



# Pollutants in the South Atlantic Ocean: Sources, Knowledge Gaps and Perspectives for the Decade of Ocean Science

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The current manuscript presents the main issues related to the “Clean Ocean” outcome that arose from the Regional South Atlantic (SA) Planning Workshop for the UN Decade of Ocean Science and five Brazilian Regional Planning Workshops. An interdisciplinary and *trans*-sectoral group constituted by the academia, non-governmental agencies, the private sector, decision-makers, the navy, and local communities discussed the main anthropogenic drivers compromising the current environmental status of the SA and its ecological services, and debated the main research gaps, priorities and needs for improving technical and structural capacities in order to roadmap the Brazilian actions for the Decade of Ocean Science. The aim of this review is to contribute to a social solution-driven understanding of the ocean ecosystems, to create conditions to promote sustainable development and to secure a clean, healthy ocean. We are proposing a list of actions to be implemented by the Decade of Ocean Science that will have the pivotal role to promote technical and scientific capacity development, increase research infrastructure and institutional frameworks, develop national public policies aimed at reducing the input of pollutants and management of impacts, and warranting food security and ecosystem health. The earlier the actions in controlling pollutants are implemented, along with the identification of key sources and prevention of crossing of thresholds will help to avert worst-case scenarios, reducing the socio-economic disparities of impacts across nations and social groups and supporting the sustainable development of a pollutant-free ocean.

**Keywords:** UN Decade of Ocean Science, pollution, anthropogenic impacts, SGD 14, research gaps, capacity building, South Atlantic, contaminant sources

## INTRODUCTION

The ocean is vast, highly dynamic, and harbors a large reservoir of unique diversity. It sustains life and provides numerous ecosystem services including food provision (e.g., food security), climate regulation (e.g., carbon sequestration and temperature regulation), habitats services, cultural services (e.g., recreation and aesthetic experience), and biogeochemical cycling of nutrients,

connecting the coastal, surface and benthic realms of the ocean (e.g., nutrient regeneration), promoting the sequestration of carbon (Hattam et al., 2015).

The quality and resilience of ocean ecosystems, nevertheless, are in peril from climate change and increased anthropogenic threats as thresholds are passed (Steffen et al., 2007; Selkoe et al., 2015). The provision of goods and services for 7.8 billion people is causing local and global environmental changes including habitat loss, pollution, harmful algal blooms (HABs), the introduction of invasive species, and climate change, causing cumulative and synergic effects that have deleterious consequences. By the year 2050 human population will likely be nearly 10 billion, a 30% increase over current population estimates (UN, 2019). The demands for food, fuel, water, and sanitation will only continue to rise. In order to guarantee food security for populations, the use of fertilizers will have to increase in developing countries. At the same time, urbanization and lack of sewage treatment will lead to an escalation in nutrient discharge to surface waters. Thus, by 2050 the HABs risk is expected to spread in developing countries of South America and Africa (Glibert, 2020). There is no doubt that ocean degradation, pollution, and human health are inextricably linked, causing adverse health and social consequences for even remote human populations (Knap et al., 2002; Weihe et al., 2016). However, the impacts of ocean pollution on human health are only beginning to be understood.

Globally, the ocean is being treated as a waste sink, mostly due to human erroneous propensity to view dilution as the solution to pollution (Knowlton, 2004). While high-income countries treat ~70% of the municipal and industrial wastewater, in low-income countries only 8% undergoes any treatment, which leads to an estimation that over 80% of all wastewater is globally discharged without any treatment (WWAP, 2017) and may end up in the ocean. Human developments in terms of agriculture, industries, and technologies have been at the price of degrading the marine environments, especially near land-based sources. In that sense, trace metals (e.g., lead – Pb, zinc – Zn, copper – Cu, and mercury – Hg) are used in many industrial processes that, inappropriately discarded, have led to contamination of the coastal and open ocean ecosystems. Similarly, the development of the organic chemistry promoted the synthesis of a diverse group of new substances including plasticizers, pesticides, brominated and organophosphate flame retardants, among others. Many of those substances and their by-products have proved to have a wide range of hazardous side effects. For instance, the resultant contaminant toxicity (e.g., methyl mercury; persistent organic pollutants), microbial pollution (e.g., cholera and antimicrobial resistance), and natural toxins (e.g., from HABs) can cause illness and death by exposure through seafood consumption or via contact with seawater (Depledge and Bird, 2009; Weihe et al., 2016; Bell et al., 2017; Miranda et al., 2021). Integrated impacts of pollutants may be further exacerbated by negative feedback loops, like microplastics carrying pathogenic bacteria, antimicrobial resistance genes, and endocrine-disrupting chemicals entering the food web (Fleming et al., 2019).

The ocean plays a key role in the achievement of the 2030 Agenda for the Sustainable Development, in particular through the Sustainable Development Goal (SDG) 14 – Life

below water (Le Blanc et al., 2017). The urgent need to foster and apply ocean science in supporting the shift of society onto a sustainable and resilient path caused the United Nations (UN) to proclaim the Decade of Ocean Science for Sustainable Development (hereafter the Decade) from 2021 to 2030 (IOC-UNESCO, 2020b). The main objectives of the Decade are to produce interdisciplinary science to provide social solution-driven understanding of the ocean ecosystems, stop degradation, and create conditions to promote sustainable development (Ryabinin et al., 2019). The UN expect to achieve a major change in the knowledge and management of the ocean by adopting a Global System Approach, generating seven interrelated societal outcomes (Table 1). Outcome 1 is a “Clean Ocean,” where sources of pollution are identified and reduced or removed in an efficient manner. The concept of a “Clean Ocean” arose during the 1st Global Planning Meeting of the Decade and was defined as an ocean where inputs of all contaminants and pollutants are minimized and do not have adverse effects on physical, chemical and biological processes, ecosystem functions and services.

Despite the efforts of the international community in large research projects such as GEOTRACES<sup>1</sup>, IMBER<sup>2</sup>, and SOLAS<sup>3</sup> that vastly expanded the amount of available data, the knowledge of the ocean systems is still limited and unevenly distributed. The South Atlantic (SA) Ocean, region between

<sup>1</sup><http://www.geotraces.org/>

<sup>2</sup><http://imber.info/about/what-is-imber/>

<sup>3</sup><https://www.solas-int.org>

**TABLE 1** | The societal outcomes for the UN Decade of Ocean Science for Sustainable Development.

Societal outcome	
Clean ocean	A clean ocean whereby sources of pollution are identified, quantified and reduced and pollutants removed from the ocean
Health and resilient ocean	A healthy and resilient ocean whereby marine ecosystems are mapped and protected, multiple impacts, including climate change, are measured and reduced, and provision of ocean ecosystem services is maintained
Predicted ocean	A predicted ocean whereby society has the capacity to understand current and future ocean conditions, forecast their change and impact on human wellbeing and livelihoods
Safe ocean	A safe ocean whereby human communities are protected from ocean hazards and where the safety of operations at sea and on the coast is ensured
Sustainably ocean	A sustainably harvested and productive ocean ensuring the provision of food supply and alternative livelihoods
Transparent and accessible ocean	A transparent and accessible ocean whereby all nations, stakeholders and citizens have access to ocean data and information, technologies and have the capacities to inform their decisions
Inspiring and engaging ocean	An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development.

the Equator and the Southern Ocean at 60°S is, for instance, less researched than the Northern Atlantic and the Pacific. This may be due to discrepancies in infrastructure and scientific and institutional capabilities. For example, the measurements for the elements Hg and Pb, important contaminants oceanwide (Boyle et al., 2014; Lamborg et al., 2014b; Hatje et al., 2018; Anderson, 2020), are less abundant in the South Atlantic. Consequently, there is a lack of data and hence knowledge to understand natural processes, to mitigate marine adverse impacts, to inform policy makers, and to support South Atlantic Ocean governance.

