Future of the Ocean and its Seas:

a non-governmental scientific perspective on seven marine research issues of G7 interest

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The document "*Future of the Ocean and its Seas: a non-governmental scientific perspective on seven marine research issues of G7 interest*" has been prepared by an *ad hoc* Working Group established by the International Association for the Physical Sciences of the Ocean (IAPSO) of the International Union for Geodesy and Geophysics (IUGG), and the Scientific Committee on Oceanic Research (SCOR) of the International Council for Science (ICSU). The information and advice presented are in response to the Communiqué arising from the Meeting of the G7 Ministers of Science, Berlin, 8-9 October 2015; the issues considered here are those identified at that meeting.

About us:

The International Association for the Physical Sciences of the Oceans (IAPSO) is an IUGG association promoting the study and the interactions taking place at the sea floor, coastal, and atmospheric boundaries by organizing international forums and publishing written materials for ocean scientists throughout the world [iapso.iugg.org]

The International Council for Science (ICSU) is a non-governmental organization with a global membership of national scientific bodies (122 members, representing 142 countries) and international scientific unions (31 members). ICSU mobilises the knowledge and resources of the international scientific community to strengthen international science for the benefit of society. [www.icsu.org]

The International Union of Geodesy and Geophysics (IUGG) is a non-governmental organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change. IUGG composed of eight semi-autonomous scientific associations on cryospheric sciences, geodesy, geomagnetism and aeronomy, hydrological sciences, atmospheric sciences and meteorology, physical sciences of the oceans, seismology, volcanology, and physics/chemistry of the Earth, the Sun, and the planets of the solar system. IUGG encourages the application of this knowledge to societal needs, such as environmental preservation, mitigation of natural hazards, and mineral resources [www.iugg.org]

The Scientific Committee on Oceanic Research (SCOR) is an ICSU interdisciplinary body that develops and coordinates international ocean science activities. SCOR identifies scientific issues that would benefit from enhanced international action, including improvement of methods and the design of critical measurements and experiments. SCOR fosters large-scale research programmes and funds working groups to develop better understanding of fundamental ocean science issues. These may also be applicable to science policy. SCOR represents the views of marine research community to the appropriate intergovernmental science organizations. SCOR co-operates with national and international organizations concerned with scientific aspects of ocean research and inter-related activities [www.scor-int.org]

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Executive summary

Fourteen international experts have considered the marine science issues raised by the G7 Science Ministers at Berlin in October 2015, providing the briefing assessments given in this report. Their work was led by the International Association for the Physical Sciences of the Ocean (IAPSO) and the Scientific Committee on Oceanic Research (SCOR). Conclusions regarding the current scientific understanding of those issues, and recommendations for future action by G7 countries, are summarised below.

i) Cross-cutting issues

The G7 countries have outstanding oceanographic capabilities: they are well-placed not only to continue to provide world leadership in marine environmental research, but also to use the research outcomes for their wider socio-economic benefit.

To further such aims, whilst also addressing the specific issues considered in greater detail here, there is need for strengthened effort in the scientific observation of the status of the global ocean and its seas. Such monitoring needs to improve and integrate the worldwide gathering of information on the on-going changes in ocean physics, chemistry and biology - to determine trends and variability, and assess their causes in a multi-stressor context. New automated and molecular technologies provide new opportunities for such data-gathering; there is also need for associated effort for data management, synthesis and interpretation. A transdisciplinary approach would help provide well-connected actions and solutions to address strategic research problems, maximising the effectiveness of science-policy linkages for marine management.

Many mechanisms already exist to foster international coordination and collaboration in marine science, developed both on a 'top down' (by governments) and 'bottom up' (by researchers) basis. Where relevant to the issues considered here, these existing mechanisms would warrant additional G7 support to accelerate scientific progress and help achieve the sustainable use of marine resources.

ii) Plastic pollution of the marine environment

Plastic items, including microplastics, are now a ubiquitous component of marine litter in the global ocean. Such material damages the environment and national economies, within and beyond the G7 countries; however, we have insufficient knowledge of its distributions, pathways and impacts, particularly for microplastic particles. Solutions to the problem of marine plastic litter exist (mostly on land, rather than at sea), but there is no single solution. Multiple benefits (with regard to resource efficiency, waste reduction and ocean health) can be achieved by product re-design and behavioural changes to ensure less wasteful end-of-life scenarios.

Research needs and G7 actions include appropriate sensors on satellites, autonomous aircraft and *in situ* observing systems, capable of monitoring larger items of floating litter as well as concentrations of smaller items; also harmonisation of relevant methods through inter-laboratory comparisons. Linkage between research centres with expertise in marine litter would benefit from facilitated exchanges and collaborative interactions, both within G7 nations and more widely. Even more rapid advances could be achieved through joint research initiatives, involving researchers, industry and governmental bodies, building on existing networks and frameworks for international collaboration.

iii) Deep-sea mining and its ecosystem impacts

Depletion of land-based mineral deposits and the growing need for rare earth elements in electronic technologies have stimulated commercial interest in deep-sea mining. The main focus to date has been on sulphides, polymetallic modules, cobalt-rich crusts, metal rich muds and marine phosphates, particularly in the Pacific. Extraction and processing technologies are currently being developed, with associated opportunity (and need) to develop appropriate environmental surveys, impact assessments and monitoring. G7 countries are well-placed to take a leadership role in ensuring that exploitation and conservation interests are appropriately balanced, based on sound science, and working with Small Island Developing States.

The key scientific need for the development of deep-sea mining is greater international coordination of research by industry and scientific institutions. Since the deep-sea ecosystem is not well-described, fundamental research on species ranges and ecosystem functioning is required over large spatial scales, and with an intensity in sampling and analyses that can only be achieved by specialist teams in different countries, knowledgeable in deep-sea ecosystems, working together. Capacity building through active engagement with Small Island States in research is required, particularly to train informed policy makers and government officials to regulate activities for the benefit of their nations and the G7 companies who will be working with them.

iv) Ocean acidification

Increasing atmospheric carbon dioxide is not only the main cause of global warming but also ocean acidification: the scale of such future changes in seawater chemistry, and its biogeochemical, ecological and socio-economic consequences, will be determined by the scale of future CO_2 emissions. Calcifying organisms, such as corals and molluscs, show greatest sensitivity to ocean acidification. However, biological responses are variable and interact with other environmental stressors. As a result, effects on marine ecosystems and ecosystem services are still uncertain. Nevertheless, even low emission scenarios seem likely to result in moderate-to-high risks by 2100. Direct mitigation (emission reduction, through implementation of the Paris Agreement) is the most effective way of reducing future impacts; there may also be potential for societal adaptation at the local level.

Additional observations and experimental research will improve model-based projections of future conditions. There is particular need to advance understanding of the many factors affecting the temporal and spatial variability of pH; the complex effects of multi-stressor interactions; and the potential for evolutionary adaptation under different rates of change. Such issues should be considered within a research framework linking chemical change to biological impacts and socio-economic consequences.

v) De-oxygenation

Current climate change is reducing ocean mixing, thereby also reducing the supply of oxygen to mid-depth ocean waters. As a result, the size of areas that already have low oxygen – Oxygen Minimum Zones (OMZs) – is increasing, with important biological and biogeochemical consequences. Oxygen depletion in coastal waters is also increasing in many parts of the world, related to nutrient enrichment. Although some species can tolerate low oxygen levels, most marine life is adversely affected.

Better scientific understanding and monitoring of de-oxygenation and its impacts are required, involving new automated platforms, capacity building and international collaboration and coordination. With the advancement in instrumentation, there are now new opportunities to use automated platforms (e.g. profiling floats and marine gliders) to observe changes in oceanic parameters with much better spatial and temporal resolution. Effort should also be directed at generating data on a regular basis from nearshore regions, where the variability and change are often the most pronounced. The G7 nations should promote such collaboration by pooling resources and assisting network-based coordination, and appropriate capacity building in developing countries.

vi) Ocean warming

The human-driven increase in greenhouse gases in the atmosphere results in the Earth gaining more energy than it is losing – with the ocean absorbing around ten times more extra heat than the atmosphere. The consequent increase in ocean temperature is spatially and temporally variable, particularly in the upper layers; such effects strongly influence decadal-scale climate variation (such as the recent 'global warming hiatus') and extreme weather events. Upper ocean warming reduces vertical mixing (increasing stratification), contributing to midwater de-oxygenation.

Temperature changes in the deep ocean are not easily measured nor fully understood, resulting in uncertainties in model projections of future sea level rise and climate. Additional full-depth monitoring, linked to other ocean measurements (e.g. oxygen and pH) is needed to better understand the processes that control ocean warming and to project its evolution in upcoming decades, under different climate change scenarios.

vii) Biodiversity loss

The ocean supports a very wide range of biological diversity, at genetic, species and habitat levels. Such biodiversity underpins the health of the planet and provides many human benefits. However, our knowledge of marine biodiversity is relatively poor: the majority of species are probably undiscovered. Without careful management, biodiversity loss will endanger some of the most vulnerable marine habitats around the world, as well as bringing high costs to human society. Sustainable development and reduction of greenhouse gas emissions can help to avert ecological problems. Marine protected areas and similar interventions can also help maintain biodiversity and function.

There are many opportunities for G7 nations to improve the coordination of marine biodiversity research, enhance marine protection and support knowledge exchange. These include establishing international working groups to evaluate the effects of ecosystem loss on ecosystem functions and services, and thereby provide policy advice on local to global solutions to address these risks; and promoting a global network of marine protected areas, linking developed and developing countries (from tropical, temperate and polar environments) in order to share lessons learned and best practices.

viii) Marine ecosystem degradation

Marine ecosystem degradation involves the loss of ocean benefits (ecosystem services) to society; it can occur either as a result of natural causes or human activities, such as those considered elsewhere in this report. Some drivers of ecosystem degradation, such as climate change and ocean acidification, are inherently global; others may be local, yet sufficiently widespread to have cumulative global effects. The many components of both kinds of impacts interact, frequently in ways that increase their combined damages and dangers. Significant marine ecosystem degradation began 100-200 years ago; within the past ~50 years it has greatly accelerated, due to economic and technical development, and population growth.

International policy actions, by G7 countries and others, are needed to reduce the drivers of marine degradation, improve marine literacy and develop a global approach to marine conservation. Such actions include: improved assessments of the state of marine ecosystems, through observation strategies that consider biodiversity and ecosystem functioning as well as physico-chemical conditions; identification of the sources of stress (often land-based) and their removal or mitigation; holistic consideration of marine systems for implementation of the ecosystem approach, maritime spatial planning, and integrated coastal zone management; promotion of technological innovation that delivers solutions to marine environmental problems; proper evaluation of (marine) environmental costs and natural capital in cost-benefit analyses to ensure sustainability of human activities; support for international legislation, e.g. through the Paris Agreement, aimed at solving global environmental problems; include ocean literacy in school curricula; and further development of marine protected areas to preserve biodiversity hot spots, while aiming for all marine waters to reach a Good Environmental Status. An overall need is for greater scientific and technical effort, combining well-trained researchers with sophisticated data-gathering and information storage systems, and thereby delivering policy-relevant knowledge and assisting in problem solving.

1. Introductory overview

On behalf of the international community of marine researchers represented through our affiliations, we greatly welcome the attention being given by G7 Ministers of Science to 'the future of the seas and oceans', arising from their meeting in Berlin, 8-9 October 2015. Such a focus is timely and fully appropriate: the G7 nations – Canada, France, Germany, Italy, Japan, UK and USA – not only have direct responsibility for around 40 million km^2 of marine habitat (nearly twice their total land area), but together they produce the overwhelming majority (more than 80%; Jappe, 2007) of oceanographic scientific publications, while also collectively having unrivalled technological capacity and infrastructure, through state-of-the-art research vessels, satellite sensors and autonomous observing platforms.

