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Contribution of ocean science to the development of ocean and coastal policies and sustainable development

8. Contribution of ocean science to the development of ocean and coastal policies and sustainable development

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8.1. Introduction

The best analogy for the development of the relationship between ocean science and ocean policy is that of a rope tied to a great weight. The rope consists of many strands that are twisted together to produce a structure that can bear great weight. The great weight represents the importance for the well-being of both humans and the rest of the living world of getting the right policies on the management of human impacts on the seven-tenths of the planet that is the ocean. Looking at how the different strands developed helps to understand how ocean science influences policy and *vice versa*. This chapter considers the organizational structures in which the science/policy interface is embedded, which affects significantly the ways in which that interface works. The chapter continues with six case studies that illustrate ways in which this interface has promoted conservation of the ocean and supported sustainable management of its resources. It describes how ocean science, based on existing capacity and infrastructure (Chapter 3), investment (Chapter 4), outcomes (Chapter 5) and data management (Chapter 6), influences stakeholders. Finally, in the context of the 2030 Agenda for Sustainable Development, it looks at how further scientific understanding is needed to achieve, and monitor, the ten targets of Sustainable Development Goal 14 (SDG 14 'Conserve and sustainably use the oceans, seas and marine resources').

8.2. The development of the interface between marine science and policy

The three main strands that have underpinned the development of marine science are: the requirements of navies; scientific curiosity; and support for maritime industries (originally fishing and shipping, but now a much wider range including offshore oil and gas exploration and exploitation, seabed mining and renewable energy).

The European wars of the eighteenth century gradually expanded the areas of conflict to cover much of the then known world: the European navies were in action with each other in the Atlantic, the Caribbean and the Indian Ocean. Such action required knowledge of sea conditions—particularly soundings and currents. As early as 1720, the French *Ministère de la Marine* had established an office to centralize French knowledge of marine charts (McClellan and Regourd, 2000). This was followed by the British, Russian and other European oceanographic surveys and hydrological services in the eighteenth and nineteenth century (Blewitt, 1957; Postnikov, 2000; David, 2004). An early example of international cooperation in such efforts was the voyage of the British ship *HMS Chanticleer*, with support from the French and Spanish navies, in the South Atlantic in 1828–1832 (Goodwin, 2004; Webb, 2010).

Scientific curiosity about the ocean is as old as science itself; phenomena such as tides and currents could not but prompt questioning. Scientific pioneers, such as Benjamin Franklin in the USA, started serious investigations. Franklin, for example, investigated the Gulf Stream in 1786 as a result of its impact on the timing of mail packets across the North Atlantic (Deacon, 1997). Pursuit of scientific enquiry in other fields led to major maritime expeditions: a British expedition in 1768–1771 to the South Pacific organized by the British Admiralty and the Royal Society (the British academy of science) to observe the transit of Venus was accompanied by experts who carried out observations of the oceanography and marine biology of that area (David, 2004). The link between the Royal Society and the Admiralty was pursued for many years, culminating in 1873–1876 in the circumnavigation of the globe by *HMS Challenger*, with a team of scientists and specially equipped laboratories, which is generally regarded as the starting point of modern oceanography (Wyville Thomson and Murray, 1880–95; Rice, 1999; Desmond, 2004).

Across Europe, interest in marine science (and in particular the interest in marine biology stemming from the general development of biological sciences) led to setting up marine research institutions, either by governments or by private initiatives: Arcachon (1867), Roscoff (1872) and Banyuls (1881) in France; Naples (1871) in Italy; Sebastopol (1871) in Russia; Plymouth (1884) in England; Santander (1886) in Spain; and Heligoland (1892) in Germany (Desmond, 2004; Borja and Collins, 2004; Egerton, 2014). Similarly, in the USA, independent research institutions were set up at Woods Hole, Massachusetts (1888) and San Diego (1903—now the Scripps Institution of Oceanography) (Ritter, 1912; Lillie, 1944). At more or less the same time, physical and biological oceanography began to be recognized as a specialism in universities; for example, the first professorship of oceanography in the University of Liverpool (England) was established in 1919 (Rudmose Brown and Deacon, 2004).

The purely scientific aspects of marine research became increasingly prominent towards the end of the nineteenth century. In particular, the link between ocean currents and the movements of fish became a subject of scientific interest in Scandinavia. This led to the creation in 1902 of the International Council for the Exploration of the Sea (ICES) – the first intergovernmental environmental body. ICES undertook an initial five-year programme of collaborative research, eventually becoming a permanent and important body for marine science (Smed and Ramster, 2002; Egerton, 2014; Chapter 7). Seventy years later, a similar organization emerged in the North Pacific: in 1990 the North Pacific Marine Science Organization (nicknamed PICES for a 'Pacific ICES') was established (PICES, 2016).

Just over 50 years ago, the necessity for worldwide collaboration in marine research was acknowledged by the setting up of the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO). The IOC has acted since then as a focal point for organizing and supporting collaborative research, providing a central repository for information on both physical and biological oceanography and promoting capacity-building for marine research, especially in the Caribbean and South-East Asia (Scott and Holland, 2010).

Scientific support for maritime industries can be seen as starting with the production of accurate charts and pilotage manuals as a by-product of survey work for national navies; the British Admiralty Charts were issued commercially as early as 1821 (Andrew and David, 2004). However, more specific scientific support started in the mid-nineteenth century. In 1843, Professor van Beneden, Professor of Zoology at the University of Louvain, established a research station at Ostend in Belgium on his family oyster farm. A little later, to improve the aquaculture of oysters in France, the Marine Biological Station was established in 1859 at Concarneau. Concerns about the development of sea-fisheries in the last quarter of the nineteenth century led to pressures to apply science to better understand fish stocks and their distribution and fishing techniques. Many governments of countries around the North Sea established fisheries laboratories and research institutes at that time. As the value of fisheries research was proven, most coastal countries followed suit.