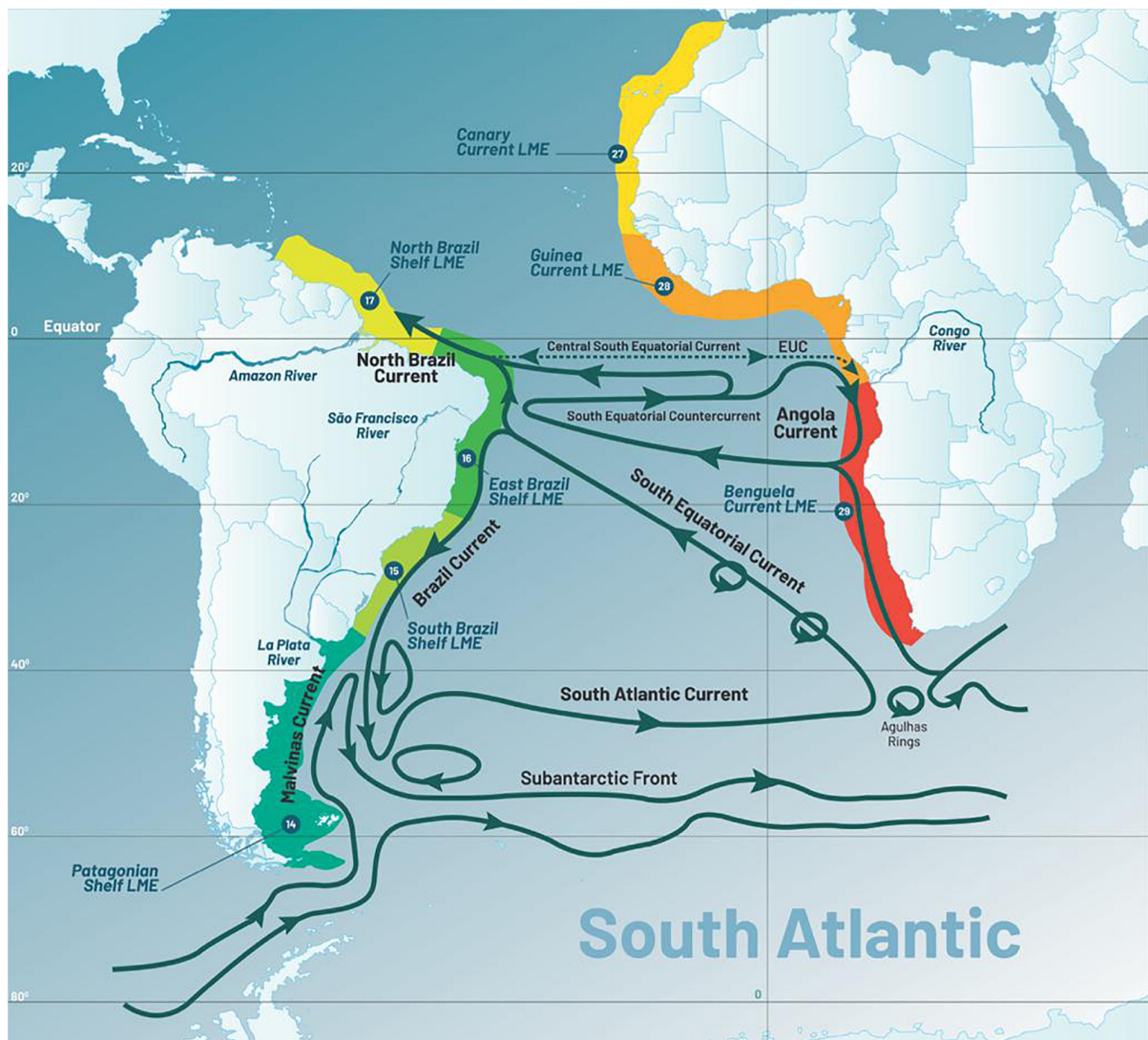
National ocean science research in the SA region, in many cases, are still modest and incremental. Partly because access to research vessels and large equipment is limited, costly, and complex to afford and maintain. Although the number of Atlantic researchers is similar in the South (731) and the North Atlantic (807) (IOC-UNESCO, 2017), scientific publications are much lower in the South (Inniss et al., 2017) and have a weak level of international collaboration, as seen by the low share of international co-authored articles (IOC-UNESCO, 2020a). Despite large coastlines in the region (e.g., Brazil and South Africa), and the diversity of ecosystems therein (mangroves, seagrasses, coral reefs, islands, major rivers, bays, and estuaries), marine and ocean research institutes are few. In addition, a large number of traditional coastal communities have a strong reliance on marine-based-diets that are safe for human consumption (Foltz et al., 2019), especially in low-income countries. Marine research capabilities, nevertheless, are limited and thus constrain the efficiency in fostering transnational, interdisciplinary research to contribute to environmental protection and informed decision making. From a social, a political, and a legal perspective, the main national and regional gaps are: the absence of instruments to ensure the implementation of modern conservation initiatives; the lack of regulation of shipping and other activities based on an integrated approach; the absence of environmental monitoring and reporting mechanisms; and the scarcity of legally binding instruments to guarantee biodiversity conservation.

The current approach adopted to regulate marine resources and issues, such as pollution in Brazil, is sectoral, disregard scientific data, and does not consider the connectivity of ecosystems along the continuum continent-ocean. The recent oil spill that occurred in early September 2019, which affected more than 3.000 km of the South Atlantic Ocean and around 1.000 Brazilian beaches (Lourenço et al., 2020; Soares et al., 2020), is a vivid example of management difficulties to address large environmental accidents. Several institutional and procedural limits complicated the management of this disaster. For example, the legal provisions that require the activation of the National Contingency Plan (Law n° 9.966/2000) were not implemented and the establishment of a competent federal group to deal with the disaster at the national level took too long, was inefficient, and is yet to deliver environmental and social solution-driven outputs. There was a lack of national coordination between the different federal, state and municipal administrative bodies. On the

contrary, the civil society and non-governmental agencies made an outstanding contribution to remove oil from mangroves, beaches, and reefs along the coast during the consecutive months after the oil reached the coast. This oil spill clearly exemplifies the need for regional organization in the SA to build up an institutional framework in order to provide competent actions and necessary preventive and remediation tools for addressing environmental disasters and for chronic pollution in the region.

The important existing collaborative initiatives within the Atlantic Ocean scientific community (e.g., AtlantOS, see deYoung et al., 2019) as well as existing regional science, innovation and technology policy frameworks (e.g., Galway and Belém Statements, BRICs, and South-South Framework for Scientific and Technical Cooperation in the South and Tropical Atlantic and Southern Oceans) and various other *trans-Atlantic* cooperation mechanisms are a good start (Polejack and Barros-Plataiu, 2020). These initiatives provide an interesting background for the South Atlantic region to move forward building on current international cooperation that will impact the Decade's implementation. Further, the Regional South Atlantic Planning Workshop for the UN Decade of Ocean Science, November 2019 (IOC-UNESCO, 2020b) triggered a series of actions in Brazil toward the implementation of the Decade. Brazil was the first IOC Member State to create a national committee to oversee the Decade's local implementation. Since then, Brazil hosted five internal workshops from which a National Science and Implementation Plan for the Decade will be designed, considering the peculiarities of each national region. All workshop discussions were framed around the societal outcomes of the Decade (Table 1).