There is, however, a caveat, as reflected in the title of this document. Whilst there are several named Oceans, there is but one global ocean: a single, interconnected body of seawater that all people and living things share, and depend on. In the same way that we recognise that the Earth has only one atmosphere, delivering worldwide weather and operating as a single dynamic system, any political boundaries drawn on ocean maps will not be recognised by currents, plankton and fish – nor pollution.

Briefing assessments of seven marine issues are given here on: marine plastic litter; deep-sea mining; ocean acidification; de-oxygenation; ocean warming; biodiversity loss; and marine ecosystem degradation. These were the topics identified in Berlin, when discussions were mostly on the first two (as also reflected here). There are, of course, many other environmental concerns relating to the ocean, such as over-fishing, the loss of Arctic sea-ice, sea-level rise, and tsunami risk. In addition, 'blue growth' opportunities, through renewable energy, novel bioresources and maritime technologies, warrant substantive scientific attention to maximise the benefits provided by the ocean as well as minimising impacts. Nevertheless, focus is necessary when resources are limited – and the information provided here justifies the choice of marine plastic litter and deep-sea mining as very high priority topics for G7 coordinated action and research investment, where new knowledge and understanding will be of exceptionally high value.

Three of the other topics – ocean acidification, de-oxygenation and warming – are closely linked, being global-scale ocean perturbations that are all driven, directly or indirectly, by changes in atmospheric composition, primarily the increase in carbon dioxide. Much international policy attention was given to the climatic impacts of greenhouse gas emissions in Paris in December 2015. The outcome was a historic agreement not only to define 'safe' future warming limits (in terms of air temperature increases), but also to 'balance the books' in terms of global emissions and uptake. The ocean plays a crucial role in both regards: in the global carbon cycle (via net CO_2 uptake and release), and by slowing (via mid/deep-water heat uptake) and also potentially increasing (e.g. El Niño events, loss of sea-ice and associated albedo change) the rate of future warming. The real challenge of the Paris Agreement lies ahead, when G7 knowledge and understanding of, and expertise in, ocean behaviour will be needed more than ever to guide energy policy, improve climate projections and safeguard marine ecosystem services.

The two final sections of this document focus on the market goods and non-market services provided by the ocean, by considering marine biodiversity loss and ecosystem degradation. As also provided in other sections, initial bulleted text summarises key research issues, and proposed actions are identified in a G7 context. Aspects covered in the concluding material may seem pessimistic, and the validity of particularly dire prognoses of ocean health requires careful scrutiny (Duarte et al., 2014). Yet, unfortunately, multi-stressor impacts are very real (McCauley et al., 2015). For example, a high proportion of tropical coral reefs are currently experiencing the combination of temperature-driven bleaching, ocean acidification and sea-level rise, as well as, in many localities, over-fishing, increased turbidity and nutrient over-supply. First stabilising, and subsequently reversing, current trends in those stressors will not be easy, but it is achievable – with full implementation of the Paris Agreement, and G7 leadership.

The following common themes emerge from the seven topic-specific briefing assessments:

- *Observations are vital, and current effort is inadequate in many regards*. Large-scale, long-term datasets provide evidence of trends and impacts; they improve understanding of relevant physical, chemical and biological processes; they assist in the design and interpretation of experimental studies; and, they can greatly improve the robustness and reliability of model-based projections. Despite the scientific importance of time series studies (Boero et al., 2014), the continued funding for many ocean monitoring programmes is in jeopardy, and much of the Southern Hemisphere remains not just under-sampled but unsampled.

- *Many new technologies are becoming available to greatly assist integrated data gathering*. The large-scale use of biogeochemical Argo floats to link physico-chemical profiling with biological measurements on a worldwide basis, and molecular techniques, e.g. DNA fingerprinting are examples. The global deployment of such novel sensors and technologies does, however, depend on adequate R&D spending, together with associated effort on inter-comparisons, standard protocols and data management. All those activities benefit greatly from international collaboration and coordination.

- *Interdisciplinarity is essential for policy-relevant science, and transdisciplinarity is preferred*. It is not just 'nice to know' information on ocean temperatures, oxygen and pH levels, marine species' distributions and abundances, or where plastics, carbon or whatever end up in the ocean; such information needs to be purposefully synthesised to help achieve sustainable use of marine resources through scientifically-based marine management. But 'marine management' is arguably a misnomer; it is human activities that may need to be regulated or influenced, rather than the sea itself or its resources. Transdisciplinary research, with built-in connections to socio-economics and stakeholders (Yates et al., 2015) is therefore the way forward. This requires specific encouragement by national research funders, who may themselves be organised into (and separated by) disciplinary silos.

- *Existing international coordination mechanisms should be used wherever possible, rather than re-inventing the wheel.* There are already very many intergovernmental and non-governmental global initiatives to facilitate international marine science (e.g. the Global Ocean Observing System, GOOS and its component bodies, co-sponsored by IOC, UNEP, WMO and ICSU). It would seem preferable for the G7 effort to strengthen, sustain and help lead what has already been established, where that exists, thereby benefitting from lessons already learnt and built-in wider partnerships, to maximise cost-effectiveness and achieve the necessary global coverage in observations and policy implementation.

The subsequent sections of this report summarise our state of understanding of the seven topic areas of G7 interest, and identify policy-relevant knowledge gaps. A more comprehensive analysis of the state of the ocean is provided by the United Nation's World Ocean Assessment (Group of Experts of the Regular Process, 2016). Pollution by plastics is also covered in two recent reports by the UN's Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2015; 2016).

2. Plastic pollution of the marine environment

Key messages

- Plastic items are the most numerous and ubiquitous component of marine litter in the global ocean. Plastic litter is accumulating on shorelines and at the sea surface, in the water column, on the seafloor and within organisms.
- Plastic litter in the ocean substantively damages the environment, national economies and presents concerns for human well-being within and beyond the G7 countries.
- Although some items of litter are highly visible, quantitative research on the scale of the problem is lacking. Collaborative, international research is needed to improve knowledge of distributions, pathways and impacts, particularly for microplastic particles.
- Global observing systems (both remote and *in situ*) need to be developed with standardized protocols for monitoring; these would provide a focus for remedial action and also provide information on the effectiveness of control measures.
- Solutions exist, but there is no single solution. Addressing the problem requires transdisciplinary research spanning, but not limited to, environmental and social sciences, health and business. Effective solutions require scientific advancement to underpin them and to project into the future.
- Multiple benefits (with regard to resource efficiency, waste reduction and ocean health) can be achieved by product re-design and behavioural changes to ensure less wasteful end-of-life scenarios.

The issue

In terms of numerical abundance plastic items represent around 75% of the marine litter recorded on shorelines worldwide with smaller quantities of glass, metal and paper. Plastics (synthetic polymers, including polyethylene, polyester and polystyrene) are a product of scientific progress and economic development, improving the quality of life in numerous ways. However, to maximise the overall benefits that plastics can bring, it is essential to address the environmental side-effects associated with their production, consumption and disposal. Globally, around 300 million tonnes of plastics are produced each year. As a consequence of their low-cost and high durability, substantial quantities of end-of-life plastics are accumulating in the environment (Thompson et al., 2009; Law et al., 2010; UNEP, 2014a). Around 40% of all the plastic items produced are single use; such items are rapidly discarded and account for much of the waste in managed systems and the litter found in the environment.

Plastic litter contaminates marine habitats from the poles to the equator, and from shorelines to the deep sea (Barnes et al., 2009) (Fig. 2.1). Its distribution is not uniform, and it can be transported to locations far from its point of entry, including relatively pristine Arctic habitats (e.g. Obbard et al., 2014). Plastic pollution in the ocean is therefore a transboundary issue that must be addressed by global research and global policy action.

Figure 2.1 Debris on Kamilo beach, Hawaii (left; photo credit: IPRC) and collected from a beach in Peru (below; photo: P Williamson)

Marine plastic litter can persist for decades. However, in the absence of established protocols for long-term monitoring, trends in abundance are not well-documented. The deep sea may provide a long-term ‘sink’ where considerable quantities of plastics accumulate after fouling reduces their buoyancy (Woodall et al., 2014). The ocean floor also accumulates other, non-plastic materials (glass, metal, etc.). While absolute quantities are not known for certain, there could already be more than 50 million tonnes of plastic in the ocean, a figure that could triple over the next decade assuming a ‘business as usual’ scenario (Jambeck et al., 2015). Only around 1% of the current total is estimated to be floating at the ocean surface (van Sebille et al., 2015). An even smaller fraction of that total is potentially removable by coastal clean-ups, which necessarily focus on easily-visible items.

The larger items of marine plastic litter are unsightly, having negative effects on tourism; they also present a hazard to mariners, and considerable expense is invested in their removal from ports and shorelines. Associated losses and costs may exceed US $13 billion per year (UNEP, 2014b). Marine litter is hazardous to wildlife causing injury and mortality as a consequence of entanglement and ingestion. Around 700 species are known to encounter marine litter, with plastic items accounting for over 90% of these encounters (Gall & Thompson, 2015). Discarded rope and netting are especially hazardous for seabirds, turtles and fish, with the scale of such 'ghost fishing’ estimated to be between 0.5-3% (by weight) of commercial catches (Brown & Macfadyen, 2007).

Of increasing concern is the accumulation of very small pieces of plastic litter (<5mm in diameter) known as microplastics (Fig. 2.2). These can occur in high abundances at the sea surface, in the water column and on the sea bed (including the deep sea), as well as in marine organisms. They arise from the fragmentation of larger items and the direct release of small particles, for example particles included as microbeads in cosmetic products (Napper et al., 2015). A high proportion of some populations of marine organisms, including those caught for human consumption, have microplastics in their digestive tract. There are concerns that ingestion of microplastic by marine organisms could lead to toxicological harm, either as a consequence of the transfer of persistent contaminants from sea water (Rochman et al., 2013; Teuten et al., 2009), or the release of chemicals that were incorporated during manufacture, e.g. plasticisers, flame retardants and anti-microbials (Rochman & Browne, 2013). However, the relative importance of plastics as a vector for the transport of chemicals to wildlife may be small compared to other pathways (Koelmans et al., 2013). Microplastics have also been shown to have physical effects on marine life with ingestion of relatively small quantities of microplastics compromising the ability of invertebrates to store energy (Wright et al., 2013). Higher concentrations may affect feeding and reproduction (Sussarellu et al., 2016).

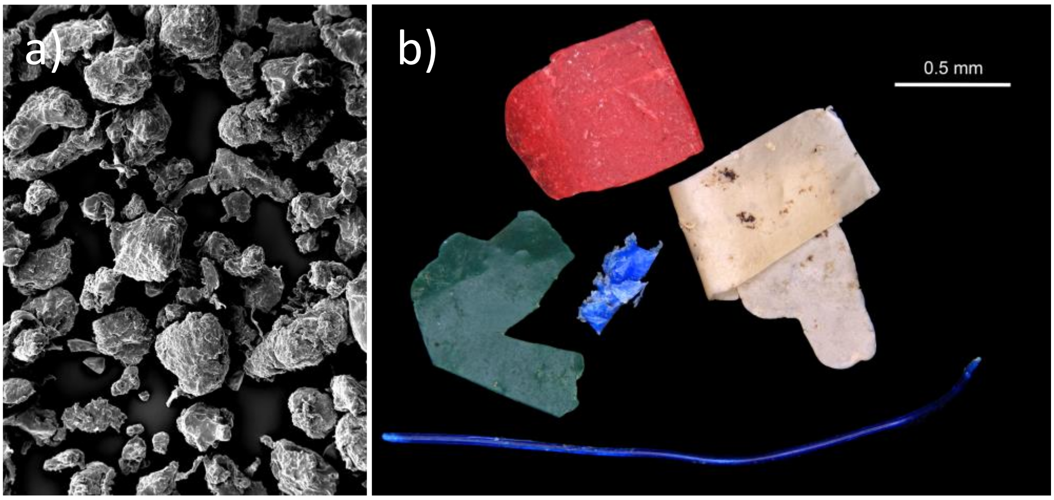

Figure 2.2 Microplastics a) particles from a cosmetic product (Source: Napper & Thompson, Plymouth Univ Electron Microscopy Suite), b) fragments of microplastics collected from a shoreline near to Plymouth, UK (Source: Thompson, Plymouth Univ). Scale bar applies to both pictures

Plastic waste, including microplastics, enters the ocean through many pathways. These include direct release by users of the sea or coast, for example in transport, fishing or recreation. Plastic litter is also widely distributed in freshwater habitats (Eerkes-Medrano et al., 2015), with transport by rivers over substantial land distances providing a major source to the ocean. Hence, the marine plastic pollution problem needs to be studied, and controlled, in a framework involving all sources and activities, not just those located in the sea or on the coast.

