other altered processes climate change drivers will also alter redox potential equilibrium. pH plays a critical role in both chemical and physiological processes. These include a vital function in maintaining cell membrane permeability [69], which may, in turn, result in increased exposure to metals and metalloids following subcellular compartmentalization, an ability inherent to this class of contaminants [70,71], which, in turn, alters their bioavailability and, thus, toxic effects. Subcellular metal partitioning is, in fact, the most adequate way to predict metal assimilation efficiencies between trophic levels from prey to predator [71,72]. As discussed previously, one of the main factors that control metal and metalloid assimilation in aquatic environments is the chemical form of these compounds [60]. Thus, both essential and toxic element assimilation and trophic transfer mechanisms are expected to be significantly altered under a climate change context.

Concerning subcellular partitioning, the metal subfraction contained in prey that best explains the metal assimilation efficiency of predators is termed the trophically available metal (TAM) fraction [73]. Some studies have been carried out to date under climate change scenarios to evaluate alterations in TAM fractions and assimilation efficiencies (AE). For example, one study aimed to understand the potential effects of two climate-related key variables, temperature and pH, on the assimilation efficiency (AE) of essential (Co and Zn) and non-essential (Ag) metals in the turbot *Scophthalmus maximus*, at two temperatures (17 °C and 20 °C) and pH (7.5 and 8.0) regimes, which were then fed radiolabeled shrimp. Temperature significantly influenced Zn AE, while pH variations did not affect the assimilation of any of the metals studied [74]. Another study assessed the of ocean acidification on the biokinetics and tissue-to-subcellular partitioning of Cd, Co, and Cd in the European oyster (*Ostrea edulis*) [75], reporting that Co kinetics were altered according to pCO_2 conditions, although no subcellular sequestration of the three trace investigated elements under low pH conditions was noted, indicating contrasting literature findings in this regard. On the other hand, systematic bleaching of oyster shells was observed with decreasing pH values [75]. However, it is important to note that species-specific accumulation patterns play an important role in subcellular partitioning in aquatic environments [70,76–80] and should always be considered in these types of assessments. Furthermore, no studies are available concerning subcellular partitioning under climate change scenarios for marine flora, only fauna, indicating a knowledge gap in this regard.

3. Conservation Physiology to Inform Policy on Metal and Metalloid Increased Risk under Climate Change

Conservation Physiology is defined as an integrative scientific branch that aims to apply physiological tools for the characterization and understanding of biological diversity and its ecological implications [81]. The use of physiological tools allows for a deeper understanding of how organisms, populations, and ecosystems respond to environmental changes and stressors, thus facilitating the assessment of conservation challenges [82]. This scientific branch goes beyond the description of patterns, aiming to understand the lethal and/or sublethal physiological mechanisms that currently compromise the efforts and effectiveness of wildlife management plans [83]. Since human influence and environmental changes are growing exponentially, understanding which aspects trigger stress responses is imperative for the development of effective countermeasures [81]. Conservation Physiology can also be combined with Toxicology, aiming to elucidate the effects of exposure to contaminants on species survival. In a review performed by [83], data on the interactive effects of trace metals and temperature on the physiology of aquatic ectotherms were presented, indicating that for most taxonomic groups tested (i.e., fishes, platyhelminths, annelids, arthropods, echinoderms, and mollusks), metal toxicity (e.g., Cd, Cr, Pb, Zn, Hg, Cu, Mn, Fe) was positively correlated with higher temperatures. Metal dynamics were significantly elevated at higher temperatures across a variety of taxa, indicating that highly conserved physiological processes are influenced by temperature-dependent increases in metal accumulation [83]. Elevated temperatures often result in increased sensitivity to metals and metalloids, leading to higher toxicity at the same internal concentrations. Moreover, metal exposure can also affect thermal tolerance, resulting in decreased temperature limits in exposed animals due to hypoxemia and loss of acid-base balance. In addition to affecting energy metabolism, exposure to metals and metalloids at higher temperatures also appears to affect mitochondrial functioning, oxygen-carrying capacity, cardiac activity, and gill structure [5,83]. Such dynamics might result in ecophysiological disturbances, affecting an individual's survival, potentially leading to local population declines and, consequently, altered biomagnification rates through trophic webs [84].