In this context, the aims of this article are: (i) to map the main anthropogenic drivers (sources and types of pollutants) potentially impacting the environmental status of the South Atlantic and its ecosystems services and functions; (ii) to identify research gaps; (iii) to identify capacity building priorities, and (iv) research infrastructure and institutional frameworks in order to implement relevant actions and effective developments to achieve the 'Clean Ocean' by 2030. This work presents a compilation of information gathered from the Regional South Atlantic Planning Workshop for the UN Decade of Ocean Science, the five Brazilian regional workshops and the authors' own views considering the areas within and beyond national jurisdiction of the South Atlantic States. Focus will be given to the challenge that ocean pollution represents in the southwest Atlantic, in particular the Brazilian scenario, in face of the ambitions presented by the Decade of Ocean Science for a 'Clean Ocean.' The current status of capabilities, infrastructures, and expertise of other countries besides Brazil has not been raised because data is still scarce and fragmented (IOC-UNESCO, 2017). This is not meant to be a complete review on pollution, but rather a snapshot of the complex confluence of factors at the nexus of ocean pollution under a scenario of rapid climate changes in a specific oceanic region to highlight the diversity therein and further be used as a case study for the Decade's implementation. We understand that a regional scientific and technological coordination is needed to exchange



**FIGURE 1 |** Environmental settings of the South Atlantic Ocean, showing surface circulation schematics, large rivers, and the Large Marine Ecosystems (LMEs) present in the region. Adapted from Talley et al. (2011).

information and provide paths for enhancing capacities to deal with pollution management.

## CONTEXT – THE SOUTH ATLANTIC REGION

### Environmental Settings

Southwestern Atlantic is limited to the north by the Amazon River plume and to the south by the Malvinas current (i.e., the northward flow component of the South Atlantic subpolar gyre) (Figure 1). The South Atlantic coastal regions differ in ecosystems, species composition, and fisheries importance/activities, mostly by changes in water temperature, the influence of continental inputs of water and nutrients (e.g., Prata, São Francisco, and Amazon rivers), and local circulation.

Mangroves, seagrass meadows, coral reefs, sandy beaches, estuaries, bays, and deltas are important systems in the tropical and subtropical areas providing numerous ecosystem services (Barbier et al., 2011; Pascual et al., 2017; Díaz et al., 2018). Unique biodiversity with high levels of endemism is found in rhodolith beds (Calegario et al., 2020; Carvalho et al., 2020), in the coral reefs of Abrolhos (Leão et al., 2003; Mazzei et al., 2017), and in the coralline-algae Rocas Atoll, the only atoll in the SA (Gherardi and Bosence, 2001; Amado-Filho et al., 2016). The western Atlantic is also composed by four Large Marine Ecosystems (LMEs), three of which are in the Brazilian coastline (North, East, and South Brazil Shelf LMEs) and a southern LME in Argentina, the Patagonian Shelf LME (Figure 1).

The eastern side of the SA presents a large area of high productivity and important fisheries zones under the influence of the Benguela Upwelling System. The African coast shows

high levels of diversity both in the tropical region (intersecting the cold upwelling oceanic waters) and further south, where the coastline has lower habitat diversity (Castilho et al., 2013). Along the eastern shoreline, the SA is bordered by the countries on the western coastline of the African continent, which constitute the three LMEs in that region, namely, the Canary LME which comprises seven countries (Cabo Verde, Gambia, Guinea-Bissau, Guinea, Morocco, Senegal, and Mauritania), the Guinea Current LME with 16 countries and the Benguela Current LME (BCLME). The BCLME includes the coastlines and exclusive economic zones (EEZs) of Angola, Namibia, and South Africa (**Figure 1**).

At the Eastern SA, the Benguela and Agulhas systems interact, playing a key role in the establishment of the oceanic teleconnection. The warm and more saline waters from Agulhas Current, originated in the Indian Ocean, travel northward and reach the northern hemisphere, feeding the global meridional overturning circulation (MOC) by becoming denser and composing the North Atlantic Deep Water (Talley et al., 2011). On the southwestern Atlantic Ocean, the Brazil-Malvinas Confluence is an area of strong mesoscale variability and important exchange of heat and freshwater between the subtropical Atlantic Ocean and the northern branch of the Antarctic Circumpolar Current (Talley et al., 2011). The section of the Atlantic that bridges South and North is also remarkable for understanding the Earth system. A specific example is the Tropical Atlantic sea surface temperature

dipole, a cross-equatorial sea surface temperature pattern that appears dominant on decadal timescales and is one of the key features in the Tropical Atlantic Ocean. Its variability has a direct impact on climate (through the displacement of the Intertropical Convergence Zone northwards or southwards) and on continental regions, such as northeastern Brazil and the neighboring Western Africa (Sahel) region, as well as on the formation of cyclones in the North Atlantic (Wainer et al., 2020).

Regarding the institutional framework for environmental protection, it is worth mentioning the importance of marine protected areas. Except for Brazil, Gabon, and South Africa, the percentages of nationally protected marine areas in countries at SA borders are much lower than the world's average of ~11% (**Table 2**). However, the fact that those areas are officially protected does not necessarily mean that they are properly managed due to the control and monitoring limits of each country.

## Socio-Economic Aspects

Brazil, Uruguay, and Argentina are at the southwestern Atlantic Coast, whereas Gabon, Congo, Democratic Republic of Congo, Angola, Namibia, Sao Tome and Principe, and South Africa are on the eastern SA. The population density of these countries is quite variable (**Table 2**) and mostly lives at the coast. As such, a large percentage of the population is vulnerable to any increase both in intensity as in the frequency of extreme events

**TABLE 2** | Socio-economic data for South Atlantic bordering countries (World Bank, 2020).

Country	GDP per capita (US\$, 2019)	Population (Million, 2019)	Nationally protected marine areas (% of territorial waters, 2018)	People using at least basic drinking water services (% of population, 2017)	People using at least basic sanitation services (% of population, 2016)	Mortality rate attributed to unsafe sanitation and lack of hygiene (per 1,00,000 population, 2016)	CO <sub>2</sub> emissions (metric tons per capita, 2016)	Poverty headcount ratio at \$1.90 a day <sup>7</sup> (% of population, 2018)
Angola	2,973.60	31.8	0.0	55.8	48.6	48.8	1.2	51.8
Argentina	10,006.10	44.9	3.8	99.1 <sup>1</sup>	94.3	0.4	4.6	1.3
Brazil	8,717.20	211.0	26.6	98.2	87.4	1.0	2.2	4.4
Congo	2,011.10	5.4	3.2	73.2	20.4	59.8	0.7	38.2 <sup>2</sup>
Dem. Rep. of Congo	545.20	86.8	0.2	43.2	19.5	38.7	--	77.2 <sup>3</sup>
Gabon	7,667.40	2.2	28.8	85.8	47.4	20.6	2.6	3.4 <sup>4</sup>
Namibia	4,957.50	2.5	1.7	82.5	34.2	18.3	1.8	13.8 <sup>5</sup>
Sao Tome and Principe	1,994.90	0.2	0.0	84.3	42.8	11.4	0.6	35.6 <sup>4</sup>
South Africa	6,001.40	58.6	12.1	92.7	74.8	13.7	8.5	18.7 <sup>6</sup>
Uruguay	16,190.10	3.5	0.7	99.4	96.4	0.4	2.0	0.1
World	11,428.60	7,591.93	11.4	89.6	72.5	11.8	--	9.2 <sup>4</sup>

<sup>1</sup>Data from 2016;

<sup>2</sup>data from 2011;

<sup>3</sup>data from 2012;

<sup>4</sup>data from 2017;

<sup>5</sup>data from 2015;

<sup>6</sup>data from 2014;

<sup>7</sup>data for purchasing power parity (PPP) from 2011.

(e.g., heat waves, heavy rainstorms, and hurricanes) resulting from global changes (e.g., temperature and sea-level rise) with significant ecological, economic, and social consequences. These threats place a disproportionate burden on the least developed countries and developing countries in the region due to the lack of proper land-use planning and effective readiness systems.

The region is socio-economically diverse (World Bank, 2020), but has similar characteristics including a low to modest economic development, with a large percentage of the population relying on informal economies, low education level, inadequate access to tap water and sanitation, as well as insufficient legal apparatus to mitigate and/or reduce the input of contaminants, and limited environmental protection. The Gross Domestic Product (GDP) per capita varies widely among the countries (Table 2). In 2019, Uruguay had the highest GDP per capita (US\$ 16,190.10) and the Democratic Republic of Congo had the lowest (US\$ 545.20) (Table 2), being the country with the highest rates of extreme poverty, reaching more than 3/4 of the population.