Framework for policy action

Policy-led action and coordination need to involve a combination of voluntary actions, incentives, taxes, regulation, enforcement and education (STAP, 2011). Key actions are discussed below. However, to achieve policy changes as efficiently and rapidly as possible, scientific advances are also imperative. This science is still in its infancy, since the scale of the problem was not fully recognised until plastic litter had spread throughout the global ocean. Specific scientific priorities are identified in the next section, with the overall aim being to create a working model of litter dynamics in the marine environment that can lead to impacts, as well as more complete understanding of the underlying causes that lie on land – and that are linked to inappropriate design, production, use or disposal of the items that become marine litter. In order to inform appropriate policy to resolve the problem, the underlying causes must be addressed. It is therefore essential to understand associated interactions between industry, society and policy, both on land and at sea.

When considering potential policy interventions to reduce the quantity of plastic litter three overarching factors should be taken into account:

- From the perspective of sustainable use of resources, around 8% of world oil production is used to make plastic items, yet around 40% of these items are discarded within a short time frame. By recycling greater quantities of end-of-life plastic it would be possible to reduce the accumulation of litter and at the same time reduce our demand for fossil carbon. Hence, marine litter is a symptom of an inefficient and outdated business model.
- Plastic items are important to society; however, unlike many other environmental challenges, the emission, in this case of litter to the ocean, is decoupled from the societal benefits that are realised from plastics items before they become litter. So it is feasible to have the benefits of plastic items, without the substantial accumulation of plastics as litter.

- While there may be discussion and sometimes disagreement about the relative importance of the various impacts, there is public and policy consensus, at a local, national and international level, regarding the need to reduce inputs of litter to the ocean.

The problems that retard progress relate to prioritising and implementing solutions: who should take the action and, if there are costs, who should pay? Most of the solutions themselves are relatively well known, as summarised in Table 2.1; most lie on land rather than at sea.

Table 2.1	Summary of policy solutions to the problem of marine plastic pollution
1. Understand the problem	Science-based understanding of the scale of the problem and the impacts is crucial; also monitoring to assess the effectiveness of remedial measures. For details see 'Research priorities' in text.
2. Reduce production and usage	Reduction in the amount of new plastic produced will reduce the quantity of end-of-life material that results. Reduction in usage is particularly important for single-use applications.
3. Re-use	Product re-use will directly reduce the need for new plastic items and so also reduce the quantity of end-of-life material.
4. Proper disposal	End-of-life items need to be disposed of in a way that will not cause pollution - wherever possible by recycling (below).
5. Re-cycle	Turning end-of-life material back into new items in a closed loop or circular economy will reduce the accumulation of waste and simultaneously reduce demand for fossil carbon. This action is overarching: it encompasses 2, 3 and 4 (above), and also requires 7, 8 and 9 (below)
6. Energy recovery	The incineration of plastic waste (that cannot be re-used or recycled) provides energy, but should be considered as a substantially poorer alternative to 2-5 above. There are also concerns about harmful effects from associated emissions.
7. Re-design	The design stage of every plastic product must consider the hierarchy of options 2-6 above in order to minimise the overall environmental footprint
8. Education and behavioural change	Concern for the health of the marine environment needs to be directed not only at discouraging individual littering, on land as well as at sea, but also at achieving the wider cultural change of re-using and re-cycling, within the wider philosophy of designing products that are compatible with a circular economy. Hence, education and behavioural change are needed along the entire supply chain.
9. Regulation and enforcement	International regulation of at-sea waste disposal is extensive (e.g. by the London Convention/London Protocol, OSPAR, MARPOL and UNCLOS), as are European marine pollution controls. However, at-sea enforcement is not straightforward. There is scope for both stronger on-land regulation and enforcement in G7 countries and elsewhere.
10. Clean-up	Whilst the priority must be to stop the flow of debris to the ocean, clean-up can help to reduce the quantities of litter in accessible locations, e.g. shorelines. It can also help raise awareness of the problem. However, it is important to recognise that clean-up is not itself a sufficient longterm solution.

There are also policy actions that could compromise the solutions outlined above. For example, the use of bio-based carbon from plants grown in agriculture is seen as a sustainable alternative to fossil carbon. However, altering the carbon source used to make plastics will not reduce the generation of waste nor the accumulation of marine litter; a more efficient solution is to supply the required carbon by recycling. Designing plastic products so that they degrade or disintegrate more rapidly may reduce the long-term accumulation of large items of debris; however, such products can compromise the potential for product re-use, contaminate recycling, shorten useful life, and accelerate the production of microplastic fragments (Thompson et al., 2009).

The need to re-educate so as to change behaviours warrants emphasis. For the last 60 years we have lived in a world of rapidly increasing production of disposable short term products and packaging, and of durable goods that cannot be repaired or renewed. In short we are currently in a growing culture of throw-away living; there is an urgent need to recognise there is no such place as '*away*'. There is considerable public interest and concern about litter in the ocean. However, there is less interest in, and engagement with, solutions that predominantly lie on land. What is needed is education that not only harnesses societal interest in the problem of litter at sea, but also focuses that interest to achieve the necessary solutions on land. Education and behavioural change should not be limited to the general public as consumers; it is essential along the entire supply chain. Current approaches for the design, production, use and disposal of plastics represent an outdated business model that is not sustainable. Hence education needs to focus on a new way of doing things; from product design through to end of life.

Research priorities

As identified above, a better understanding of the problem – through strategic research delivering new knowledge – is of fundamental importance to the control of marine plastic litter. Scientific research can also provide more direct support for relevant policy decisions. Specific topics in those two areas are identified below (Table 2.2), with a focus on plastic litter. However, the wider marine litter problem is also important, and much of the proposed research should take account of other debris within a wider pollution-control context.

Table 2.2 Research priorities for marine plastic litter

A. Defining the extent of the problem:

- **Understand the sources**: quantitative assessment of the sources: direct, indirect, point and diffuse.
- **Understand the pathways**: establish connections between sources and sinks for different types of debris, and how these are influenced by oceanic and atmospheric dynamics.
- **Understand the rates of degradation**: the lifecycle and timescale for marine litter from point of entry, via fragmentation to mineralisation; including biological and chemical interactions (e.g. release of chemical additives).
- **Understand the sinks**, including accumulation in remote locations, fragmentation, suspension in the water column and sedimentation.
- **Quantify the impacts** of plastic litter and develop a risk assessment framework to predict potential harm for wildlife (individuals, populations, assemblages), for human health and economic consequences, both now and in the future.
- **Design and build effective observing systems** to monitor marine litter. For example to track larger objects from accidents and natural disasters and to map spatial and temporal accumulations of micro-litter.

B. Science support for policy decisions:

Scientific justifications, recommendations and projections as well as technological innovations, are needed to optimize our use of resources and reduce the risk of side-effects such as the generation of waste. Science support for policy decisions includes but is not limited to:

- **Prioritization of measures according to sources and impacts** of marine litter and comparison between scenarios (similar to dependence of global warming on greenhouse gas emissions).
- **Reducing inputs** by developing better understanding of how and why some items escape waste management and move to the ocean.
- **Optimization by considering alternative scenarios for product design to reduce waste and litter,** reviewing feasibility and long-term efficacy of design for material reduction, reuse, recycling, combustion or storage.
- **Biodegradable materials**: assessment and labelling to indicate appropriate and inappropriate usage.
- **Changing behavior:** better understanding along the supply and usage chain of perceptions relating to waste generation, versus circularity of material usage.
- **Education:** develop better understanding of the appropriate points for intervention to facilitate change.
- **Optimization of economic and political measures:** to increase the value of waste and thereby help prevent waste becoming litter. Promote by enforcement, taxes, investments, incentives and education.
- **Quantify microplastics in seafood:** determine concerns for human health, as well perceptions that might affect marketability.

Integration of new (and existing) information is crucial, within a framework model of marine litter dynamics. Such a model could provide a testbed for simulations of the effects (and side-effects) of proposed measures, and could develop an efficient observing system to monitor changes in marine litter. Measures to be optimized and monitored include recycling before items can become litter, product design, and educating the general public in order to achieve an overall reduction in the sources and underlying causes of marine litter.

Whilst G7 countries might individually wish to focus their national funding on only a subset of the research issues identified in Table 2, maximum cost effectiveness and added value would be achieved by an international framework programme, preferably involving both G7 and non-G7 partners. Mechanisms to facilitate G7 collaboration and coordination are discussed further in the next section.

Proposed G7 actions

The G7 nations have excellent facilities for remote observation of the ocean surface: from space via satellites (NASA and ESA), from aircraft (e.g. NERC facilities in the UK) and from ships [EU Joint Research Centre; US University-National Oceanographic Laboratory System (UNOLS); and Japan). New technologies and new missions are needed to include appropriate sensors on orbital, suborbital and *in situ* observing systems, capable of monitoring larger items of floating litter as well as concentrations of smaller items, both remotely and, for example, by high-throughput analysis of water samples from ships.

For more direct analyses, several G7 nations have excellent facilities for microplastic identification, characterisation and monitoring (e.g. via Raman and FT-IR spectroscopy). These provide opportunities for harmonisation of protocols, and quality assurance and quality control through inter-laboratory comparisons. There are currently major gaps in global observational coverage (Fig. 2.3), particularly in the deep-ocean and in/under sea ice where capabilities for marine litter monitoring have yet to be developed. New opportunities may be related to the fast-developing aerial drone and sea-glider technologies.

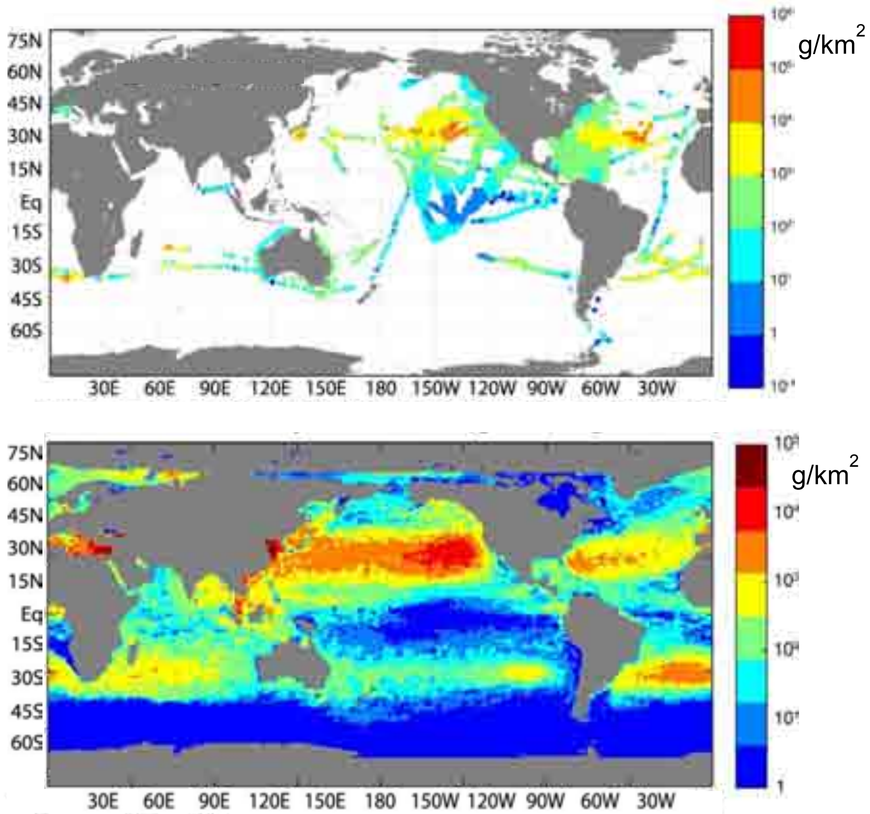

Figure 2.3 Distribution of microplastic mass in the surface ocean (g/km^2, $\log_{10}$ scale).