In a little more than 125 years after the first marine research institutions were established, the various strands have become more closely linked, and most marine research institutions now address a wide range of oceanographic questions. The interlinked nature of all marine science, including not only physical and biological oceanography, but also social and environmental aspects, has now been fully recognized by the establishment and organization by the United Nations General Assembly in 2006 of the Regular Process for the Global Reporting and Assessment of the State of the Marine Environment, including Socio-Economic Aspects (United Nations General Assembly resolution 65/37A). This produced the first integrated global assessment of the world's oceans – World Ocean Assessment I – in January 2016. The essential links between ocean and atmosphere have also been recognized in the work of the Intergovernmental Panel on Climate Change and the research that it has prompted – in particular the Special Report on Oceans and Cryosphere in a Changing Climate, which is due to be completed in September 2019.

8.3. Institutional arrangements for marine science

Because the driving forces for the development of marine science have been manifold, the arrangements that have emerged in different countries of the world are equally diverse. One crucial issue that has often emerged is the tension between the parts of government responsible for the development of policy and the research institutions. On the one hand, it is important for the research undertaken to be what is needed to satisfy policy needs. On the other hand, new, innovative developments in science depend on basic, wide-ranging investigation. Experience suggests that such high-quality science is best produced when the research is conducted independently of political pressures, and is subject to peer review with evaluation from a strictly scientific standpoint (Haas, 2004; Ruggiero, 2010). Countries try to achieve these dual goals in the context of their individual organizational history, by applying different models of institutional ocean science organization.

Many countries concentrate much of their marine scientific research (apart from that conducted within universities) in a single institute of marine research, usually dependent on a ministry that takes the lead on maritime and marine issues. Depending on national history, this is often the ministry responsible for the country's naval forces (as in Brazil) or the ministry responsible for agriculture and fisheries (as in Peru). Alternatively, a single marine research institute may be answerable to a range of ministries such as transport, natural resources and agriculture and fisheries (as in Ireland). To safeguard the independence of the research, such an institute is often governed by a separate board appointed by the country's government as a whole for a fixed term.

With a view to safeguarding the independence of scientific research, the majority of research institutes are placed under the supervision of a ministry for science, thus insulating them from the immediate policy pressures of the specialist ministries. This approach was influentially developed in the United Kingdom in 1915, when the Department for Scientific and Industrial Research was created. Similar structures were developed and continue in, for example, Australia (the Commonwealth Scientific and Industrial Research Organization), India (the Department of Scientific and Industrial Research) and Spain (Consejo Superior de Investigaciones Científicas). Such structures do not, however, rule out the existence of other marine research bodies directly controlled by the relevant specialist ministry (e.g. the Instituto Español de Oceanografía in Spain).

One aspect of the relationship between specialist ministries and marine research establishments is the focus of research programmes. Scientists often want to pursue research which will bring them attention, respect and advancement in their chosen discipline. This research may not be as responsive to the needs of policy-makers for research to resolve policy issues. Various means have been tried to resolve this dilemma. Increasingly, marine research institutes are agreeing to a customer/contractor relationship, under which their programmes are focused on the requirements of a funding ministry or agency, which pays for the specified research, without, however, having any management control over the institute.

Such arrangements frequently also ensure that a proportion of the research funding is for 'blue sky' research—research that is not tied to any particular policy goal, but chosen for its intrinsic scientific interest. As part of this 'customer/contractor' approach, some countries (such as New Zealand) are setting their national research bodies up in such a way that they can also compete in the open market for research contracts.

A sound balance between marine scientific research 'customers' and 'contractors' is crucial today and will be even more so in the years ahead. As the use of the ocean becomes more extensive, the need for knowledge is bound to increase and so are the necessary resources to carry out scientific research and related ocean observations. Extensive and constructive dialogues among the science community, marine industries, ocean managers and governments, both nationally and internationally, will be essential to ensure that necessary knowledge, covering the full range of issues required to inform policy-making effectively, is developed without compromising scientific quality. Recognition of the need for greater research coordination and cooperation was one of the reasons why the United Nations General Assembly agreed that part of the task of the Regular Process for the World Ocean Assessment should include the identification of knowledge and capacity-building gaps.

8.4. The science/policy interface in action

An understanding of how marine science can work together with marine policy is essential for both the design of marine scientific research programmes and the development and implementation of marine policy. Case studies of particular issues can promote such an understanding. Six are briefly presented here: fisheries management in the North Sea, harmful algal blooms, the spread of non-native organisms, anti-fouling treatments, the Benguela Current large marine ecosystem, and geoengineering of carbon dioxide absorption.

8.4.1. Fisheries management in the North Sea

In the nineteenth century, concerns for fisheries management in the North Sea focused mainly on defining who should benefit from the fishery, rather than on managing the impact of fishing on the marine environment. This reflected an approach typified in a remark by Thomas Huxley, a prominent supporter of Charles Darwin's theories. Speaking at a London Fisheries Exhibition in 1883, he said *'In relation to our present modes of fishing, a number of the most important sea fisheries...are inexhaustible'*. He added that the natural 'destructive agencies' at work on fish stocks were so great that fisheries could not significantly increase the death rate (Huxley, 1883).

Huxley's qualification about 'the present modes of fishing' was crucial. Over the next few decades, technology converted the fishermen's activities into an even larger 'destructive agency' than natural forces – a process which continued throughout the twentieth century. More reliable means of propulsion, larger fishing vessels (so that more could be caught before a return to port was necessary), refrigeration as a method of preserving fish, new fishing gear, better navigation aids and the use of echo-location of fish – all these have enabled a massive increase in the size of the catch.