In general, oil and gas exploitation, as well as mining, are relevant activities for the economies of countries on both sides of the South Atlantic. Brazil is a world-class producer of oil, natural gas and mineral resources. The total production of oil and natural gas was ~3,120 million barrels/day and 139 million m<sup>3</sup>/day, respectively, in January 2020 (ANP, 2020). Offshore platforms accounted for 97 and 81% of the national oil and gas production, respectively. Historically, mining is also a relevant activity in the coastal zone and the territorial sea of Brazil (Lima, 2019). Most of the continental shelf of the SA is still unexplored and at present, deep-sea mining is not economically viable compared to traditional mining practices.

For the countries on the American border, agricultural production is also very important, with Brazil, Argentina, and Uruguay presenting strong economic dependence on agribusiness. However, on the African border, with the exception of South Africa, agricultural production is mostly for subsistence.

There are 4 megacities on the countries boarding the South Atlantic that significantly impact the coastal zones: São Paulo and Rio de Janeiro, in Brazil; Buenos Aires, in Argentina; and Kinshasa, in Democratic Republic of Congo (Cirelli and Ojeda, 2008; Rocha et al., 2009, 2010; Wagener et al., 2010; Avigliano et al., 2015; Fries et al., 2019; Mata et al., 2020). Though São Paulo and Kinshasa are not coastal cities, they are both connected to the Atlantic through fluvial systems (e.g., Congo River).

All in all, countries bordering the SA share similar socio-economic challenges. They lack scientific capacities both in ocean research infrastructure as well as in human capital. Marine research capacities, ranging from expertise, well-equipped laboratories to research vessels and other instruments, are not well distributed along the region. For the Decade of Ocean Science to be successful, it will need to tackle this unbalanced set of scientific capabilities and search for ways to even the basic production of knowledge in the SA.

We advocate that beneficial international cooperation will be deeply needed to unveil the vast ocean unknowns necessary for improved management of the anthropogenic drivers challenging the resilience of the ocean.

## ANTHROPOGENIC DRIVERS THAT THREATENS THE OCEAN

### Land-Based and Ocean Sources of Pollutants

During the Regional SA Workshop, the 'Clean Ocean' working group, constituted by participants of all relevant stakeholders (i.e., academia, non-governmental agencies, private sector, decision-makers at different governmental levels, the navy, and local communities), identified a list of pressing issues and pollutants for the Science Action and Implementation Plan for the Ocean Decade (IOC-UNESCO, 2020b). This list was later extended with the specific contributions gathered during the 5 Brazilian regional workshops and further with the input of the authors of this manuscript to compile the main anthropogenic activities and pollutants for the Brazilian coastal waters and the SA ocean in general. Ocean pollution is a complex mixture of anthropogenic chemicals and biological material, and changes in physical conditions (e.g., turbidity, sound, and light). Table 3 summarizes the main continental and oceanic anthropogenic drivers in the SA Ocean and the associated pollutants types, whereas Figure 2 also lists potential resulting impacts in biota and on the ecosystem services (i.e., seafood provision, climate mitigation, fisheries, recreational and aesthetic values, and genetic resources), that are the conduit between nature and good quality of life.

Figure 2 illustrates how a large range of pollutants enters the coastal waters from multiple sources, most of which are land-based (~80%; UNESCO, 2020), such as surficial runoff, industrial discharges, agricultural and mining activities, and poor waste management, while other are ocean-based, primarily shipping, commercial and recreational fishing, oil exploration, mining, and atmospheric deposition. For instance, agriculture discharges nutrients and pesticides, harbor and shipping activities cause the introduction of invasive species and release of fossil fuel gases; animal wastes, runoff, and atmospheric deposition in the downwind plumes from major cities are important sources of nitrogen and may lead to harmful algal blooms (HABs), while urban settlements release a load of different pollutants including, nutrients, metals, pharmaceuticals, among others. Noise and light pollution have also become a growing global concern due to their damaging effects on aquatic species. These kinds of pollution are caused by urbanization and industrialization of coastal zones, recreational boating, seismic and drilling operations at sea (Depledge et al., 2010; Bugnot et al., 2019). They can cause ecological shifts in natural communities, cognitive impairment and affect the underwater behavior of organisms (Buxton et al., 2017; Leduc et al., 2021). Pollution is more severe in coastal environments (e.g., mangroves, bays, and estuaries) due to proximity to land-based sources. The inputs

**TABLE 3** | Pressing anthropogenic drivers and associated pollutants for the coastal ecosystems and the South Atlantic Ocean.

Source	Activity	Receiving waters	Main pollutants	
Terrestrial	Domestic sewage, sewer outflows, and sewage spills	Rivers, estuaries, and groundwaters	Pathogens, biohazard (parasitic organisms), metals, endocrine disruptors, pharmaceutical and personal care products residues (PPCPs), plastics, plasticizers, antimicrobial resistance, nutrients, HABs, persistent organic pollutants (POPs), brominated and organophosphate flame retardants, perfluoroalkyl and polyfluoroalkyl substances (PFASs), polycyclic aromatic hydrocarbons (PAH)	
	Mining (industrial and artisanal)	Rivers, atmosphere, and groundwaters	Metals (Hg, Cu, Pb, Zn, etc.)	
	Submarine sewage outfalls	Ocean	Pathogens, biohazard (parasitic organisms), metals, endocrine disruptors, pharmaceutical and personal care products residues (PPCPs), plastics, plasticizers, antimicrobial resistance, nutrients, HABs, persistent organic pollutants (POPs), brominated and organophosphate flame retardants, perfluoroalkyl and polyfluoroalkyl substances (PFASs), polycyclic aromatic hydrocarbons (PAH)	
	Industries	Rivers, estuaries, and groundwaters	Organic pollutants (polychlorinated and polybrominated biphenyls, organochlorine pesticides, PAH, PFASs, etc.), metals, plastics, CO <sub>2</sub> , heat, light, sound	
	Agriculture	Rivers, estuaries, and groundwaters	Nutrients, POPs (e.g., pesticides), PAH, and metals	
	Harbors/ports	Coastal areas	CO <sub>2</sub> , antifouling paints (metals), organometals, plastics, and PAH	
	Aquaculture	Estuaries, rivers	Nutrients, metals, antibiotics, HABs, and antimicrobial resistance	
	Fossil fuel combustion	Estuaries, rivers	CO <sub>2</sub> , metals (Hg is particularly important for coal burning), and organic contaminants (PAH), polycyclic aromatic sulfur heterocycles (PASHs)	
	Tourism	Coastal zone	Invasive species, solid waste, sound, and light	
	Nuclear plants	Coastal zone, atmosphere	Radionuclides and heat	
	Damming	Rivers	Erosion, remobilization of contaminants	
	Run off	Coastal zone	Metals, diverse group of organic compounds, nutrients, PPCPs, brominated and organophosphate flame retardants	
	Oceanic	Oil rigs	Ocean	Noise, light, invasive species, metals, PAH, and PASHs
		Fisheries	Ocean	Plastics, light
Aquaculture		Ocean	Nutrients, metals, antibiotics, exotic species, plastics	
Shipping		Ocean	Noise, light, invasive species, fossil fuel exhausts, metals (e.g., Zn and Cu)	
Seismic surveys		Ocean	Noise, light, and invasive species	
Fossil fuel combustion		Ocean	CO <sub>2</sub> , metals, and organic contaminants (e.g., PAH and PASHs)	
Tourism		Ocean	Noise, light, invasive species, and plastics	
Bottom trawling		Coastal areas	Turbidity, erosion and remobilization of contaminants	
Dredging		Coastal areas	Physical disturbance of the seafloor, turbidity, and contaminants remobilization	
Mining		Deep sea and coastal	Noise, metals, physical disturbance of the seafloor, and turbidity	
Atmospheric*	Mining	Ocean, continental	Hg	
	Fossil fuel combustion	Ocean, continental	CO <sub>2</sub> , metals, PAH, and PASHs,	

\*Anthropogenic activities based mostly on land but cause contamination in open, remote environments.