Upper panel, observations; lower panel, modelled data. Note that different models may give slightly different distributions, but all show the same general patterns. From: van Sebillet et al (2015)

The power of computers continues to grow exponentially and has already reached the level where data storage and processing of the trillions of marine litter items with numerous intrinsic characteristics is technically feasible.

Sustainable funding is critical for successful scientific research on marine litter. Several research centres are currently establishing expertise and facilities for the scientific investigation of marine litter. Such studies would greatly benefit from facilitated exchanges and collaborative interactions within G7 nations, and more widely, as follows:

- Short international collaborative exchanges, with funding to support: travel, accommodation, and some basic research needs. These would facilitate cross fertilisation of ideas, proof of concept, and pump priming for future research.
- Longer term sabbatical exchanges for research collaborations, with funding to support: travel, accommodation, and more extensive research consumables and facilities (e.g. ship time).
- Support for transdisciplinary collaboration is essential to address the problem of marine litter. This is especially important where national, competitive research funding is constrained to single-discipline areas, as occurs in many countries.
- Bridging of grants to facilitate interactions between existing funded projects. To support collaboration between nations and/or disciplines where added value on the topic of marine litter can be gained from some additional collaboration (e.g., 6 months additional funding for existing post-doctoral researchers to work between institutions).
- Mechanisms to support international exchanges of PhD students working on marine litter.
- In the longer term, alignment of funding deadlines between G7 nations and/or developing models for co-funded international projects. There are precedents (e.g. the US/NSF's Partnerships for International Research and Education (PIRE) program), but the application and award process can be logistically difficult.
- Creation of new courses and specializations, resulting in the graduation of well-informed students to address problems in the marine litter field.

Within G7 nations, no single government department or funding agency is likely to possess full jurisdiction over marine litter research (that would probably be undesirable anyway). Relevant agencies should therefore support research on corresponding pieces of the puzzle: for example, space agencies should facilitate invention of new technologies and their application to the remote monitoring of marine litter. A wide range of research areas is identified in Tables 2.1 and 2.2, with many benefitting from the involvement of academic researchers, industry and governmental bodies. Such joint initiatives require co-planning as well as co-delivery, in order to be carried forward in a joined-up way. In particular, to achieve multi-disciplinary research, multi-year agreements are required between different funding bodies. Adequate research funding is necessary to secure the scientific support of the wider framework provided by relevant intergovernmental legislation, agreements and partnerships, at both the global and regional level (e.g. through UNCLOS, London Protocol/London Convention, IOC/UNESCO, OSPAR, ICES, and PICES) as well as by non-governmental bodies that promote scientific collaborations relevant to marine environmental health (e.g. ICSU, SCOR, SCAR and Future Earth).

3. Deep-sea mining and its ecosystem impacts

Key messages

- Commercial interest in deep-sea mining is increasing, relating to the future exploitation of seafloor massive sulphides, polymetallic nodules, cobalt-rich crusts, metal rich muds and marine phosphates.
- Extraction and processing technologies are being developed. New technologies for surveying and monitoring are required.
- The environmental impacts of deep-sea mining could be significant, including physical disturbance, the creation of suspended sediment plumes, water mixing effects, and the impacts of mining ships and other infrastructure.
- Standard protocols are needed for environmental impact assessments, based on coordinated research and information-sharing at regional and global scales.
- G7 countries are well-placed to take a leadership role in balancing exploitation and conservation interests, based on sound science, and working with Small Island Developing States.

Introduction

The growing demand for advanced and green technologies in daily life is fuelling a steady increase in the need for metals. Knowledge-based economies require a wide variety of 'technology metals' for innovative goods and export markets. To date, mineral deposits on land have been adequate to meet demand; however, easily accessible, high-grade deposits are becoming scarce. Securing a greater choice and stable supply of metals may keep metal prices down. Can G7 industries afford to ignore two-thirds of the planet in the quest for raw materials?

A major constraint, and hence risk, especially for obtaining financial backing, is the lack of detailed knowledge of the deep ocean environment (European Commission, 2014). Enterprises are concerned that environmental 'show-stoppers' may become apparent only after considerable investments have been made, or that poor knowledge and environmental practice by early movers might influence the 'societal licence to operate' for the mining sector as a whole. This includes not only international waters (Areas Beyond National Jurisdiction) but also the Exclusive Economic Zones (EEZs) of individual States, notably Pacific Island States, and the overseas territories of a number of G7 countries. Issues relating to deep-sea mining are truly global.

There are five main types of oceanic mineral deposits (Table 3.1. The pace towards their exploitation is accelerating (Secretariat of the Pacific Community, 2013). Mining is planned within the EEZ of Papua New Guinea in 2018 by a Canadian exploration company. Mining tests within the EEZ of Japan may start on a similar timescale. A site in the Red Sea has received an exploitation licence from Sudan and Saudi Arabia. The International Seabed Authority has awarded (or has pending) 27 licences for the exploration of marine minerals in international waters. Of the G7 countries, licences are held by France (2), Germany (2), Japan (2) and the United Kingdom (2), with interests also from Canada, the United States and the wider

Table 3.1. The five main types of oceanic mineral deposits.

	Seafloor massive sulphides	Polymetallic nodules	Cobalt-rich crusts	Metal rich muds	Marine phosphates
Occurrence	Mid-ocean ridges, and other areas of hydro-thermal activity	Deep ocean basins on abyssal sediments	Summit and slopes of seamounts as well as flanks of volcanic islands	Red Sea brines	Continental margins, banks and seamounts
Form	Massive sulphide and oxide deposits on the seafloor and sub-seabed	Potato sized nodules and encrustations	Thin (<25cm) encrustation on rock surfaces	Viscous metalliferous sludge under deep-sea dense brines	Limestone and gravels
Water depth (m)	1,000 – 5,000 m	4,000 – 6,500 m	800 – 2,500 m	1,000-2,000 m	0 to 1,000 m
Thickness	10s of metres	Top 10 cm	Patchy, up to 25 cm	30 m	Varies. New Zealand gravels 1 m thick
Extent	100s of m^2	1,000s of km^2	10s of km^2	10s of km^2	1,000 km^2
Major minerals	Copper, lead, zinc	Manganese, iron	Manganese, iron	Zinc, copper, manganese	Rock phosphate
Minor minerals	Gold, silver	Nickel, copper, cobalt, rare Earth elements (REE) technology metals)	Nickel, cobalt, platinum, tellurium, REE technology metals	Silver, gold	
Suitability for mining	Currently only c. 10 individual deposits of sufficient size and grade. Multiple small deposits may be grouped to mine..	Lying on sediment surface. Comparatively easy to collect.	West Pacific guyots and South Atlantic banks of interest. Most seamounts unsuitable.	Environmental concerns of toxic metals disturbed in an enclosed sea.	Exploitation licence for New Zealand phosphates rejected on environmental grounds in 2015

Figure 3.1 An example of a seafloor sulphide deposit: the Jabberwocky edifice, a mineral-rich hydrothermal vent chimney about 5m high and at depth of 2757m in an area of the South West Indian Ocean Ridge. Image ©University of Southampton; also see https://www.youtube.com/watch?v=y6iK19xaYJg

European Union. Exploration licences have been granted or are being sought within the EEZs of the Cook Islands, Fiji, New Zealand, Papua New Guinea, Portugal (The Azores), Solomon Islands, Tonga, and Vanuatu (International Seabed Authority, 2015).

As an example of the scale and potential of deep sea minerals, the Clarion-Clipperton Zone, an area covering about 4.5 million km^2 between the coast of Mexico and Hawaii (Fig 3.2), is estimated to contain copper to the equivalent of about 20 per cent of the global land-based reserves.

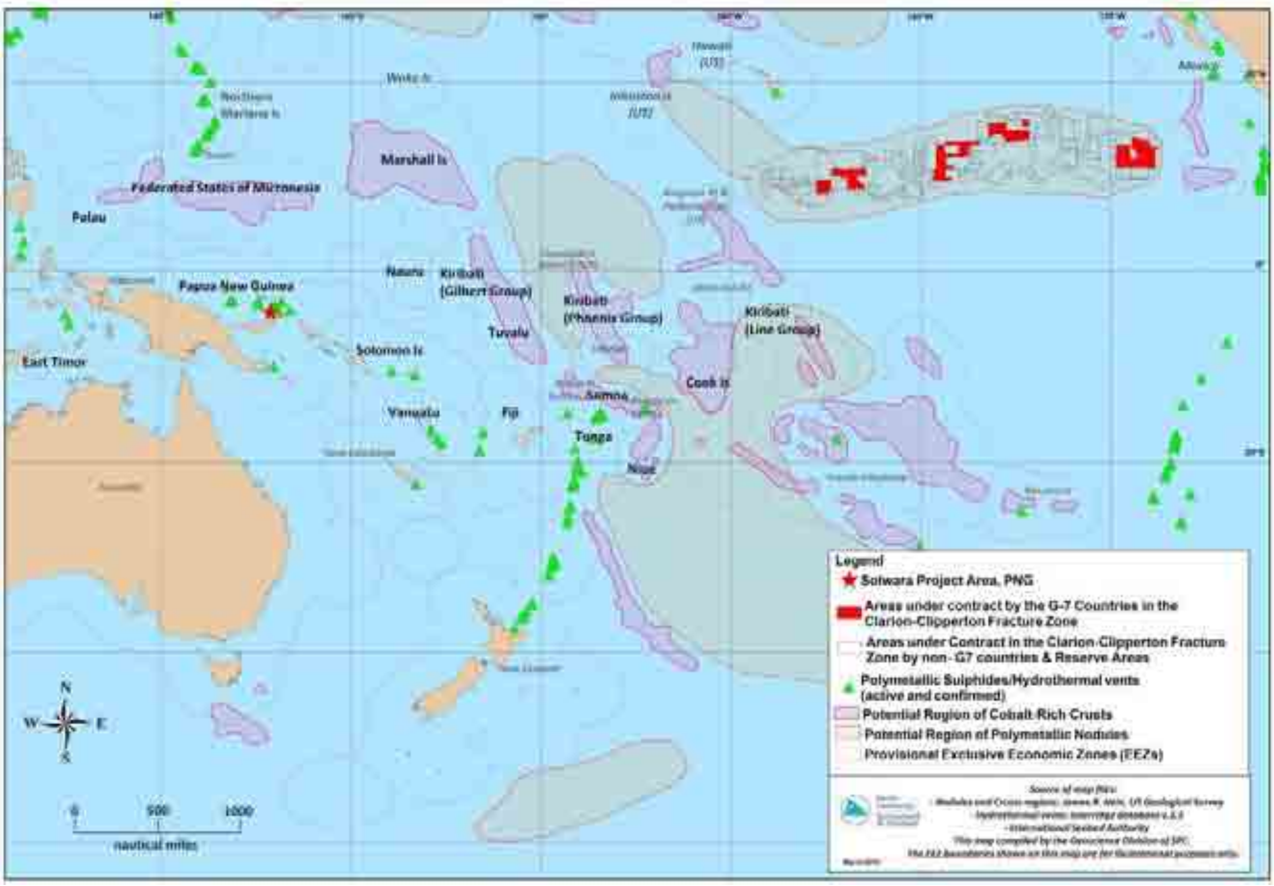

Figure 3.2 Areas of potential deep sea minerals (seafloor massive sulphides, cobalt-rich crusts and manganese nodules) in the central/south Pacific, showing G7 contract areas in the Clarion Clipperton Zone and the Solwara 1 Project (Canada) in Papua New Guinea.