As Conservation Physiology is a relatively new discipline, it is often unclear to conservationists and decision makers its relevance and applicability [85]. In a recent review, reference [85] identifies key themes in Conservation Physiology that need further attention, aiming to generate relevant data for the creation of management strategies and conservation measures. In the topic "pollution", the authors emphasize that different forms of pollution, whether traditional (e.g., inorganic and organic) or emerging (e.g., noise, light) should be considered in future studies using physiological tools (Figure 2). Once again, plastic, and more specifically microplastics, are emphasized, with contamination by metals and metalloids being treated indirectly. The authors also discuss the importance of validating biomarkers to assess the deleterious effects of contamination on exposed organisms, aiming to elucidate the impacts of pollution on the health and resilience of more taxa. Moreover, the authors emphasize the importance of establishing sentinel species, which can be used not only for environmental monitoring but also as flagship species in conservation initiatives focused on pollution. Although indirectly, pollution is also addressed in other topics, such as "adaptation and phenotypic plasticity" (Figure 2). This is particularly relevant in the context of climate change and the potential interaction between metals/metalloids and an increase in temperature, as studies aimed at determining the ability of a given taxon to deal with these stressors can generate data for conservation, determining which species will be most affected, either by increased mortality rates or by changes in their distribution patterns or ecosystem services provided by them [5]. The interactions between metals and climate change are also emphasized in the topic "human-induced environmental changes", as the synergy between these stressors is magnified by anthropic actions that need to be mapped and, whenever possible, mitigated. The synergistic effect between metals and climate change is also relevant in the context of "Policy, engagement, and communication", as data generated through physiological analyzes can guide public policies and raise awareness of the impacts of pollution (e.g., extensive campaigns on impacts negative effects of plastic in the oceans) (Figure 2). Interactions between metals and climate change can also inform species' risk of extinction (topic "threatened species"), as population decline as a result of mortality due to pollution is used as a criterion to assess the risk of extinction of a given taxon [86], although data of this nature are rarely available, precisely because of the logistical difficulties in assessing population reduction due to pollution in natural systems. Lastly, studies on the synergy between metals/metalloids and climate change are also relevant for "urban systems" frameworks, as human disturbances caused by urbanization include inorganic contamination, and therefore, studies on Conservation Physiology can benefit from coupling contamination assessments with biomarkers indicative of urban impacts on wildlife.

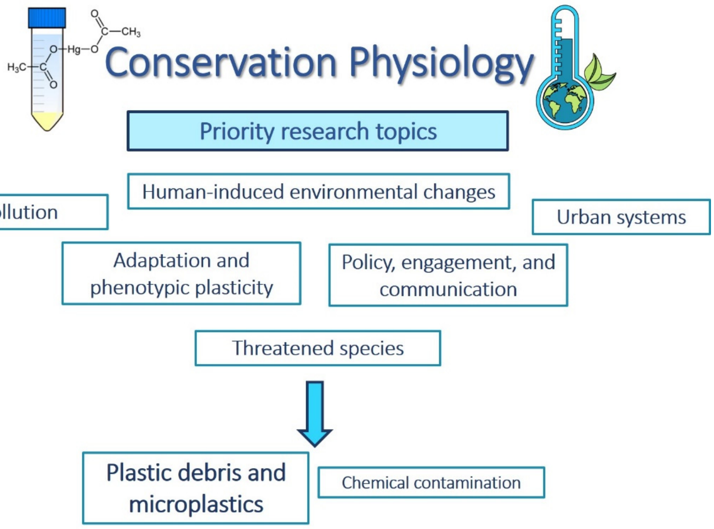

Figure 2. Research priority topics on climate change and ocean contamination according to Conservation Physiology experts (adapted from [85]).

4. The Decade of the Ocean—Efforts to Mitigate Environmental Pollution

The Decade of Ocean Science (2021–2030) aims to expand international research cooperation for the protection of the ocean and the management of its resources [87]. Within the vision "The Science We Need for the Ocean We Want", the initiative is based on seven key outcomes to be achieved by 2030, including a clean, healthy, and safe ocean. In a recent review, Ryabinin et al. [88] emphasizes the motivations for the Decade of the Oceans, discussing the numerous international treaties previously established aimed at protecting the oceans. However, a holistic model for its effective management, based on synergistic actions (research, public policies, and environmental education), is still necessary to advance this initiative. According to the authors, the growing interest of the private sector in participating in this movement has also been noted. The United Nations states that "based on science, policies to mitigate and adapt to global change are urgently needed, but neither science nor policymakers can do it alone" [87]. Therefore, it becomes clear that multidisciplinary approaches are extremely valuable and must be implemented to achieve this goal. Sustainable Development Goal (SDG) 14, in particular, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", in the form of its sub-items 14-2 (protect and restore marine ecosystems), 14-5 (conserve coastal and marine areas), and 14-A (increase scientific knowledge, research, and technology for ocean health), clearly indicates the importance of monitoring the oceans in a context where pressures such as pollution, overexploitation of marine resources, invasive alien species, habitat destruction and climate change are increasingly compromising the oceans′ ability to provide economic, social and environmental benefits, collectively termed ecosystem services [89]. Ecosystem conservation is, in fact, economically more profitable than the economic values arising from the acquisition and use of natural resources, which generally lead to serious environmental impacts [90]. For example, although coastal regions represent only 8% of the world′s land surface, their services and benefits account for about 43% of the estimated total value of global ecosystem services, from USD 12.6 trillion in the 1990s and beyond, greater today [91]. Therefore, translating ecological risks into losses of ecosystem services [92] results in paradigm shifts in the conservation of several taxonomic groups, such as fish, for example [93], which can make it easier to implement effective management and conservation actions.