By the 1930s, there was sufficient concern about over-fishing for North Sea States to start to take action. Little progress, however, was made on regulation, largely because the scientific knowledge of fish populations was still in its early stages. In the 1930s and 1940s, better understanding of the fish life-cycles

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was achieved, and after the Second World War, fisheries science continued to improve with major developments in the statistical understanding of how fish populations responded to natural events and the pressures from fisheries (Hardy, 1959).

As the science improved, the need to maintain high levels of fish catch and achieve a fair sharing of the North Sea catch between States led to further efforts at regulation, but it would be nearly 40 years before a system slowly emerged. A new convention was agreed in 1946 – though it did not come into force until 1953. This provided for some conservation measures, but no limits on fishing effort. Provision was made for further conservation measures on the advice of ICES, and ICES began to make recommendations, but none were ever adopted. There was, therefore, no effective set of agreements on fisheries, largely because of the continuing arguments over the extent of national control of the sea.

In 1976, proposals were agreed for a European Community Common Fisheries Policy, implementing a commitment which dated back to 1956 and providing for the introduction – *in the future* – of a system of European Community conservation measures. Thus, although there was by then a good understanding of the science behind the performance of fish populations, legal uncertainty over fisheries jurisdictions and conflicting national interests meant that there was little success in applying this scientific understanding to fisheries management.

Into the middle of all these developments on the legal and management structures came an event in the real world that required urgent action. The collapse of the North Sea herring stock under the pressure of over-fishing created the need for immediate action in the absence of an agreed framework (Bjørndal and Lindroos, 2002). An agreement emerged for bans on herring fishing, resulting in the recuperation of the herring stocks so that catches could resume in the mid-1980s in the North Sea.

This collapse made the States realise the need for an overall framework and, after hectic negotiations over the period to 1983, the North Sea States ended up with a system based on total allowable catches (TACs). These were negotiated annually by fisheries ministers in December, for the following calendar year, on the basis of advice from ICES. Ministers had a difficult political task: on the one hand, they could understand the need to follow scientific advice; on the other, they were under intense domestic political pressure to deliver to their national fishing fleets the potential economic opportunities. Not surprisingly, these conflicting pressures proved irreconcilable. TACs were frequently set higher than the levels recommended by scientists. This pattern continued well into the 2000s. For example, in 2002, ICES recommended a complete moratorium on all catching of North Sea cod. The European Commission proposed an 80% reduction in the cod TAC. The Council of Ministers eventually agreed on only a 45% reduction in TAC, with the result that the actual catches were too large for a sustainable fishery.

The fishers lost confidence in the system and began to evade it. The pressures from the TAC limits led to large amounts of fish being discarded (because they would have been over the quotas) and 'high-grading' (the discarding of economically less worthwhile fish, to stay within the quota). These discards in turn led to a sevenfold increase in scavenging seabirds, fed by the discards. At the same time, the evasion of the controls on landing fish undermined the data on which the scientists based their assessments, so that forecasts became less reliable (Daw and Gray, 2005).

During the 1990s, the thrust of fisheries science slowly broadened: the initial emphasis on single-stock management developed into the ecosystem approach to fisheries management, taking into account the interactions between different fish species, the relationship between fish and other wildlife species and wider environmental issues such as pollution (North Sea Intermediate Ministerial Meeting, 1997). Further, at the end of the 1990s, Aberdeenshire County Council (whose area covers a very large part of the Scottish fishing industry) decided to try to rebuild a climate of trust between fishers, fisheries scientists and fisheries managers. A series of conferences around the North Sea organized by major local authorities invited multiple stakeholders (fishers' organizations, fisheries scientists, fisheries managers, environmental managers and NGOs) to discuss the uncertainties of fisheries science and the problems of fisheries management. This series of conferences led to European Union's Regional Fisheries Advisory Councils (Chapter 7). New approaches were adopted in other fields, so that by 2014 a complete reform of the EU Common Fisheries Policy had been achieved, to come into effect over the following few years. This is intended to incorporate the EU's international commitments to an ecosystem approach and the limitation of fishing effort to the maximum sustainable yield, to ban discards and to adjust fishing capacities to be in balance with fishing opportunities (EU, 2016).

From the point of view of the interface of marine science with marine policy the main messages of this history are: (i) the need for a sound scientific understanding of aspects of the environment that should be regulated; (ii) the need for scientists to present material clearly to policy-makers, so that they understand the uncertainties inherent in the scientific results; (iii) the need to involve all stakeholders so that they understand the scientific messages; and (iv) the need to avoid creating situations in which political pressures are likely to distort the science.

8.4.2. Excessive nutrients and algal blooms

There are many facets to the problems caused by the excessive growth of marine algae – a broad grouping of photosynthesizing organisms found in the parts of the ocean to which light can penetrate. Some of these problems result from toxins produced by the algae. Others result from the sheer quantity of non-toxic algae that can be produced.

Where there are massive blooms of non-toxic algae, one of the frequent outcomes is the *marées vertes* (green tides) that disfigure beaches in many parts of the world. Other outcomes are hypoxic and dead (anoxic) zones, where the action of bacteria in the decay of algae and phytoplankton (microscopic plants) in the bloom causes declining oxygen concentrations or even results in the effective absence of dissolved oxygen. Fish flee from such zones and the immobile sea-bed animals die. These problems are found all around the world. More than 500 sites are currently facing these problems continuously or during parts of the year (Diaz and Rosenberg, 2008), including large parts of the Baltic Sea, the Gulf of Mexico, nearly all the major river estuaries of China and Manila Bay in the Philippines (Sotto *et al.*, 2014; GOERP, 2017).