Technology states of readiness

Technologies for exploring and sampling in the deep ocean (e.g. multibeam sonar, cameras, corers and *in situ* seabed drills) are fairly well developed. Modern technologies, such as Autonomous Underwater Vehicles and Remotely Operated Vehicles are transforming seabed surveying techniques, particularly in areas with rough terrain. New advanced methods and technologies will be needed for environmental monitoring including environmental DNA, precision sampling, the collection and transfer of organisms under pressure, and high-resolution photographic and video surveys. Currently, only few G7 countries have access to such specialised systems. A focus on robotic technologies and molecular techniques is required.

Technologies for extraction operations such as seabed cutters (for sulphides) and collectors (for nodules, phosphates and muds) are at advanced stages of development; systems for the mining of seafloor massive sulphides off Papua New Guinea have been built. For the lifting system, various concepts are being studied, including adapting oil and gas vertical riser pipes. It is unlikely that the ore will be processed at sea; instead, the recovered ore will be dewatered and shipped to a land-based facility for concentrating.

Processing technologies are generally well known; however, mineral composition differences – and the desire to recover a wide variety of metals from the same resource – may require the development of advanced separation techniques. Science and industries in G7 countries are in an ideal position to capitalise on these technologies.

Potential environmental impacts of deep sea mining

The different mineral deposits are associated with different ecosystems, each with unique characteristics and fauna. There are four main sources of potential impact common to all deep-sea mining activities:

- Physical impacts on the seabed from cutting/grinding/collecting machines, which disturb or remove biota and habitat
- Suspended sediment plumes from operations at the seabed, which could smother and clog surrounding benthic and pelagic biota
- Transport of large volumes of cold, nutrient-rich water to the sea surface requiring subsequent discharge and thereby creating a plume laden with very fine particles and dissolved metals
- Sound, noise, vibration and lights from machinery and vessels which could affect biota.

These impacts will vary in scale and effect depending on each type of deposit and technology used to recover the ore. For instance, a polymetallic nodule mine could disturb physically and directly about 300 km^2 of seabed per mine per year (about the size of a large town or a Pacific island). An additional equivalent or greater area may be impacted by operational sediment plumes per mine per year, depending on the mining technologies used. In contrast, a large seafloor massive sulphide mine might disturb less than 1 km^2 over 20 years. However, a seafloor massive sulphide mine may cause additional pollution from disturbed toxic metals, such as cadmium and antimony, depending on the minerals contained in the deposit and if acidic conditions are created during their recovery.

To date only one publically available environmental impact assessment has been completed for a deep sea mine site (Nautilus Minerals, 2008).

Most deep-sea ecosystems take a very long time to recover from impacts. This is because most species in the deep ocean have very long generation times. Black corals on the mid Atlantic Ridge have been dated to be as old as 2,300 years. In manganese nodule environments, once the nodules have been removed they, and the fauna that lives attached to them, will not be replaced on human timescales. Compacted tracks from polymetallic nodule test mining operations made 35 years ago on the Eastern Pacific abyssal plain show little sign of recovery in either faunal diversity or ecosystem functioning. Therefore, deep sea communities are particularly sensitive to physical impacts, such as bottom trawling and mining.

A notable exception are some seafloor massive sulphides where particular conditions (such as actively venting hydrothermal activity) could lead to faster biological recovery rates on time scales of tens of years, due to the specific vent biota's dispersal and recruitment capabilities and their adaptations to frequent and intense natural disturbances.

The effects of deep-sea mining on other sea uses (such as fisheries, tourism, submarine cabling, bio-prospecting and marine scientific research) is limited; it is thought that, with appropriate management, such interactions will be minimal. Geographical separation of activities will minimise potential cumulative effects of multi-sector impacts.

As deep-sea mining develops, it will be necessary to monitor environmental impacts effectively. As deep-sea mining activities will, for the most part, be carried out in remote locations, which may make independent observation difficult, transparency will be a key consideration in developing monitoring approaches and sharing available data and information. It will be important to define tools which would allow comparing and rating the extent of impacts of different mining operations.

Knowledge and environmental management

Scientific knowledge has been generated on the physical attributes of deep-sea minerals. However, there remain significant gaps in the understanding of large-scale distributions of fauna, ecosystem structure, ecosystem functioning, connectivity and resilience. The great depths, remote localities and inhospitable geomorphology of deep-sea environments have made them difficult to study; however, new technologies are transforming the pace and quality of data gathering. Far greater sampling effort is required to generate meaningful results. This can be achieved only by coordinating research at regional and global scales in a coordinated and standardised manner. The International Seabed Authority has recognised the need for developing standards and protocols for environmental impact assessments in the deep ocean, particularly in relation to biological studies. However, the Authority does not have the structure or funding to compel the standardisation and collection of data.

The social acceptability of large-scale, long-term impacts is unknown. There is a trend evident in recent years of internet campaigning mobilising massive public concern on environmental issues. Socio-economic studies are required in different cultures to assess social attitudes to deep-sea mining, in order to strike the right balance between the exploitation of ocean resources and the conservation of biodiversity.

Proposed G7 actions

The key to answering many of the fundamental scientific questions facing the development of deep-sea mining is greater international coordination of scientific research by industry and scientific institutions, especially within G7 and affiliated countries.

Fundamental research on species ranges and ecosystem functioning is required over large spatial scales, and with an intensity in sampling and analyses that can only be achieved by specialist teams in different countries, knowledgeable in deep-sea ecosystems, working together. Many mineral resources occur within the EEZs of developing Island States. Capacity building through active engagement of those States in research is required, particularly to train informed policy makers and government officials to regulate activities for the benefit of their nations and the G7 companies who will be working with them.

Technological developments of deep-sea submergence and robotic monitoring systems are required.

4. Ocean acidification

Key messages

- Ocean acidification is mainly driven by increasing atmospheric carbon dioxide (CO_2). The scale of future ocean acidification, and its biogeochemical, ecological and socio-economic impacts, will be determined by the scale of future CO_2 emissions.
- Calcifying organisms, such as corals and molluscs, show greatest sensitivity to ocean acidification.
- Wider biological responses are variable and interact with other factors: effects on marine ecosystems and ecosystem services are therefore uncertain. Nevertheless, even low emission scenarios seem likely to result in moderate-to-high risks by 2100.
- Direct mitigation (emission reduction) is the most effective way of reducing future impacts; there may also be potential for societal adaptation at the local level.
- Additional observations and research will improve model-based projections of future conditions.

What is ocean acidification?

The ocean is beginning to face a serious threat—its basic chemistry is changing because of the uptake of carbon dioxide (CO_2) released by human activities. The human-generated CO_2 emissions since about 1850 have not only caused warming of the ocean and atmosphere, but have also altered seawater chemistry through a process known as ocean acidification. This involves a fall in pH (increase in hydrogen ion concentration, a measure of acidity) as well as other chemical changes. Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur may all exacerbate ocean acidification locally.

Chemistry and projections

Ocean acidification is driven by the global ocean absorbing ~ 26% of the CO_2 released into the atmosphere by the burning of fossil fuels and land-use changes (Wanninkhof et al., 2013) – an uptake of around 30 million tonnes per day. As a result, the pH of open-ocean surface water has decreased by ~ 0.11 units since the beginning of the industrial era, corresponding to a 30% increase in seawater acidity. By the end of this century a business-as-usual scenario (Representative Concentration Pathway, RCP 8.5 of the Intergovernmental Panel on Climate Change, IPCC) would decrease surface ocean pH by another 0.4 units (or a tripling of its acidity), making it lower than it has been for more than for at least 20 million years (Fig. 4.1).

Recent international decisions through the UN Framework Convention on Climate Change (UNFCCC) should, however, reduce both future global warming and ocean acidification. Thus the goal of the Paris Agreement is to hold "*the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*…". That goal would – by constraining CO_2 emissions – also limit the future pH fall to less than 0.1 units, closely similar to IPCC scenario RCP 2.6. Current indicative national contributions towards this goal do not yet achieve those aims: they would result in further acidification at values projected between RCPs 4.5 and 6.0 (Fig. 4.1).

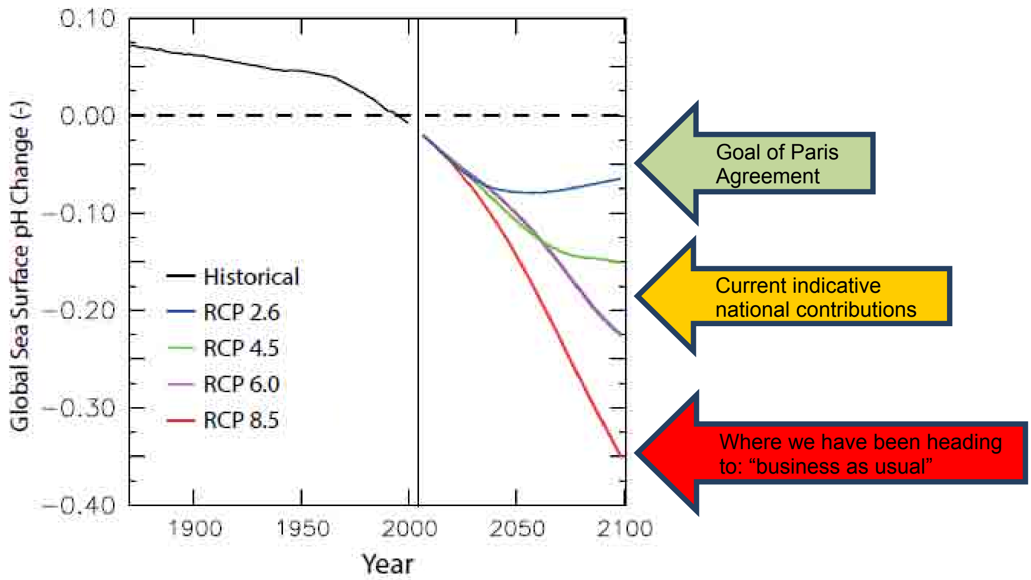

Figure 4.1 Model-based hindcasts and projections of global sea surface pH change over 1870-2100, with projections based on IPCC Representative Concentration Pathways (RCPs) and related to outcomes of the Paris Agreement. All changes are relative to 1990-1999. After Bopp et al. (2013).

Biological and ecological impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, with most studies carried out in the past 5-10 years. A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms (Fig 4.2), with a trend for greater sensitivity in early life stages.