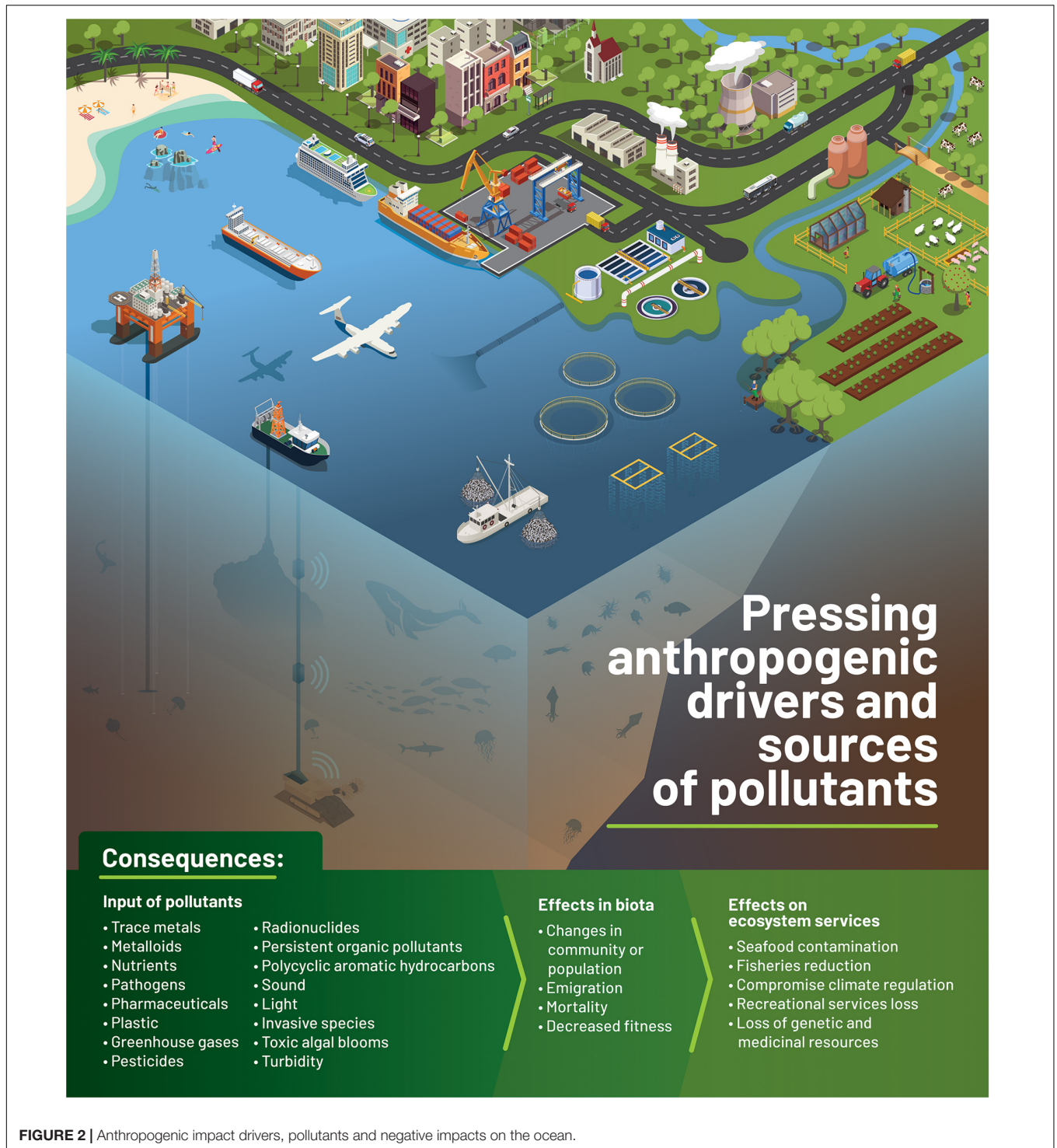
of pollutants in the environment (Table 3) can cause local problems at various levels of biological organization (from cells to communities), compromising ecosystem functions and services, and producing risks at small spatial scale, or causing large-scale impacts (CO<sub>2</sub> pollution), which pose risks at the regional or global level (e.g., climate change). Diffuse emissions, such as agriculture and road runoff are especially difficult to handle, because they are characterized by strong seasonal variation and poorly traceable origins due to the many possible sources (Houtman, 2010).

The SA region is expected to present an upward trend in land-based pollution sources as a result of increasing urbanization and industrialization in the coastal zone and the lack of comprehensive regulation, appropriated enforcement, and

mostly abatement. In recent years in Brazil, for instance, there has been a dismantling of the environmental regulatory authorities that suffered a drastic reduction in investments and loosening of existing legislation that protects important ecosystems and human health (Abessa et al., 2019; Araújo, 2020).

## The Main Problems

There are several commonalities regarding the main problems associated with the high demographics and amount of waste per capita of the diverse coastal zones of the SA and possible solutions to address regional challenges. While in the North Atlantic pollutants derive mostly from industrial activities and burning of fossil fuels by developed economies, the



foremost source of pollution identified in the SA workshop for the Decade of Ocean Science was the lack of adequate sewage systems and wastewater treatment plants (Table 2; WWAP, 2017). The untreated sewage discharged in the aquatic systems contains high loads of organic matter that may cause deoxygenation and increase dead zones, altering biogeochemical

cycles and marine biodiversity (Breitburg et al., 2018). Sewage also presents a myriad of toxic pollutants, some carrying human pathogens and some others contaminating the food chains in detrimental ways to ecosystems and human well-being (Iwamoto et al., 2010; Bradley et al., 2017; Nilsen et al., 2019). These have a disproportionately greater impact



on the traditional communities' economic security and health, mostly because marine resources (fish and shellfish) tend to play a fundamental role in providing food and financial resources (de Souza et al., 2011; World Bank, 2020; Miranda et al., 2021). Coastal economic activities, such as fisheries, aquaculture, and tourism are also acutely dependent on the ocean environmental quality and the increasing environmental status changes. Despite the known interactions between the ocean and human well-being, more interdisciplinary research is needed to uncover the uncertainties related to how each group of pollutants affects local human populations, ecosystem functions and services.

Untreated sewage, sewer overflows, wastewater treatment plant effluents, ocean submarine outfalls, and land runoff are vehicles of diseases and parasites (e.g., typhoid and cholera) that cause gastrointestinal illness as well as life-threatening diseases in humans on both sides of the SA (Table 2), with death numbers attributed to unsafe water and lack of sanitation in the African border being generally higher than world's average. It may also cause eutrophication in rivers, bays, and coastal waters. Besides, there is also increasing concern about the spread of antibiotic-resistant pathogens (Gullberg et al., 2011). Since they don't degrade in the environment, bacteria reproduce and can amplify antibiotic resistance genes and pass them through the microbial community and, thus, can represent a critical environmental and human health risk (Pruden et al., 2006). The introduction from land-based allochthonous bacteria carrying resistance genes may account for the acquisition of antimicrobial resistance by indigenous pathogens such as *Vibrio* (Landrigan et al., 2020). Developing countries around the SA lack infrastructure for waste and water treatment and to recycle waste to prevent epidemics. For example, the sewage network in Brazil collects only ~61% of the sewage generated in urban areas, but only ~50% of the sewage is treated (SNS, 2018). The focus of management efforts on reducing visible impacts such as solid waste generation can divert attention from the impacts of untreated domestic effluents (e.g., diseases, toxicity, eutrophication, and biodiversity loss).