Ocean science has revealed that the main cause of many of these problems is the input to the sea of excessive amounts of nutrients, in particular nitrogen, which in undisturbed ecosystems regulates and limits primary production (eutrophication). There are four main sources of nitrogen compounds (mainly nitrates) for the ocean: (i) compounds containing nitrogen that are emitted from internal-combustion engines; (ii) sewage (i.e. human faeces and urine) and associated organic material from industrial processes (especially brewing and distilling); (iii) agricultural run-off (including run-off from fertilizers applied in arable agriculture and slurry from livestock rearing); and (iv) emissions to air (mainly methane) from livestock. The effects of these sources can be limited in various ways.

The environmental, social and economic effects of these eutrophication problems are manifold. Tourists avoid affected beaches. Fish and other marine life are killed and ecosystems are disrupted, leading, for example, to the 1991 European Community Nitrates and Urban Waste Water Directives and the Environmental Protection Agency's Chesapeake Bay Program (GOERP, 2017).

A wide range of disciplines needs to collaborate to understand and tackle the problems of excess nutrients resulting in excessive algal growth and a consequent loss of dissolved oxygen in the ocean. Studies have had to, and continue to need to, link at least plankton and algae, the management of sewage, agriculture and traffic, the chemistry of nitrogen compounds, the toxicology of shellfish and hypoxic and anoxic zones, together with regular monitoring of the ocean's physical conditions, state of relevant coastal areas, seawater contents and chlorophyll.

In addition to problems resulting from excessive growth of non-toxic algae, there are also problems with algae species that produce toxins. Some phytoplankton species are toxic; their blooms cause illness and death in humans, fish, seabirds, marine mammals and other oceanic life, often as a result of toxin transfer through the food web. Six human poisoning syndromes are caused by consumption of seafood contaminated by toxins from harmful algal blooms. Other threats to human health are posed by toxic aerosols and water-borne compounds derived from toxic algae that cause respiratory and skin irritation.

The harm from toxic algal blooms arises not only from the illnesses and deaths caused by poisoning but also from the damage to shellfish and other fisheries that have to be closed to protect people from poisoning, and the disruption of ecosystems caused by deaths of fish and other top predators that ingest the algae or the toxins that they produce. Many toxic algal bloom events are reported annually from all parts of the world, and the number is growing. Some of these increased numbers are due to improved observation and recording but there is reliable evidence that there is a real increase in the incidence of this problem, through the interaction of many factors including rising sea temperatures, increased inputs of nutrients to the ocean, transfer of non-native species by shipping and changes in the balance of nutrients in the sea.

Toxic algal blooms are complex phenomena that require the involvement of many disciplines to address the problems that they cause, ranging from molecular and cell biology to large-scale field surveys, numerical modelling and remote sensing. Under the leadership of the IOC, the Scientific Committee on Oceanic Research (SCOR), the United Nations Food and Agriculture Organization (FAO) and regional marine science organizations, major programmes have developed over the last 30 years to bring together all the many strands of science that are needed to understand and manage harmful algal blooms. In the early 1990s, an intergovernmental panel was set up by IOC and in the late 1990s, a coordinated international scientific programme on the ecology and oceanography of harmful algal blooms GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms) was set up under the auspices of IOC and SCOR. GEOHAB has brought about a major increase in understanding of the processes that result in harmful algal blooms, including their relationships to upwelling systems, stratification and eutrophication. It is now becoming possible to forecast when they may occur and better techniques for testing for toxins have improved the protection of human health and markets. At the same time, capacity-building under the programme is helping more States set up monitoring systems to ensure that food from the sea is not contaminated by algal toxins (Anderson *et al.*, 2010).

The successes in this field have shown the importance of collaboration both between States and between scientific disciplines. Much work has been required to establish the cross-disciplinary links and to set up global monitoring and reporting systems. The time span between detecting the issue and policy action, the spatial variability and the different scientific disciplines involved in investigating the problem of harmful algae blooms emphasize the importance of long-term commitments in the field of marine science.

8.4.3. Movement of non-indigenous species

The dispersal of plants and animals over long distances has been part of evolution. Some species (for example, the coconut – *Cocos lucifer*) have probably spread by sea without human intervention of any kind, although the present distribution of coconuts appears to involve deliberate human transfers both in the prehistoric and historic periods (Foale, 2003). Ships have long played a role in transferring species from one part of the world to another. However, recently there has been a massive increase in ship traffic. International trade carried by ships increased by between twofold (oil and gas) to fivefold (coal and ore) between 1970 and 2012 (UNCTAD, 2014). There has therefore been a large increase in the potential for the transfer of marine species between different parts of the world.

One aspect of this is the potential for the carriage of species in ballast water—particularly for tanker ships where ships regularly return in ballast for their next load-bearing voyage. In the late 1980s, Canada and Australia raised the issue in the IMO's Marine Environment Protection Committee (MEPC). In 1991, the MEPC adopted guidelines for preventing the introduction of unwanted organisms and pathogens from ships' ballast water and sediment discharges. In 1993, the IMO Assembly followed this up by asking the MEPC to review the guidelines with a view to develop an international convention. By 1997, the IMO invited States to use the guidelines to address this problem. More than 14 years of negotiations were needed to develop the *2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments* (BWM Convention). Another 13 years have been needed to achieve sufficient ratifications for the convention to enter into force, expected to happen in September 2017 (IMO, 2016b).

Scientific evidence has played an important role in winning the arguments for action in this field, such as widespread surveys of the scale and distribution of the problems of non-indigenous species (Figure 8.1). In 2000, for example, a survey identified 295 non-indigenous species (NIS) in North America and concluded, with some hesitation, that: (i) the rate of reported invasions has increased exponentially over the past 200 years; (ii) most NIS are crustaceans and molluscs, while NIS in taxonomic groups dominated by small organisms are rare; (iii) most invasions have resulted from shipping; (iv) more NIS are present along the Pacific coast than the Atlantic and Gulf coasts; and (v) native and source regions of NIS differ among coasts, corresponding to trade patterns (Ruiz *et al.*, 2000).