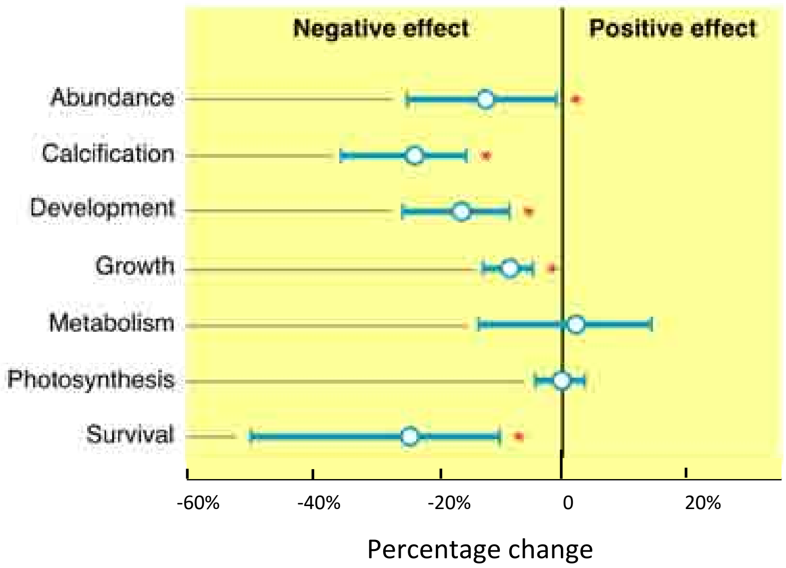

Figure 4.2 Effect of potential future acidification (0.5 pH decrease) on key biological and ecological processes, based on meta-analysis of 228 experimental studies on a wide range of marine organisms (after Kroeker et al., 2013). * denotes a statistically significant effect.

Most, but not all, marine calcifiers such as corals, coralline algae, bivalves and gastropods, are negatively affected by ocean acidification, reducing their competitiveness with non-calcifiers. In parts of the ocean with naturally low pH (upwelling areas, polar regions and in mid/deep water), ocean acidification can result in the net dissolution of carbonate structures (e.g. coldwater coral reefs) and loss of associated habitat. However, positive as well as negative impacts can occur, and biological responses can be influenced (often exacerbated) by other drivers, such as warming, hypoxia (low oxygen), food and nutrient availability, light levels and metal pollution. As a result, many uncertainties remain in our understanding of the impacts of ocean acidification on organisms, life histories, and ecosystems (Gattuso et al., 2014; CBD, 2015).

Studies of the geological past indicate that mass extinctions in Earth history have previously occurred during periods of much slower rates of ocean acidification. Whilst other drivers were also changing then (as now), such findings suggest that evolution rates are unlikely to be fast enough for sensitive animals and plants to adapt to the projected rate of future change.

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution would change predator–prey relationships and competitive interactions, with effects on food webs and higher trophic levels . Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity of communities. Shifts in community structure have also been documented in regions with rapidly declining pH.

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood. This represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not yet well-investigated.

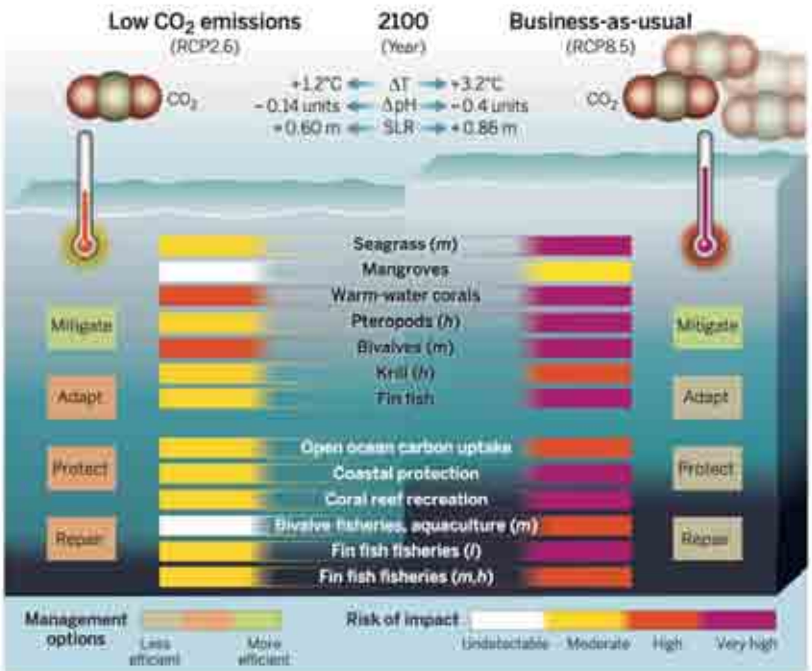

Figure 4.3 Changes in ocean physics and chemistry and impacts on organisms and ecosystem services according to stringent (RCP 2.6) and high business-as-usual (RCP 8.5) CO_2 emissions scenarios (Gattuso et al., 2015).

Risks and socio-economic impacts

Key marine organisms and ecosystem services face contrasting risks from the combined effects of ocean acidification, warming, and sea level rise (Fig 4.3). Even under the most stringent emissions scenario, warm-water corals and mid-latitude bivalves are considered to be at high risk by 2100. Under our current rate of CO_2 emissions, most marine organisms are expected to have very high risk of impacts by 2100 and many by 2050. These results are consistent with evidence of biological responses during high-CO_2 periods in the geological past. Impacts to the ocean's ecosystem services follow a parallel trajectory. Many ecosystem services that humankind depends on for food and survival, such as capture fisheries and coastal protection,

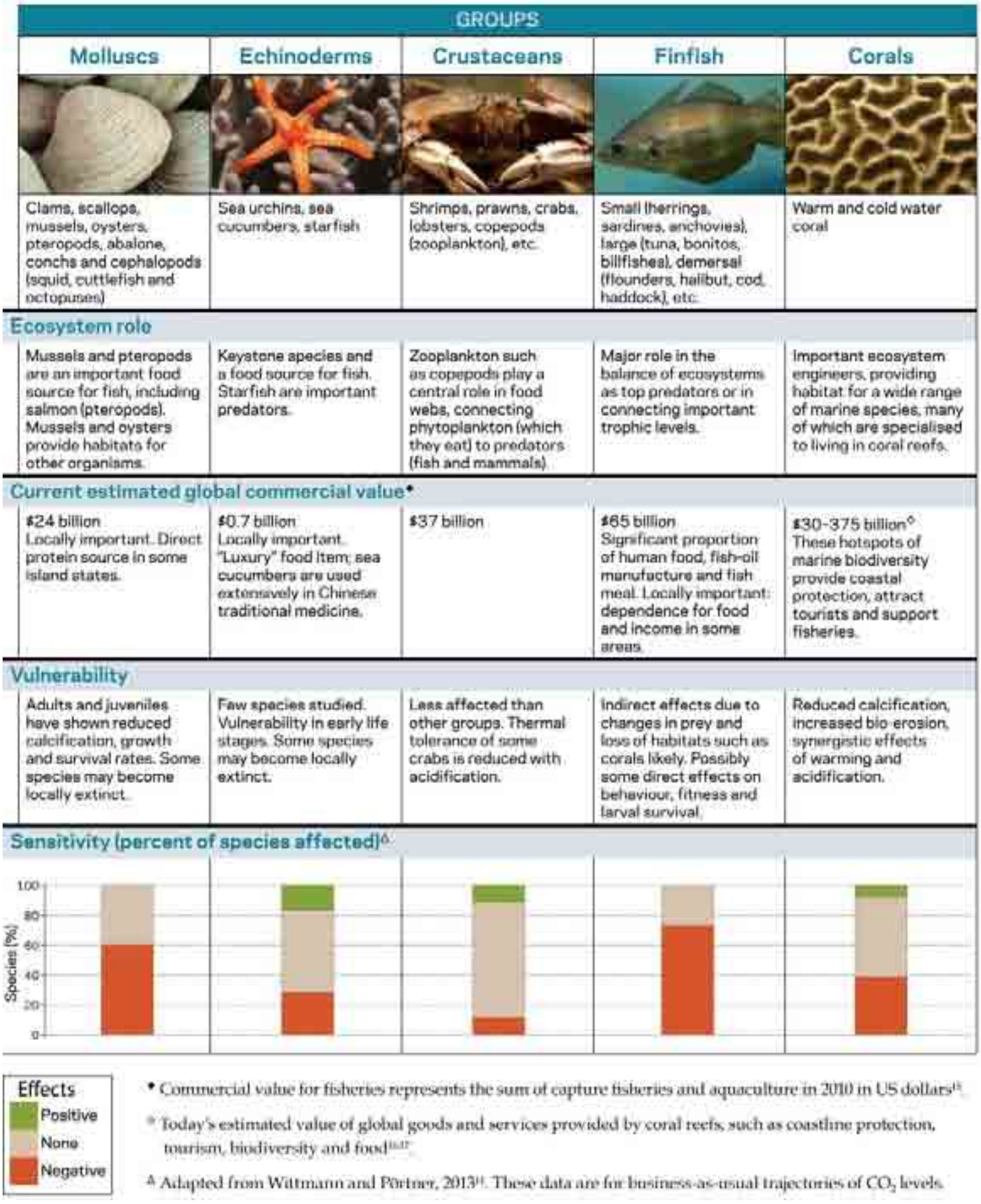

Figure 4.4 Ocean acidification impacts on ecologically and economically-important taxonomic groups of marine species (IGBP, IOC & SCOR, 2013).

are already impacted by ocean warming and acidification. The risks of impacts to these services increase with continued emissions. They are predicted to remain moderate for the next several decades for most services under stringent emission reductions, but the business-as-usual scenario would put all ecosystem services at high or very high risk over the same time frame (Fig 4.4).

Mitigation and adaptation

Successful management of the impacts of ocean acidification includes two approaches: (1) mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO_2) and/or (2) societal adaptation, by reducing the consequences of past and future ocean acidification. Direct mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management will not directly abate ocean acidification, since CO_2 levels would continue to increase. Techniques to remove CO_2 from the atmosphere, by either biological, geochemical or chemical means, could directly address the problem but are not yet well-developed. They seem likely to have additional environmental consequences or may be very costly, or may be limited by the lack of CO_2 storage capacity. In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels.

A low-regret approach (although with relatively limited effectiveness) is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution. Mitigation approaches for the reduction of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nitrogen and sulphur gases, nutrients and organic matter in the coastal ocean. Adaptation strategies include drawing seawater for aquaculture only when pH is in the right range; chemically-treating the seawater used for aquaculture, raising its pH; selecting for less sensitive species or strains; or relocating industries elsewhere to regions where acidification is less severe.

Proposed G7 actions

Although enough is known of the impacts of ocean acidification to justify support for the policy decisions of the Paris Agreement, there are still many knowledge gaps relating to the state of the future ocean – and hence the future influence of ocean acidification on species, ecosystems and ecosystem services. In particular, there is need for improved understanding of the many factors affecting the temporal and spatial variability of pH; the complex effects of multi-stressor interactions; and the potential for evolutionary adaptation under different rates of change. Additional observations, experiments and modelling efforts are all needed to address these issues, within a research framework linking chemical change to biological impacts and socio-economic consequences.

Coordinated, global-scale observations of ocean acidification will contribute to the United Nations Sustainable Development Goal 14. That goal includes an indicator for ocean acidification measurements, which could be developed by, and implemented through, the Global Ocean Acidification Observing Network. Wider international collaboration would be strengthened by further support for the Ocean Acidification International Coordination Centre, hosted in Monaco by the International Atomic Energy Agency.

5. De-oxygenation

Key messages

- Low oxygen levels naturally occur in mid-depth waters, as Oxygen Minimum Zones (OMZs), particularly in the tropics. Such conditions have important biological and biogeochemical consequences.
- Current trends are for oceanic OMZs to expand and intensify, associated with human-driven global warming. Oxygen depletion in coastal waters is also increasing in many parts of the world, related to nutrient enrichment.
- Although some species can tolerate low oxygen levels, most marine life is adversely affected.
- Better scientific understanding and monitoring of de-oxygenation and its impacts are required, involving new automated platforms, capacity building and international collaboration and coordination.