On the other hand, the impacts of plastic pollution, the second major pollutant identified in the regional debate, capture attention from stakeholders through emotional images of entangled biota and voluminous material in beaches. Many marine biota taxa are deeply impacted by plastic pollution, not only through entanglement but also ingestion and bioaccumulation that cause life-threatening complications (Vegter et al., 2014). The share of plastics in municipal solid waste increased from less than 1% in 1960 to more than 10% by 2005 in middle- and high-income countries (Jambeck et al., 2015) and correlate strongly with gross national income per capita (Wilson, 2015). Once they are stable, durable, and resistant to degradation, they persist for decades in the marine environment and travel considerable long distances, resulting in a rapid and substantial increase in plastic debris in all ocean basins (Barnes et al., 2009). Plastics and fibers can be a major vector for the dispersal of fouling organisms including hazardous microbes, vectors for human disease (Zettler et al., 2013). Typically, about 500 items of anthropogenic debris strand on SA shores per linear

kilometer per year (Barnes and Milner, 2005). In fact, Brazil and South Africa are among the top 20 countries responsible for ~80% of the land-based plastics that end up in the ocean (Jambeck et al., 2015). Recently, the first global review using a holistic approach to assess the ecological, social, and economic impacts of marine plastic pollution suggested that all ecosystem services are impacted to some extent by the presence of plastics (Beaumont et al., 2019). The need for strong actions to prevent plastic pollution's worst consequences on marine life and in the health of the ocean has long been cautioned (Van Rensburg et al., 2020). Improving waste management infrastructure of plastics and other pollutants along with changes in consumption habits are paramount and need concerted implementation actions of scientists, the private sector, governments, and the civil society.

A detailed assessment of all sources will be crucial to identify and prioritize the resolution of problems associated with all potential pollutants (e.g., plastics, CO<sub>2</sub>, domestic sewage, nutrients, metals, technology critical elements, pesticides, exotic species, noise, etc. Table 3 and Figure 2). Although we lack pollutant source inventories, several contaminants, such as metals, are already well understood in terms of sources, sinks, fate and toxicity (Iwamoto et al., 2010; Abdel-Shafy and Mansour, 2016; Gworek et al., 2016; Bradley et al., 2017) and evidence exist to warrant a reduction of inputs if political actions are motivated (e.g., Clean Air Act Amendments, Minamata and Stockholm Conventions). At the same time, new groups of yet unregulated contaminants, the so-called emerging contaminants (e.g., plasticizers, personal care products, pharmaceuticals, rare earth elements, and platinum-group elements), have attracted attention and their continuous introduction in surficial waters may lead to still unknown adverse effects. The synergetic and cumulative effects, added to the impacts of global changes (e.g., changing water temperature, deoxygenation, acidification, sea level rise, extreme events, and coastal erosion), can bring even more complexity to the system, changing both the environmental conditions (e.g., anoxia) and the state of ecosystems, causing, for instance, loss of habitats and associated services. Global environmental changes superimposed upon the effects of local pressures can maximize the remobilization of pollutants accumulated in soils and sediments, which are long-term archives of contaminants (UNEP, 2019; Lacerda et al., 2020), leading to an increase in pollutant fluxes into the ocean. It is then expected an enhanced of contaminants' bioaccumulation in coastal food webs (Emmerton et al., 2013; Miranda et al., 2021), and loss of ecosystem services which may translate into food insecurity and impacts on cultural integrity, health, and wellbeing (Newton et al., 2020). Ocean acidification, associated with global changes, may also modify the speciation of metals in seawater, which can alter their bioavailability and therefore toxicity (Millero et al., 2009).

The anthropogenic pressures change the dynamics of ecosystem functions, affecting their natural resilience as well as eventual impacts on human welfare such as food safety, public health, and decrease fisheries and aquaculture revenues. Preventing degradation, setting measurable pollution reduction goals, and implementing environment-friendly management

practices provide a road map for involving scholars, private sector, non-profits organizations, citizens, and government agencies to form the basis for the ambitious Decade of Ocean Science agenda on “Clean Ocean” and climate mitigation.

## RESEARCH KNOWLEDGE GAPS AND PRIORITIES

Consideration of the full scope of human and ecosystem risks from pollutants requires a comprehensive evaluation of single and combined impacts on ocean and coastal ecosystems. The SA, however, still is one of the least studied systems, where baselines for most contaminants do not exist. South Atlantic bordering African countries present limited and uneven information of contaminants in coastal systems compared to the western Atlantic coast, hampering the identification of sources and temporal trends (GESAMP, 2018). A detailed assessment of the contaminants’ distribution and their temporal dynamics is then urgent to inform prioritization of actions and strengthening the governance regimes in search for solutions within the SA region. A good start is to consider that whereas we lack pollutant source inventories, several pollutants, such as metals and persistent organic pollutants (POPs), are well known, and evidence exist to warrant emissions reduction at short-time scales.

The reduction and elimination of pollution sources rely on the accurate measurement of contaminants in the environment. In order to address pollutant’s knowledge gaps, it is necessary first to debate technical aspects, establish and implement clear quality assurance and quality control procedures to make all data comparable and in accordance with the best available international practices (Hatje et al., 2013). Documentation of quality assurance and quality control (QA/QC) data facilitates related capacity development and the use of best practices. The database to be generated must comply with the FAIR data principles (Wilkinson et al., 2016) to promote its maximum use by all stakeholders.

Future strategic research planning should include:

- Inventory of sources of the main impact drivers (e.g., mining, fisheries, tourism, aquaculture, industries, maritime transportation, etc.) considering their synergic interactions.
- Sampling, sample treatment, and quality assurance protocols. A series of protocols and standards for sampling, processing, and data reporting will need to be developed or adapted from existent material which will then be applied to the whole region in order to support the construction of a regional database according to internationally accepted quality standards.
- Baselines of target macro and micro contaminants (e.g., plastics, nutrients, trace metals, organic contaminants, radionuclides, nanomaterial, CO<sub>2</sub>, invasive species, among others) aiming to identify hotspots areas that need immediate attention, and/or remediation and restoration.
- Life cycle assessment as a tool to evaluate environmental impacts of pollutants (e.g., plastics) on the basis of multiple impact categories (e.g., climate change, acidification, eutrophication, solid waste generation, human and ecological toxicity, energy and water use, etc.) that occur along the supply chain of products (Hauschild et al., 2013).
- Design of a strategic environmental assessment and long-term monitoring, which is critical to track trends, identify hot spots, and to evaluate the effectiveness of interventions. It is important to apply the ecosystem approach, considering the connection between ecosystems, its functions and services, the position of humans within these systems, and the participation of all stakeholders (Atkins et al., 2011).
- Development of environmental quality indicators for different ecosystems. There is no single indicator that shows when ecosystem tipping points are reached and the resilience of marine ecosystems can no longer be maintained (Hattam et al., 2015). A suite of specific indicators will have to be developed or adapted to inform policy and evaluate progress not only of water quality or pollution but also to track degradation of ecological services and functions, considering their temporal variability and tailored to local and regional particularities.
- Risk assessments. Human risks relative to the ocean are typically associated with (a) consumption of pathogen-contaminated or chemically contaminated seafood; (b) spread of human pathogens (e.g., cholera) via the release of untreated sewage into coastal waters; (c) exposure to toxins from harmful algae; and (d) effects of weather and climate on the rates and means of transmission and severity of infectious diseases (Sandiffer et al., 2004). We need to understand the human and environmental risks of ongoing and future types of single and multiple pollutants, including the atmosphere global pollution transport and its exposure pathways. Attention should be given to emerging contaminants, such as the technology critical contaminants (e.g., rare earth elements, platinum group of elements, and nanoproducts) (Cobelo-García et al., 2015), newly registered pesticides, pharmaceuticals, personal care products, and fire retardants (Houtman, 2010; Nilsen et al., 2019). Since 2019, nearly 500 new pesticides have been approved in Brazil, accelerating the trend of previous years and introducing new contaminants, possibly impacting environmental quality and food safety, at an unprecedented rate (Braga et al., 2020). The majority of these chemicals have not been tested for safety or toxicity and even less is known about their potential synergic effects.
- Development and improvement of models to predict and assess long-term trends and risks of pollutants and propose preventive solutions;
- Evaluation of trade-offs of interventions, restoration and replacement of practices and substances. Trade-off analysis is an important aspect in assessment studies of pollution and its effects on ecosystem services and it is a key issue in decision making and in the analysis of alternative pathways that lead to future sustainable land use (Rounsevell et al., 2012). Points to be considered are i. population and individual risks and the cost of risk reduction by using cost

per life saved as a criterion and ii. cost-effectiveness as a justification for remediation.