The International Union for the Conservation of Nature (IUCN) identified 84 non-indigenous invasive marine species, which have appeared in marine habitats outside their natural distribution (GISD, 2014). Another study in 2008 found 205 species, of these: approximately 39% are thought to – or are likely to – have been transported only by fouling of ships' hulls; 31% in ballast water; and 31% by one or other of these routes (Molnar *et al.*, 2008). Some regional reviews have also identified high numbers of non-indigenous species; for example, 120 in the Baltic Sea and over 300 in the Mediterranean (Zaiko *et al.*, 2011).

These surveys build on an enormous amount of groundwork where individual cases have been examined. The case of the BWM Convention is therefore a good example of the need for worldwide, detailed examination of the marine environment, and effective reporting that provides results that can be accessed and used to produce an integrated global picture, detecting the cause of invasive species and, hopefully in the near future, stagnating or decreasing distribution.

8.4.4. Anti-fouling treatments

From the start of long-sea voyages, the hulls of wooden ships were attacked by the naval shipworm (*Teredo navalis*), which bored into and destroyed the wood. From around 1760, attempts were made to prevent this by covering the hulls with thin sheets

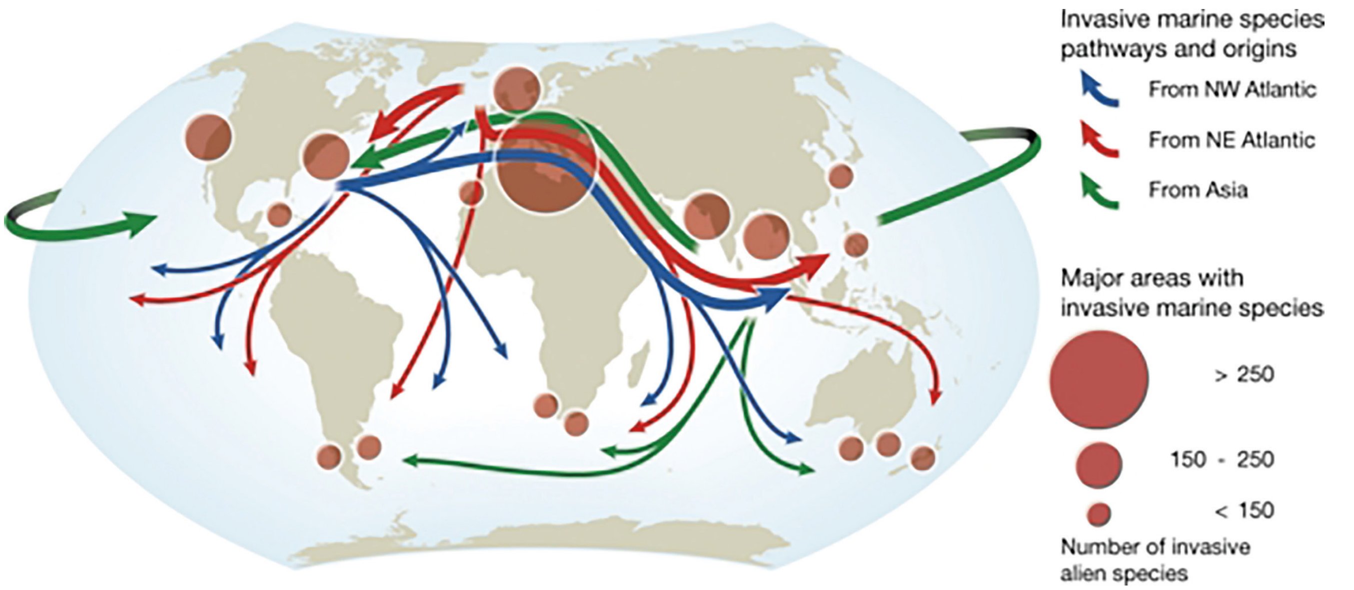

Figure 8.1. Major pathways and origins of invasive species infestations in the marine environment. *Source*: Nelleman *et al.*, 2008 (GRID-Arendal, H. Ahlenius, http://www.grida.no/resources/7191).

of copper. These were also found to help navigation by reducing the accumulation of barnacles, seaweed and other biofouling, which slowed the speed of ships (Rosenberg and Gofas, 2010). Even after steel hulls replaced wooden ones, the impact of accretions of marine life has been important for the operation of shipping. Biofouling reduces ship speed owing to the extra drag, which increases fuel consumption and engine stress. A biofilm 1 mm thick can increase the ship hull friction by 80%, which translates into a 15% loss in speed. Furthermore, a 5% increase in biofouling increases ship fuel consumption by 17% with a 14% increase in greenhouse gas emissions. In 1980, the US Navy estimated that 18% of its fuel consumption was due to biofouling (Bixler and Bhushan, 2012).

Given these substantial economic implications, it is not surprising that a great deal of effort has been applied to finding effective anti-fouling treatments. In the 1960s and 1970s, techniques were developed for embedding compounds of tributyltin (TBT), long known as an effective biocide, into resin bases that would slowly abrade (under the effect of water flowing past) and thus continuously release the TBT. Anti-fouling treatments based on this approach proved highly effective and were quickly and widely adopted (Piver, 1973).

It was not long after that adverse effects from the introduction of TBT anti-fouling treatments started to be detected. As early as 1981, the appearance of male traits in female mud snails was being observed, and it was noted that this could be produced in the laboratory by very low levels (a few parts per billion) of TBT (Smith, 1981). At about the same time, the Pacific oyster (*Crassostrea gigas*) was introduced to aquaculture in Europe, especially in France. Shell malformations appeared in these oysters, and these were found to increase in proportion to the amount of surrounding boating activity. Furthermore, this effect diminished if the affected oysters were re-laid in waters removed from boating activity (Alzieu and Portmann, 1984).