Introduction

Before the *Challenger* Expedition (1872-1876), the deep sea was believed to be anoxic. Consequently, one of the most exciting results of this expedition was the discovery of life in diverse forms even in the deepest parts of the ocean, made possible, as we know today, by an effective ventilation of the abyss due to formation of cold, dense waters at high latitudes. While the deep sea and the surface layer are well oxygenated, there is nevertheless a mid-depth layer in all ocean basins where the oxygen content of water is depressed substantially, albeit by varying degrees. These natural Oxygen Minimum Zones (OMZs) are most pronounced in the tropics and subtropics along the eastern boundaries of the Atlantic and the Pacific Oceans and in the northern part of the Indian Ocean as a result of the combined effect of restricted re-oxygenation (through water circulation/mixing) and elevated respiration rates, the latter fuelled by organic matter sinking from the surface layer. In upwelling areas, waters from the OMZs may be transported to shelf seas and coastal regions, thereby extending low-oxygen conditions to relatively shallow depths.

Reduced oxygen levels in water can affect marine life in many ways. Sub-lethal impacts include loss of habitats, changes in food web structure, reduced growth and reproduction, physiological stress, migration, vulnerability to predation, and disruption of life cycles. The threshold oxygen concentrations at which these effects begin to appear are highly variable among taxa, even within the same group, but a nominal threshold of 2 mg O_2 per litre (1.4 ml/l; 62.5 μM) is often used to define 'hypoxia'. More severe oxygen depletion may result in mortality to many higher organisms that cannot escape from the affected area (e.g. benthic species, restricted to the seafloor). In addition to biological effects, very low oxygen levels in sea water also have important biogeochemical consequences, as microorganisms shift to anaerobic modes of respiration. Alternate electron acceptors (oxidized nitrogen, manganese, iron, and sulfate) are utilized sequentially in order of decreasing energy yield for the oxidation of organic matter.

However, as nitrate ions – the most preferred oxidant after oxygen – are seldom fully used up in the water column, the biogeochemistry of the OMZs is dominated by the nitrogen cycle. Denitrification (conversion of nitrate to molecular nitrogen) in oceanic OMZs and in reducing marine sediments is by far the most important fate of fixed nitrogen that keeps the atmospheric nitrogen content constant over geological time scales. An important aspect of redox chemistry of nitrogen is the production of nitrous oxide (N_2O), a potent greenhouse gas both as an intermediate during denitrification and as a byproduct during the oxidation of ammonium to nitrate (nitrification). Denitrification is confined to low-oxygen waters, but even during nitrification, the yield of N_2O is greatly enhanced as the waters get depleted with oxygen. As a result, oxygen-poor environments are important sites of N_2O production – and oceanic N_2O emissions (that account for a significant fraction of the atmospheric N_2O budget) are likely to vary with time depending on the size and the intensity of the OMZs.

Examination of the sedimentary record has revealed that the extent of naturally caused deoxygenation in the ocean varied significantly in the geological past, with the deep ocean experiencing several anoxic events. In the relatively-recent geological past, there have been changes in the size and intensity of the OMZs associated with glacial-interglacial cycles. Variability on centennial time scales has also been observed during the last glacial period, and related to climate changes in the North Atlantic inferred from polar ice and marine sedimentary records. Thus, the Arabian Sea OMZ weakened during the last glacial maximum (~21,000 yr before present), during the Younger Dryas (~12,000 yr before present) and during the cold Heinrich Events. By contrast, OMZs were stronger during the warm Dansgaard-Oeschger Events (Schulz et al., 1998).

Human influences

Among the changes that human activities are now bringing about in the marine physico-chemical environment is the general loss of dissolved oxygen (ocean de-oxygenation). Time-series analysis of available data has shown that oceanic OMZs have been expanding and intensifying over the past few decades, losing oxygen at a rate of 0.1-0.7 µmol/kg per year (Keeling et al., 2010; Falkowski et al., 2011)(Fig. 5.1). While the role of decadal and multi-decadal natural variability on these observed oxygen trends – particulary in the North Atlantic – is still not clear, there is evidence that human effects are indirectly involved (through global warming) in the open ocean, and more directly in coastal waters.

Thus, the observed decrease can at least be partly accounted for by the decreased solubility of oxygen at higher temperature: a warming of the upper ocean by 1°C (lowering oxygen solubility by ~5 µM) is estimated to result in ~10% increase in the volume of hypoxic waters – and a tripling of the volume of water with oxygen concentration below 5 µM. In addition, ocean warming is also expected to result in stronger thermohaline stratification and a change in subsurface ventilation, which would also contribute to deoxygenation of subsurface waters.

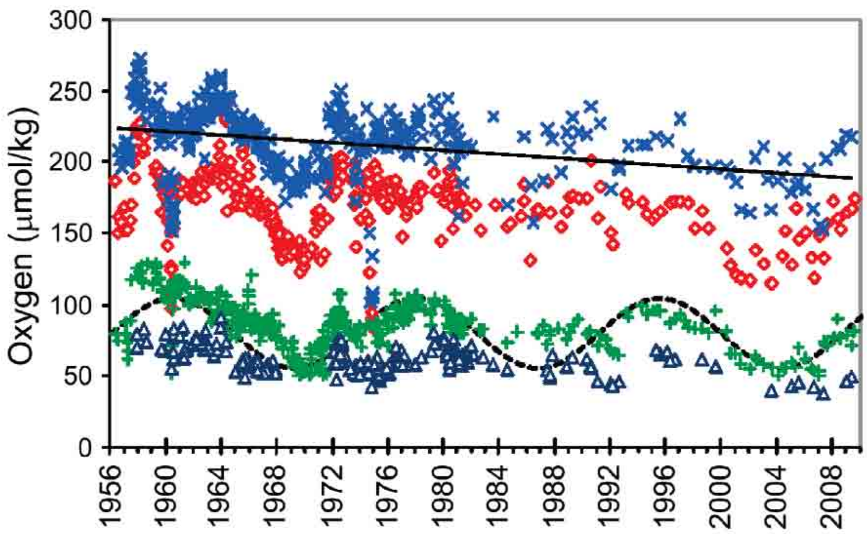

Figure 5.1 Declining oxygen levels, and decreases with water depth, at Ocean Station P in the North Pacific, 1956-2010. Symbols relate to constant potential density surfaces (isopycnals) that increase with water depth: **x**, 26.5, **◊**, 26.7, **+**, 26.9 and **Δ**, 27.0. From Falkowski et al. (2011).

Model projections indicate that there could be a decrease in oxygen levels of ~5 μM in the depth range 200-600 m by the end of this century. This implies a very significant expansion of suboxic zones, and many regions that are presently at the threshold of becoming anoxic (e.g. the Bay of Bengal, Gulf of California, California Borderland Basins) may become fully suboxic. This will significantly alter geochemical fluxes (e.g. denitrification rates and N_2O efflux to the atmosphere) and marine ecology.

The ocean is also becoming more acidic (see preceding Section) due to the uptake of CO_2 from the atmosphere: about 42% of the cumulative fossil-fuel CO_2 emissions have so far ended up in the ocean. This is expected to affect the export of organic matter from the surface layer that maintains subsurface respiration. Specifically, a decrease in calcification rate in a more acidic ocean will lower the ballast of sinking particles, likely to result in more organic matter being respired within the OMZs – and making them more intense. Furthermore, as the OMZs and areas affected by upwelling of low-oxygen OMZ water are sites of naturally low pH, the combined effect of ocean deoxygenation and ocean acidification on marine biology is expected to be more severe than the individual stresses due to these phenomena.

Consequences of de-oxygenation

An increase in the supply of nutrients to the euphotic zone (eutrophication) is another important contributor to ocean deoxygenation, particularly in shelf seas and coastal areas. Although recent enhancement of biological productivity has been inferred from higher chlorophyll levels observed by satellite-borne sensors in several open ocean areas, the resultant increase in oxygen demand at depth is probably still a minor contributor to the observed decreased in oxygen concentrations. However, in coastal areas the situation is completely different. The number of hypoxic zones in coastal seas, popularly known as dead zones, has increased abruptly to over 600 over the past few decades. Development of these hypoxic sites is undoubtedly related to nutrient over-enrichment caused by fertilizer runoff from land (Rabalais et al., 2014).

Many of these hypoxic sites are located at the mouths of major rivers. The best known of these sites is the dead zone of the Gulf of Mexico at the mouth of the Mississippi River that occupies an area of ~20,000 km^2 at its peak in summer. Apart from the development of new coastal hypoxic sites, eutrophication is also expected to lead to intensification/expansion of the naturally formed oxygen-deficient systems in coastal areas, with complex biological responses (Levin & Breitburg, 2015).

An example of this is the western Indian shelf where seasonal anoxia has been known to occur (during summer/autumn) due to upwelling of waters from the perennial OMZ of the Arabian Sea. This system was not known to be sulfidic previously, but frequent events of sulfate reduction have been observed over the past two decades, underlying the sensitivity of coastal waters to human perturbations.

Most organisms that can tolerate – and find special niches – in low oxygen waters are microbial. Thus anaerobic bacteria and archaea are able to obtain energy through diverse redox transformations of biogenic polyvalent elements such as carbon, nitrogen, sulfur, iodine, and trace metals (Fe, Mn, etc). However, some higher animals are also able to tolerate low oxygen. In size, they range from a few millimetres (e.g. the copepod *Pleuromamma indica*) to a couple of meters (the Humboldt Squid). The lantern fish (myctophid, a few centimeters in length) is specially adapted to live in nearly-anoxic waters where it can hide from its predators during the day. The total myctophid biomass in the Arabian Sea is estimated to be several tens of million tonnes. Ocean deoxygenation is expected to expand the habitat of such organisms, while compressing that of other species less tolerant of low oxygen, e.g. tuna and billfish (Stramma et al., 2012). The overall effect on marine life is expected to be deleterious (Stramma et al., 2010; Moffit, 2014), and further deoxygenation, especially in coastal seas, could therefore have enormous socio-economic implications.

Figure 5.2 Species that are likely to be negatively impacted by lower oxygen levels include top predators with high oxygen demand, such as the blue marlin. Photo credit: Gray Fishtag Research/J Masreliez.

Proposed G7 actions

Like other human-induced changes in the ocean, deoxygenation requires better scientific understanding and regular monitoring – in order to assess the scale of the problem and consider possible responses. With the advancement in instrumentation, there are now new opportunities to use automated platforms (e.g. profiling floats and marine gliders) to observe changes in oceanic parameters with much better spatial and temporal resolution.

In this context, recent efforts to equip Argo floats with oxygen sensors are particularly promising. These floats carry several other physical and biogeochemical sensors and are programmed to go up and down the water column to a fixed depth (e.g. 2 km), transmitting data every time they come up to the surface. Information generated by such floats has already provided new insights into oxygen variability in the ocean. However, a lot more of these floats need to be deployed covering all parts of the ocean. G7 support for the development of a full Biogeochemistry-Argo Program (as currently under intense discussion in the oceanographic community) would therefore be highly desirable.

However, Argo floats have limited utility in shallow waters of shelf seas and coastal areas. Generating data on a regular basis from nearshore regions, where the variability and change are often the most pronounced, is still a big challenge, especially in the coastal waters of developing countries. Putting in place a global observing system for monitoring changes in oxygen in conjunction with other core physical, chemical and biological variables not only requires greater international collaboration but also capacity building in the less-developed countries. The G7 nations should promote such collaboration by pooling resources and assisting network-based coordination.