Regarding ocean pollution, a set of international conventions dealing with the subject has been established, and the objectives permeate aspects ranging from the identification of contamination sources to the proposition of mitigation measures [88]. More recently, plastic pollution has received greater focus, to reduce dumping and map the negative effects already in place. Within societal outcomes, in the topic "clean ocean" anthropogenic pollution is presented as the main stressor, but except for plastic, there is no highlight for more traditional contaminants, such as metals and metalloids (Figure 3). Focus is given to identifying sources, as well as quantifying and reducing them. Moreover, practical solutions to efficiently remove pollutants are also foreseen [87]. As stated above, the major concern on metals and metalloids is their environmental persistence and capacity to incorporate within the food chain, posing an extra challenge in "solving" this issue. That being said, further research should focus on bringing subsidies to reduce future dumps, and properly evaluate the health risks of currently established ocean concentrations. The topic "healthy and resilient ocean" refers to the need to quantify and whenever possible, reduce the upcoming effects of climate change, with a focus on ocean acidification [88]. Data on climate change is also presented as a societal outcome in the topic "predicted ocean", aiming to ensure that enough information is available to direct ocean policy (Figure 3). Of course, all societal outcomes are expected to interact with each other, aiming at multidisciplinary scientific knowledge to improve decision making, thus encouraging the synergy between the stressors to be investigated. It is also important to consider how the health and resilience of exposed marine organisms will be affected, with potentially deleterious consequences for the ecosystem balance. More specifically, few studies have been developed to understand the effects of metals and metalloids on the health of marine animals in the context of climate change. Among the factors, the challenges posed in developing appropriate experimental designs to answer such questions stand out, at least for some taxonomic groups, as is the case of most representatives of marine megafauna. Thus, predictions are made considering mathematical modeling, or extrapolation of data based on animal physiology in general (e.g., the expected effects of the increase in temperature on the energy metabolism of organisms and, consequently, the assimilation of metals and metalloids) [5,83]. The negative impacts of metal and metalloid contamination under climate change also needs to be evaluated from a food security perspective, although not directly considered in the topic "sustainably harvested and productive ocean" (Figure 3). With the potential of enhanced assimilation of metals and metalloids by fishery resources in a warming ocean, humans are expected to be more affected even if seafood consumption does not increase, leading to an increasing concern regarding human safety. That being said, in the Decade of Ocean, studies focusing on how metals and metalloids will behave in warmer waters are imperative, considering not only the need for a healthier and cleaner ocean, but also considering the need for healthier animals, to ensure both ecosystem services and human food security.

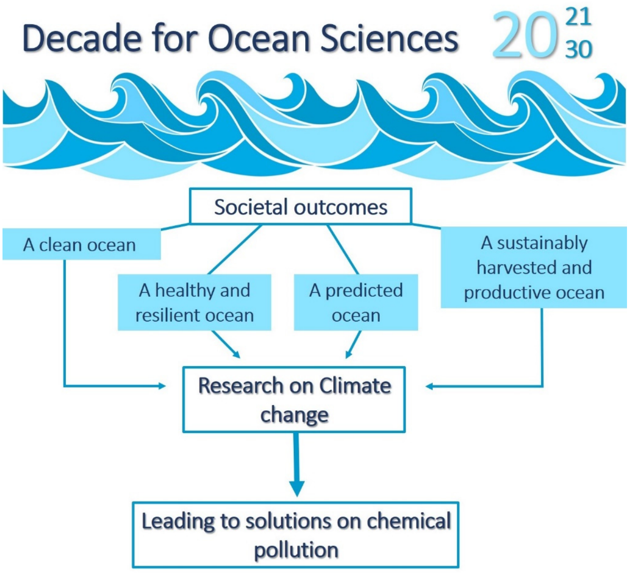

Figure 3. Societal outcomes set by the Decade of Ocean Sciences that are somehow related to climate change and marine pollution.

5. Conclusions

Although metals are one of the best-studied forms of pollution, many significant knowledge gaps are still noted. Plastic, for example, has increasingly become the main focus in environmental assessments, with less attention being given to more traditional pollutants. This is aggravated by the fact that under climate change, not only the bioavailability of metals and metalloids will increase, but also their deleterious effects on exposed organisms. Such dynamics are not only a conservation concern but also a public health issue, as the well-established toxic effects of non-essential metals can be aggravated in the case of the consumption of aquatic organisms. Currently, little attention is being given to the effects of climate change on the dynamics of metals and metalloids when compared to plastic/microplastic pollution. This is reflected in the financial investment of funding agencies, with little or no interest in investigations of this nature. Such negligence is also exacerbated by the fact that to study such effects, laboratory studies are necessary, which often do not generate the interest/mobilization to actually attract funding, at least when compared to more comprehensive studies with greater immediate applicability. That being said, it becomes imperative that funding agencies and the third sector understand the relevance of baseline studies and laboratory experiments to determine the effects of metals under climate change in an increasing number of taxonomic groups. Obviously, some limitations exist, including the challenges in studying large-sized species, and the extrapolation of experimental data to wild populations, in which the synergistic effects of environmental factors are much more pronounced, potentially interfering with the assimilation and accumulation/magnification of these inorganic compounds. Indeed, it is essential that calls for grants consider this as an emerging topic, along with plastic and blue carbon pollution, thus fulfilling the UN 2030 agenda.

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