The scientific evidence was sufficiently clear that countries began prohibiting the use of TBT as an anti-fouling treatment on boats of less than 25 m. This caused a major outcry and campaign from the yachting community, who saw large numbers of amateur sailors being disadvantaged for the benefit of a 'few oyster farmers'. Nevertheless, the authorities in many States persisted with this regulation/prohibition (Corrick, 1985).

The scientific evidence of endocrine disruption and other adverse effects, particularly in molluscs, continued to accumulate. In 1990, the IMO recommended that governments should eliminate the use of anti-fouling paints containing TBT. This resolution was intended as a temporary restriction until the IMO could implement a more far-reaching measure. The *2001 International Convention on the Control of Harmful Anti-fouling Systems on Ships*, which entered into force in 2008, prohibits the use of organotin compounds as biocides in anti-fouling paints (IMO, 2016a).

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The case of TBT anti-fouling paints shows the importance of regular monitoring of the ocean. The level of TBT at which harm was caused is so low that, at the time, it could not be detected by chemical analysis; only the observation of reaction of biota to the presence of the chemical enabled it to be detected.

8.4.5. Benguela Current Commission

The world ocean is a single, interlinked system, but in order to understand it and to manage human impacts on it, it is necessary to divide it into more manageable units. As a result of many studies, originally started by the National Oceanic and Atmospheric Agency of the United States, a series of Large Marine Ecosystems (LMEs) has been identified. Sixty-six LMEs are usually recognized, being defined by geomorphic features such as the extent of the continental shelves, oceanographic features such as major ocean currents and ecological factors giving rise to distinct ecosystems.

Off the west coast of Africa, the Benguela Current LME is dominated by the current of that name off the coasts of Angola and Namibia and the western coast of South Africa. In the context of its international waters portfolio, the Global Environmental Facility (GEF) strongly endorses the strategy of country-driven LME management. Through its International Waters focal area, GEF promotes the incorporation of an interdisciplinary approach, along with a development component to improve the management of marine resources (IOC-UNESCO and UNEP, 2016).

GEF places priority on the development of a Strategic Action Programme (SAP) that addresses changing sectoral policies and activities responsible for the root causes of transboundary environmental concerns. The SAP for the Benguela Current LME was implemented between 2002 and 2008. During that time period, 75 projects hosted by a wide variety of marine science bodies and supported by GEF through the United Nations Development Programme were conducted, and a comprehensive picture of the status of the LME was generated. Subjects studied included the cumulative impact of offshore marine diamond mining, the biodiversity of the estuarine, coastal, near-shore and offshore environments of the region and the important fisheries of the area. Extreme environmental events, including the sustained warming of the ocean ('Benguela Niño') and large-scale eruptions of sulphur, were also assessed.

This major improvement in the knowledge of the LME resulted in an acknowledgement by the Governments of Angola, Namibia and South Africa that improved arrangements were needed to coordinate the governance of human activities in the LME. In 2013, the Benguela Current Commission was established, to promote a coordinated regional approach to the long-term conservation, protection, rehabilitation, enhancement and sustainable use of the LME. This is the first inter-governmental commission in the world to be based on the Large Marine Ecosystem concept of ocean governance (BCC, 2017).

The process of establishing the Benguela Current Commission shows how a thorough examination of the science of a marine region can create the knowledge base needed for improved international collaboration and thus strengthen the political will for the necessary agreements.

8.4.6. Geo-engineered sequestration of carbon dioxide

Due to the problems of climate change, much thought has gone into the possibilities of mitigating emissions of greenhouse-gases, especially carbon dioxide. One suggestion involved large-scale ocean fertilization, by adding iron or other nutrients to surface waters. The intention would be to enhance microscopic marine plant growth, on a scale large enough to significantly increase the uptake of atmospheric carbon by the ocean and to remove it from the atmosphere for time periods long enough to provide global climatic benefit. This suggestion grew out of scientific ideas developed in the late 1980s. The suggestion was controversial and in 2008, the ninth meeting of the Conference of the Parties to the *1992 Convention on Biological Diversity* decided that no further ocean fertilization activities – for whatever purpose – should be carried out in non-coastal waters until there was stronger scientific justification, and that it be assessed through a global regulatory mechanism.

At the same time, the **c**ontracting parties to both the *1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Convention) and the *1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Protocol) – the global instruments regulating the dumping of wastes in the sea – adopted a resolution agreeing that the scope of those instruments includes ocean fertilization activities. Under this denomination is any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans (not including ordinary aquaculture, mariculture or the creation of artificial reefs). They also agreed to consider in more detail what that conclusion implied.

The IOC decided to commission a scientific report on the issue and provide it as input to the debate. The report was prepared with the assistance of the Surface Ocean Lower Atmosphere Study, an international programme that focuses research effort on air-sea interactions and processes, and which is sponsored by the International Geosphere-Biosphere Programme, SCOR, the World Climate Research Programme and the International Commission on Atmospheric Chemistry and Global Pollution.

The report concluded that, while experiments had shown that inputs of iron to high-nutrient regions can greatly increase the biomass of phytoplankton and bacteria, and thus the drawdown of carbon dioxide into surface water, it is not yet known how iron-based ocean fertilization might affect zooplankton, fish and seafloor biota. Furthermore, the report concluded that there is even less information on the effectiveness and effects of fertilizing low-nutrient regions. The report also pointed out that large-scale fertilization could have widespread (and difficult to predict) impacts locally, but also far removed in space and time. It recommended careful study of the issue and monitoring of any experiments (Wallace *et al.*, 2010).

The report was influential in helping the discussions under the London Convention and London Protocol. In 2010, the contracting parties to these instruments adopted the Assessment Framework for Scientific Research Involving Ocean Fertilization and in 2013, the contracting parties of the London Protocol adopted amendments, which incorporated ocean fertilization and other marine geo-engineering activities as well as provisions for regulation of these into the Protocol (GOERP, 2017).