- Determination of the caring capacity for ecological and biological significant areas to sustain human impacts and economic development (e.g., Abrolhos reef system, and mangrove belt of Amazonia and the Amazon reef system).
- Strengthening governance regimes to encourage more sustainable production and consumption practices under national, regional and international legal frameworks.
- Integrated management of the coastal zone, marine space, and areas beyond national jurisdiction through precise principles, rules, obligations and instruments.
- Consider the knowledge of traditional communities and indigenous peoples when building databases and discussing management decisions.
- Promote ecosystem conservation and restoration of coastal vegetated systems (wetlands) to help improve water quality, reducing pollutants (e.g., pathogen and nutrient concentration) and promoting ecological functions.

Altogether, these measures will augment the science capacity and make it fit to minimize total environmental impacts of pollutants, informing sustainable development and addressing human and environmental short- and long-term risks from all forms of pollution.

## THE WAYS TO SEEK SOLUTIONS

The long-term changes in the ocean or the seriousness of the impacts of ocean degradation on human and ecosystem health are hard for the public and decision-makers to grasp, as they challenge the eyesight and short-term thinking. The consequence may be the establishment of irreversible outcomes, beyond the resilience of ecosystems. To date, response to early warnings has been limited to only timid measures to reduce pollutant emissions. The overarching aim of the Decade with regard to a 'Clean Ocean' is to severely reduce the input of pollutants and hence limit anthropogenic impacts, leading to very low acceptable levels of plastics, noise, light, chemical, and microbial contaminants in coastal and open waters. This result, nevertheless, needs bold, urgent, and efficient measures. The longer we take to act, the costlier and more challenging the measures to revert the degradation cycle will become. We need to remember that modifications in the distribution of contaminants, such as Hg and Pb may set large-scale changes that reverberate for decades or centuries, once contaminants will be trapped and circulated along with the meridional overturning circulation (Boyle et al., 2014; Lamborg et al., 2014a). Future research on the interface between ocean and human health should focus on how to better manage interacting pollutants and other stressors in the long-run, as well as exposures to actual contaminants while capturing the potential for co-benefits available through intelligent management (Deprietri and McPhearson, 2017). This will demand collaborations by individuals and institutions working across sectors, and responsible economic development administered through environmental sustainability and social

inclusion to ensure that the voice of those most affected by ocean pollution is heard (e.g., traditional and indigenous communities) (Fleming et al., 2019). In this respect, a greater focus on truly transdisciplinary research and training will be especially valuable. From a legal perspective, there is a lack of effective instruments of compliance and management of the marine environment that integrate the coastal zone and adjacent areas, in particular in Brazil (Spolidorio, 2018). There is also a need to better define additional criteria and standards to measure ocean resilience in service of legal measures (Tanaka, 2004; Long et al., 2015; Silva and Moraes, 2020).

The research capabilities and expertise required to achieve the 'Clean Ocean' we want, as for the 2030 agenda, are very heterogeneous across the SA region and rely on the implementation of better research infrastructure, capacity building, and mechanisms of transfer of marine technology. The solutions developed should lead to cost-effective prevention, monitoring, and mitigation actions. As such, we need coordinated efforts to promote regional and national capacity building solutions for technical and institutional capabilities, research funding, and regional coordination to support the ambitious goals of the Decade.

## Regional Scientific Capabilities

The SA marine scientific facilities and research infrastructure are neither mapped nor easily assessed. Brazil and South Africa are among the countries in the region with the best infrastructure in terms of platforms to perform ocean sciences and on-land based measurements of organic and inorganic pollutants and to apply nuclear and isotopic techniques in environmental studies. Recent changes in the Brazilian administration policies for universities have jeopardized the hiring of technicians and lab assistants. As a consequence, complex instruments, in many cases, rely on the work of graduate students even in the Brazilian largest universities. That creates a huge problem in the continuity of the activities, dependence on student flows, and the need for continuous training. The number of laboratories currently capable of performing trace level measurements of organic contaminants and metals in seawater is extremely low (less than half a dozen, being optimistic). In fact, many laboratories lack the basic equipment and capability to measure macronutrients in seawaters. Certainly, there is no need for equipping labs for all sorts of chemical and physical measurements, but reference laboratories across the region are needed to work as analytical and capacity building hubs, to serve the whole community. The connection of reference laboratories to a regional network will enhance the technical and operational capabilities of reference laboratories in the identification of pollution, control, mitigation, and management of sources. Reference laboratories will also benefit from the expertise and knowledge acquired by the other laboratories in the network.

## Research Funding

The list of the necessary actions identified here can only be carried out if continuous support is provided. Current funding for ocean sciences is largely inadequate and variable over time,

undermining the capability of ocean sciences to support the sustainable provision of ocean services (IOC-UNESCO, 2020a). Long-term research funding is rare everywhere. In Brazil, for instance, one of the very few exceptions is the Long-Term Ecological Research Program (PELD<sup>4</sup>). The implementation of such programs, which include long time series of data on ecosystems and their associated biota, are crucial to produce knowledge, create expertise, research capabilities, and infrastructure. Besides, they are critical to allow temporal evaluation of phase-out of contaminants, remediation, and restoration measurements and provide information for the sustainable use of the ocean, securing that its ecosystem services and functions are preserved. The amount of total expenditure for research in Brazil (1.3% of the GDP), although substantially higher than other SA bordering countries like South Africa (0.8%), Argentina (0.5%), and Namibia (0.3%), is much smaller than the investments of industrialized nations [e.g., United States (2.8%), China (2.2%), United Kingdom (1.7%), and Germany (3.0%)] (World Bank, 2020). Moreover, the current Brazilian Government has devaluated science and the role it can have in advising public policy. Cuts for science research budget in the past few years have led to a drop in investments from a peak of about US\$2.6 billion in 2014 to less than one-third of this value in 2020 (Tollefson, 2020). Additional funding is the only way to bolster efforts to better understand, evaluate, and manage the ocean and coastal ecosystems.

## Capacity Development

Discussions during the Decade's SA planning workshop, plus results from the Brazilian regional workshops have identified not only sources and types of pollution, but also diverse capacity building needs. These are listed below.

- Chemical and data analyses of nutrients, microplastics, petroleum hydrocarbons (PAHs), legacy (POPs listed in Stockholm Convention) and emerging contaminants (e.g., pharmaceuticals, novel flame retardants, personal care products, pesticides, nanomaterials, and technology critical elements);
- Public and private decision-making regarding pollutants and strengthening of the science-policy interface;
- Ecosystem and human health risk assessments;
- Mitigation of pollution and restoration of marine ecosystems/habitats;
- Prevention, preparedness and response to environmental disasters. The need for such action can be illustrated by the delayed and lack of coordination actions for the recent accidents of a mining dam's burst (Gomes et al., 2017; Hatje et al., 2017) and the oil spill in 2019 (Lourenço et al., 2020) that led to substantial negative environmental, social and economic impacts;
- Cross-sectors integration between public and private organizations and across disciplines;
- Evaluation of socio-economic impacts.

As alluded to earlier, capacity development is one of the core areas that need to be fostered in the SA region. This includes building up programs targeted to produce the necessary knowledge to properly manage ocean pollution in the region, involving not only academia but also government officials, and the industry. In addition, there is a need to foster an effective technology transfer mechanism so countries in the region will grant access and co-develop marine technologies that are fit for the purpose. The current international standards for data acquisition and quality assurance and control post a further need for enhancement in the regional science capacity. Technology and knowledge transfer will also need to be more effective and inclusive than the currently available mechanisms, such as the IOC guidelines, that have not yet fulfilled their goals (Harden-Davies, 2016; Salpin et al., 2018).