This example shows how a well-organized and well-focused scientific report can help international negotiations to improve the management of human activities and reduce the impacts on the marine environment.

8.5. Looking ahead

An important part of any report looking at ocean science around the world is to identify the gaps in knowledge. Part of the work of the first global integrated assessment of the ocean – World Ocean Assessment I – was to identify the knowledge gaps that hamper the understanding of the ocean and the management of human activities affecting the ocean in order to deliver the services and maintain the ocean resources the world needs (GOERP, 2017). Filling knowledge and associated capacity gaps, investing in ocean science and tracking the impact of marine research, as presented in the Global Ocean Science Report, will be important for sustaining ocean and human health, i.e. achieving SDG 14 and in particular its SDG target 14.a (increase scientific knowledge, develop research capacity and transfer marine technology…).

The information, that the world community needs to understand the ocean, can be divided into four main categories: (i) the physical structure of the ocean; (ii) the composition and movement of the ocean's waters; (iii) the biota of the ocean; and (iv) the ways in which humans interact with the ocean. In general, the North Atlantic and its adjacent seas are probably the most thoroughly studied – though even there, major gaps remain. Parts of the Atlantic Ocean and the Pacific Ocean in the northern hemisphere are better studied than those in the southern hemisphere. Least is known about the Arctic, Southern and the Indian Ocean.

The following examples present a scientific perspective of ocean research topics relevant to SDG 14 targets.

8.5.1. Physical structure of the ocean

Our knowledge of the geomorphic features of the ocean has been greatly enriched over the past 25 years by local and global studies. Although charting the oceans has been in progress for more than seven centuries in coastal waters and for 250 years along the main routes across the open ocean, many features still require more detailed examination. The designation of exclusive economic zones (EEZs) has led many countries to carry out more detailed surveys as a basis for managing their activities in those zones. Ideally, all coastal States would have such detailed surveys as a basis for their EEZ management. Surveys beyond national jurisdiction will sensibly be organized internationally (for example the GEBCO Seabed 2030 project). Such surveys will contribute to SDG target 14.2 (…manage and protect marine and coastal ecosystems…).

It is possible to characterize the physical structure of the ocean in areas beyond national jurisdiction, but the reliability and detail of such characterizations varies considerably among different parts of the ocean. Improvements in information of that kind are highly desirable to understand the interaction between the physical structure and the biota of the ocean, in terms of conserving biodiversity and managing living marine resources. Effective comparison between different parts of the world requires comparable approaches, which are best organized internationally. Such information will contribute towards SDG targets 14.3 (Minimize and address the impacts of ocean acidification…) and 14.7 (…increase economic benefits to small island developing States (SIDS) and least developed countries (LDCs) from sustainable use of marine resources…).

8.5.2. State of the ocean waters

Gaps persist in knowledge of changes in sea temperature (both at the surface and at depth), sea-level rise, salinity distribution, carbon dioxide absorption, and nutrient distribution and cycling. The atmosphere and the ocean form a single linked system. Much of the information needed to understand the ocean is also needed to understand climate change and it is thus important to ensure that oceanic and atmospheric research is coordinated. This information will also be important for SDG 13 (Take urgent action to combat climate change and its impacts) and for the work under the auspices of the *1992 United Nations Framework Convention on Climate Change* and the *2016 Paris Agreement*.

Ocean acidification is a consequence of carbon dioxide absorption, but understanding the implications for the ocean requires more than just a general understanding of how carbon dioxide is being absorbed, as the degree of acidification varies locally. The causes and implications of those variations are important for understanding the impact on marine biota. Such information will further contribute towards SDG target 14.3 (ocean acidification). The Global Ocean Acidification Observing Network is being put in place, involving many national administrations, universities and marine research institutes with the participation of IOC and the International Atomic Energy Agency.

In order to track primary production (on which the overwhelming majority of the ocean food web relies), routine and sustained measurements of dissolved nitrogen and biologically active dissolved phosphorus are highly desirable across all parts of the ocean. Such research involves satellite observation and gliders and floats (for example Argo floats; Chapter 3), and therefore generally requires international cooperation. Such information is crucial not only to achieve SDG target 14.2 (manage and protect management of marine and coastal ecosystems), but also SDG target 14.1 (…prevent and significantly reduce marine pollution of all kinds… especially that related to nutrient inputs).

8.5.3. Biota of the ocean

Plankton are fundamental to life in the ocean. Information on their diversity and abundance is important for many purposes. Such information has been collected for over 70 years in some parts of the ocean (such as the North Atlantic) through continuous plankton recorder surveys and sustained ship based time-series (Chapter 3). Such information is important to complement information on primary production (Section 8.5.2).

Information on biodiversity in the ocean and the number and distribution of the many marine species is also highly useful for understanding the health and reproductive success of individual populations. Many species contain separate populations that have limited interconnections. Since many populations are found in more than one national jurisdiction and some both in areas within and beyond national jurisdiction, effective surveys require international cooperation.

Fish stock assessments are essential to the proper management of fisheries. A good proportion of the fish stocks fished in large-scale fisheries are the object of regular stock assessments. However, many important fish stocks are still not regularly assessed. More significantly, stocks important for small-scale fisheries are often not assessed, which has adverse effects in ensuring the continued availability of fish for such fisheries. This is an important knowledge gap to fill. Likewise, there are gaps in information about the interactions between large-scale and small-scale fisheries for stocks over which their socio-economic interests overlap, and between recreational fishing and other fisheries for some species, such as some trophy fish (marlins, sailfish and others) and other smaller species.

Information on marine species and on fish stocks is important for SDG target 14.4 (…effectively regulate harvesting and end overfishing, and implement science-based management plans…), as well as 14.2 (management and protection of marine and coastal ecosystems), 14.7 (economic benefits for SIDS and LDCs) and 14.B (provide access for small-scale artisanal fishers to marine resources and markets). Better information on fish stocks in areas beyond national jurisdiction is also important for the development of a new international legally-binding instrument for the conservation and sustainable use of biodiversity in areas beyond national jurisdiction, under the *1982 United Nations Convention on the Law of the Sea*–because of the depth of the ocean, ocean areas beyond national jurisdiction represent over 90% of the space occupied by life on earth in all its forms. Further new data will support the implementation of legislation put in place via illegal, unreported and unregulated fishing (IUU) regulations, which combats the depletion of fish stocks, the destruction of marine habitats, distortion of competition, disadvantages for honest fishers, and weakening of coastal communities, particularly in developing countries[1] (FAO, 2001; SDG target 14.6).

1 Regulation (EC) No 1005/2008—EU system to prevent, deter and eliminate illegal, unreported and unregulated fishing.

8.5.4. Ways in which humans interact with the ocean

Some of the issues relating to the ocean and to ocean biota (for example, ocean acidification and fish stock assessments) are linked to the way in which humans affect some aspects of the ocean (for example, through carbon-dioxide emissions or fisheries). However, there are many more areas in which we do not yet know enough about human activities that affect or interact with the ocean to enable us to manage those activities sustainably.

For shipping, much information is available about where ships go, their cargo and the economics of their operations. However, important gaps remain in our knowledge about how their routes and operations affect the marine environment. Those issues include primarily the noise that they make, continued discharges of oil and the extent to which non-native invasive species are being transported. This information is needed for SDG target 14.1 (prevention and reduction of pollution).

Land-based inputs to the ocean have serious implications for both human health and the proper functioning of marine ecosystems. In some parts of the world, those have been studied carefully for over 40 years. In others, little systematic information is found. There are two important gaps in current knowledge. The first is how to link different ways of measuring discharges and emissions. Much information is available from local studies about inputs, but those are frequently measured and analysed in different ways, thereby making comparison difficult or impossible. There are sometimes good reasons for using different techniques, but ways of improving the ability to achieve standardized results and to make comparisons are essential to give a full global view, which will be needed to understand the connectivity of the ocean, affecting local and regional coastal and ocean health. Global understanding is required to effectively design local conservation and protection of marine ecosystems, in order to maintain the provision of marine ecosystem services, for example carbon sequestration and food provision. Secondly, different regions of the world have developed different approaches for assessing the overall quality of their local waters. Good reasons for such differences almost certainly exist, but knowledge of how to compare the different results would be helpful, particularly in assessing priorities among different areas. Again, all this is needed to achieve for SDG target 14.1 (prevention and reduction of pollution).

Another area with many knowledge gaps is the extent to which people (and, consequently, economies) are suffering from diseases that are either the direct result of inputs of waterborne pathogens or toxic substances, or the indirect result of toxins from algal blooms. This information is relevant for targets in SDG 3 (ensure healthy lives and promote wellbeing for all at all ages) as well as for SDG target 14.7 (increase economic benefits for SIDS and LDCs) for example tourism and recreation, as well as manufactured products, for example construction material or charcoal (GOOS, 2003; GOOS, 2005).

The existing offshore mining industries are very diverse and, consequently, their impacts on the marine environment do not have much in common. Where they occur in the coastal zone, it is important that those responsible for integrated coastal zone management have good information on what is happening, particularly in relation to discharges of tailings and other disturbances of the marine environment (Ramirez-Llodra *et al.*, 2015). As offshore mining expands into deeper waters and areas beyond national jurisdiction, it is indispensable to ensure that information about their impacts on the marine environment is collected and published. Such information supports the successful implementation of SDG target 14.2 (management and protection of marine and coastal ecosystems).

Our knowledge of marine debris has many gaps. Unless we understand better the sources, fates, and impacts of marine debris, we shall not be able to tackle the problems that it raises. Although the monitoring of marine debris is currently carried out in several countries around the world, the protocols used are not aligned, preventing comparisons and the harmonization of data. Because marine debris is so mobile, the result is a significant gap in knowledge. More scientific data are needed to evaluate the impacts of marine debris on coastal and marine species, habitats, economic well-being, human health and safety, and social values. Marine food chains are altered by marine debris, potentially impacting human health. More information on the origin, fate and effects of plastic microparticles and nanoparticles is highly desirable. The Joint Group of Experts on the Scientific Aspects of Marine Protection (GESAMP—an advisory body sponsored by nine United Nations agencies and programmes) has carried out a global assessment of microplastics in the marine environment. Likewise, because of their potential biocidal effects on phytoplankton, there is a gap in knowledge about titanium dioxide nanoparticles when subject to ultraviolet light. All this information is necessary for achieving SDG target 14.1 (prevention and reduction of marine pollution, including marine debris).

Many aspects of integrated coastal zone management are still under development. Those responsible for managing coastal areas need information on, at least, coastal erosion, land reclamation from the sea, changes in sedimentation as a result of coastal works and changes in river regimes (such as damming rivers or increased water abstraction), the ways in which the local ports are working and dredging is taking place and the ways in which tourist activity is developing (and is planned to develop), and the impacts that those developments and plans are likely to have on the local marine ecosystem (and, for that matter, the local terrestrial ecosystems). This information is needed for SDG target 14.2 (management of marine and coastal ecosystems). It will also be important for SDG target 14.7 (economic benefits to SIDS and LDCs), since SIDS and coastal LDCs depend largely on effective use of their coastal zones.

Closing those gaps in our knowledge would amount to an ambitious programme of research. Research is already taking place on many more issues on which more information is desirable (for example, on how the genetic resources of the ocean can be used and what the practical possibilities are for seabed mining). Collaboration and sharing will be important for making the best uses of scarce research resources.

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