## National Institutional Regulatory Frameworks

National institutional frameworks, designed to regulate the management of the coastal zone and the marine space in an integrated way, are also key to improve environmental protection and conservation. In general, countries in the SA region possess sectoral and uncoordinated instruments to combat pollution, disregarding the synergic effects and cumulative impacts of different activities, and the ecosystem connectivity along the continuum continent-ocean. In this sense, there is a need to establish procedural and substantial norms to prevent, to remediate, and to repair environmental impacts. The polluter-pays principle (Adshead, 2018) needs to be strengthened, resulting in better economic instruments, such as tax incentives to adopt the use of best-suited technologies to avoid pollution or produce preventive labels/certifications to encourage sustainability. Countries should also invest in public and private collaborations to develop their marine spatial planning and water quality monitoring programs. Finally, actions need to be taken even in face of great scientific uncertainties. Therefore, the precautionary principle should be further applied and instruments such as adaptive licensing need to ensure effective pollution protection for the marine environment (de Sadeleer, 2009; Krämer and Orlando, 2018; Oliveira et al., 2019).

The development of a coordinated act or bill could provide such integration between different sectors and ocean activities. Developing a sole legislation would contribute to the harmonization of procedural and substantial rules applicable to the marine environment and to the coastal zone. In the case of federal states such as Brazil, where the federation, states, and municipalities have different competences to legislate and to manage the marine environment, a comprehensive norm would clarify and better distribute the competences of each entity to manage the impacts of pollution. This scenario would bring more clarity and legal certainty to stakeholders on their rights and obligations. Moreover, this integration would strengthen the management of cumulative impacts of different sources of pollution, based on a more precise connection between the public bodies (which are responsible for the allocation of budget) and

<sup>4</sup><http://cnpq.br/apresentacao-peld>

the environmental agencies. By better designing the national institutional frameworks to deal with the impacts of different types of pollution within the areas under national jurisdiction, South Atlantic countries will be more prepared to consolidate a regional coordination on this issue.

## Regional Coordination

Ocean pollution is largely based on non-point sources. Thus, relies on regional and international collaborations to tackle the issue. These collaborations should include deliberations about sampling monitoring designs, thresholds, and management of decision-making, particularly because of the links to human food security and other potential impacts on ecosystem services. Some level of regional institutional coordination will be required to bring together all the States from the region as well as big business with a key role in the sustainability governance (Blasiak et al., 2018) to deal with marine pollution, fostering cross-ocean basin assessments and mitigation actions.

There are international and regional treaties and organizations that already address the impacts caused by some pollutants like mercury (Minamata Convention), hazardous wastes (e.g., plastics) (Basel Convention) and persistent organic pollutants (Stockholm Convention) to protect human health and the environment. Other types of pollution are regulated by treaties related to shipping, mining and fishing (Montego Bay Convention, MARPOL Convention, Regulations of the International Seabed Authority). In the context of the Southwestern Atlantic, there is a binational commission ratified by Argentina and Uruguay (Comisión Técnica Mixta del Frente Marítimo) and created by the Tratado del Río de la Plata y su Frente Marítimo (November, 1973) that deals with continental pollution inputs to the ocean. SA countries need to work together even in the lack of a broader intergovernmental framework regulating marine pollution. In this regard, science diplomacy might play an interesting role to unveil all the possible exchanges that science and international relations may have in dealing with cross-border and global concerns and interests (Flink and Rüffin, 2019).

A well-coordinated science diplomacy effort among the countries in the region could help to address marine pollution issues dealing with national policies and international cooperation. This coordination should be certainly informed by scientific evidence taken up to policy making and finally to diplomacy. Negotiations will need to face multiple challenges such as balancing national interests, in particular industry's interests, with regional concern over pollution (Berkman, 2019). Another challenge will be to agree on leveled actions which are mostly State-led policies to combat marine litter. Thus, informal scientific peer-to-peer cooperation needs to be formalized through adequate international instruments. Researchers and civil society need to organize the debate and present the available evidence, so countries are pressured to act collectively. As evidenced during the current COVID-19 pandemic, in which States adopted diverse national plans of actions, despite the available scientific evidence, many times contributing to spread and intensify the crisis. On one hand, diversity of actions was

caused by the high scientific uncertainties with regard to this new virus, and on the other, due to political statements and actions overruling the available scientific evidence and generating insecurity. Thus, a regional bidding commitment should level and inform national policies on the best course of action, resulted from a negotiation informed by science and in balance with national interests and regional concern. One interesting example, designed under the auspices of the International Seabed Authority for mining activities, is the development of the Regional Environmental Management Plans (REMPs). They are part of an environmental policy by establishing standards and guidelines for the region to determine thresholds to mining exploitation. This type of instrument is an example of what a solid institutional framework can provide for the region (Domingos and Barros-Plataiu, 2021).

The Decade of Ocean Science calls for long-term commitment and investments to promote continuous funding for science, relevant and effective institutional and human capacities to deal with the complexities involved in stopping the degradation of the ocean ecosystems services and functions, and aggravating impacts associated with climate change. Finally, we will only be successful if we integrate the social, economic, and natural sciences in the search for solutions and in the development of public policies aimed at reducing the input of pollutants and warranting food security, in addition to, of course, the restoration of degraded ecosystems.

## CONCLUSION

Like many scientific advances, our better understanding of the ocean and reversal of its degradation cycle will evolve not only through research and development of innovative solutions in individual institutions but mostly through collaborations between national and international groups of stakeholders, including scientists, traditional communities, indigenous peoples and the private sector who could contribute with their experience, time, and other resources. The planning for the Decade is a voluntary pact that sought to build momentum by allowing countries to better define priorities for the Ocean Decade. The actions to be implemented by the Decade of Ocean Sciences have the potentially pivotal role to:

- (1) Advance the knowledge on the fate of pollutants to prevent the contamination of the environmental resources and associated human health and ecosystems impacts;
- (2) Develop cost-effective technologies and solutions to prevent, monitor (marine ecosystems and biota), mitigate and remediate polluted ecosystems in an integrated manner for protecting human health and marine ecosystems. Prevention of pollution from land-based and ocean sources is critical;
- (3) Development and improvement of models to predict and assess long-term trends and risks of pollutants and propose preventive solutions;
- (4) Promote technical and scientific capacity development and technology transfers reducing regional inequalities;

- (5) Improve on-land scientific facilities and ocean research infrastructure;
- (6) Advance regulatory science based on the latest scientific evidence to develop national public policies aimed at reducing the input of pollutants, better management of solid residues (e.g., plastics), and warranting food security and ecosystem health;
- (7) Facilitate national and international cooperation in marine research and regional institutional frameworks;
- (8) Improve risk assessment to facilitate risk management and data communication of regulatory relevance;
- (9) Foster interdisciplinary and *trans*-sectoral collaborations between marine, terrestrial, and social scientists, as well as public health researchers, promoting social inclusion, to ensure that those least able to influence the process but often most affected (e.g., traditional communities and indigenous peoples) are heard when addressing the local and global challenges of human-ocean interactions.

The earlier the actions in controlling pollutants are implemented, identifying key sources and preventing the crossing of thresholds, there will be higher chances of averting worst-case scenarios and reducing the economic and social costs having disparate impacts across nations and social groups. Ensuring that the most vulnerable and unpowered are properly protected from pollution and its consequences requires the early establishment of agreements, protections, and policies that will minimize social inequality and secure a clean, healthy ocean. Finally, controlling land-source pollutants will help to attain multiple Sustainable Development Goals (SDG), besides the preservation of life

below water (SGD14), contributing to the improvement of human health and well-being (SDG 3), clean water and sanitation (SDG 6), the end of hunger (SDG 2) and responsible consumption (SGD 12).

## AUTHOR CONTRIBUTIONS

VH conceived the manuscript and wrote the first draft. All authors contributed to the writing of the manuscript and gave final approval for publication.

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