6. Ocean warming

Key messages

- As a consequence of changes in atmospheric composition, the Earth is absorbing more energy than it is losing. Around 90% of that extra energy is absorbed by the ocean, increasing its temperature.
- Ocean warming is spatially and temporally variable, particularly in the upper layers, with large influences on decadal-scale natural climate variation and extreme weather events.
- Temperature changes in the deep ocean are not well-measured nor fully understood, resulting in uncertainties in model projections of future sea level rise and climate.
- Upper ocean warming reduces vertical mixing (increasing stratification), contributing to midwater de-oxygenation.
- Sustained, full-depth monitoring is needed to improve our understanding of ocean warming and its consequences.

Our understanding of ocean warming

Global warming is the result of energy imbalance at the top of the atmosphere. The energy imbalance is one of the significant consequences of increased concentration of greenhouse gases in the atmosphere, which trap part of the outgoing long-wave radiation. About 90% of the excess heat on Earth in the last five decades has been stored in the ocean, due to the large amount of water volume on the Earth's surface and its large heat capacity, leading to recent ocean warming (e.g. Trenberth et al., 2014 and reference therein). The remaining fraction of excess heat leads to ice melting, increased freshwater cycle and warming of land and the atmosphere.

Recent increase of aerosols in the atmosphere, most likely derived from increased emissions due to volcanic eruptions and human activities, act to reduce the radiation reaching the Earth’s surface. Thus, though there is a continuous increase of atmospheric greenhouse gases, the rate of change of the ocean warming is not uniform. Heat absorbed at the ocean surface is conveyed by ocean circulation and mixing to deeper layers, causing the redistribution of heat within the ocean. Because the precise contributions of aerosol emissions and of the heat content of the deep ocean are still uncertain, the closure of the Earth energy balance based on observations remains a serious challenge (Church et al., 2011).

Present status of global ocean warming

Despite differences in measurement techniques, recent studies indicate a multi-decadal increase in ocean heat content. This warming spans through the upper to deeper layers and reflects the impact of anthropogenic warming (Abraham et al., 2013).

The most recent estimates of ocean warming reveal that, though global average surface temperatures are strongly modulated by short-term natural climate variability, such as El Niño events, the ocean slab between 300 and 2000 m depth displays a consistent warming through the year 2015 (Wijffels et al., 2016). The global, full water column ocean heat content is steadily rising, at a rate of 0.80-0.95 W m^{-2}. These analyses further reveal that ocean warming is asymmetric in hemispheric distribution: the Southern Hemisphere gains heat at a rate about four times faster than the Northern Hemisphere. Even within either

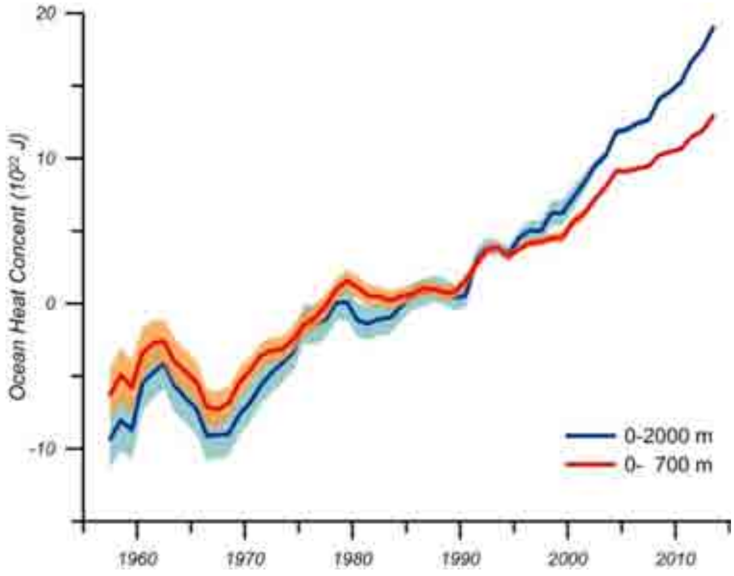

Figure 6.1 Changes in global ocean heat content for the upper 700 m (blue) and upper 2000 m (red) of the water column relative to the 1955-2006 mean. Data updated from Levitus et al. (2012), https://www.nodc.noaa.gov/. The shadings around each curve indicate one standard error. Note the larger rate of increase in heat content in the 0-2000 m layer after the early 1990s.

hemisphere, warming is not uniform both in time and space. There are regions of the ocean that have cooled in the last decade. Such heterogeneity of changes in heat content arises from natural variability in ocean circulation, surface air-sea heat exchanges, and the vertical redistribution of heat between upper and deep ocean (see Fig 6.1). The ocean heat redistribution is a plausible explanation for the relatively large inter-annual fluctuations in Earth´s surface temperature, and the recent warming 'hiatus' (e.g. Nieves et al., 2015).

The implementation of a global ocean observation network based on autonomous Argo floats (Fig 6.2) has significantly advanced our understanding of the changes in heat content in the upper 2000 m of the ocean (Roemmich et al., 2009), thus also providing data required for tracking the ocean's role in the planetary energy balance. Model analyses reveal that though the upper ocean heat content variations are well constrained by these observations, this is not yet the case for the deep ocean, which presents the largest differences in regions of high mesoscale variability. This result might be expected since the majority of the Argo floats are limited to the upper 2000 m of the water column, leaving nearly 50% of the ocean volume unsampled. The lack of sufficient deep ocean observations leads to uncertainties in the Earth´s energy balance and estimates of the ocean heat content and thermosteric sea level rise. Monitoring the deep ocean with sufficient spatial and temporal coverage, and maintaining the accuracy required to detect the small changes in temperature, poses a significant technological and financial challenge. Efforts are underway to expand the Argo network to span the deep ocean (e.g. Johnson et al., 2015).

Impacts of ocean warming

As the ocean temperature rises the water expands, leading to sea level rise. Observationally-based estimates indicate that since 1972 ocean warming has contributed about 40% of the total sea level rise. The major uncertainty in this estimate arises from the scarce and unevenly distributed temperature observations in the deep ocean. Additional contributions to sea level rise are due to changes in ocean mass, associated with continental ice melt, which are of the same magnitude of the thermal expansion effect, and minor contributions from changes in land and atmospheric storage of water (Church et al., 2011).

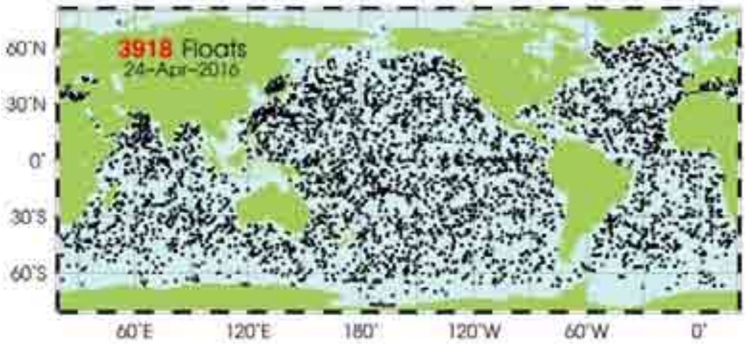

Figure 6.2 *Left*: Preparing an Argo profiling float for deployment (photo: A Piola). *Above:* Current global deployment (from http://www.argo.ucsd.edu). Although coverage is generally good, there are still gaps associated with ice cover in the Arctic and Southern Ocean, and depth profiling is limited to ~2000 m.

Because ocean warming is forced from the overlying atmosphere, the upper ocean is expected to warm faster than the deep ocean. This large-scale differential warming will enhance the vertical stratification of the ocean, with significant biological and biogeochemical consequences. Analysis of the relatively homogeneous and global upper ocean data collected by the Argo floats confirms a widespread increase of ocean stratification since 2006 (Roemmich et al., 2015; Wijffels et al., 2016). The upper ocean stratification plays a key role in determining the mixed layer depth, which in turn regulates the nutrient supply from deep to upper layers and the ventilation of subsurface layers, thereby determining the oceanic uptake of atmospheric carbon and oxygen (e.g. Hollowed et al., 2013). Model analyses projecting future climate based on increased greenhouse gas concentrations predict increased vertical stratification and decreased productivity in response to upper ocean warming (e.g. Steinacher et al., 2010; Jang et al., 2011; Capotondi et al., 2012).

Because the solubility of gases in seawater decreases as temperature rises, ocean warming reduces the absorption of atmospheric gases, such as oxygen and carbon dioxide, which are important for ocean ventilation and climate. Global warming and the associated increased vertical stratification in the ocean are thought to be the main cause leading to the expansion and shoaling of the so-called low oxygen zones in the tropical ocean (Stramma et al., 2008); see previous Section for additional discussion. Model projections of future climate further indicate that the oxygen depletion will continue during the 21st Century, affecting ocean productivity, nutrient and carbon cycling, and the marine habitat (Keeling et al., 2010).

Changes in upper ocean heat content, at inter-annual to inter-decadal and centennial time scales, modulate natural climate variations. They also cause changes in frequency and magnitude of extreme events, such as typhoons and hurricanes.

Uncertainty in ocean warming

Ocean warming is best monitored in the surface layer by infrared sensors mounted on satellites, but these observations are restricted to the skin layer of the ocean and are only globally available since the late 1970s. Subsurface observations are sparser and are derived from a variety of sensors, with inhomogeneous accuracies (see Abraham et al., 2013). Since the early 2000s the Argo float program also provides estimates of the changes in ocean temperature in the upper 2000 m of the water column, but the spatial coverage of the array is not uniform as float locations are determined by the ocean circulation, leaving gaps particularly in the ocean interior, where it is logistically more difficult to deploy new instruments. Uncertainties in estimates of long-term trends and variability are susceptible to errors of the different instruments. For the period 1970–2012, the contribution of the upper 700m to changes in the planetary heat storage is ~ 0.27 ±

0.04 Wm^{-2}. This is equivalent to an increase in global upper ocean heat content of ~ 190 × 10^{21} J and implies an averaged ocean warming of ~ 0.2°C (or ~0.048°C per decade) in the upper 700 m (Abraham et al., 2013). Our knowledge of changes in ocean temperature (and heat content) in the deep ocean are less reliable. However, studies based on ocean re-analyses show that in the first decade of the 21st Century about 30% of the warming has occurred below 700 m (Balmaseda et al., 2013). This finding is in agreement with observational evidence which indicates that since the early 1990s the increase in ocean heat content of the upper 2000 m is significantly faster than in upper 700 m alone (Fig 6. 1).

Proposed G7 action

More research and observations, particularly sustained monitoring from the surface down to the ocean bottom, in regional and global scales, are necessary to better understand the processes that control ocean warming and to project its evolution in upcoming decades.

7. Biodiversity loss

Key messages

- The ocean supports a very wide range of biological diversity, underpinning the health of the planet and providing many human benefits.
- Our knowledge of marine biodiversity is relatively poor: the majority of species are probably undiscovered.
- Without careful management, impacts on biodiversity will endanger some of the most vulnerable marine habitats around the world, as well as bringing high costs to human society.
- Sustainable development and reduction of greenhouse gas emissions can help to avert ecological problems. Marine Protected Areas and similar interventions can also help to maintain diversity and function.
- Specific G7 actions are identified to coordinate research, improve marine protection and support knowledge exchange.

Introduction

Marine biodiversity encompasses the genetic, species, and habitat diversity of some 70% of the Earth's surface and more than 90% of the habitable volume of the planet (Snelgrove et al., 2010). This diversity spans from tiny, but hugely abundant microbes from the ocean's surface to deep in its ocean crust, to the largest animals on the planet (marine mammals), and a wide range of vertebrates and invertebrates in between (Fig. 7.1). With the notable exceptions of insects and vascular plants, marine biodiversity greatly exceeds that on land for most major taxa at lower and at higher taxonomic levels. For example, 34 of 36 known animal phyla occur in the ocean, in contrast to just 17 found on land; 15 phyla occur only in the ocean.

Biodiversity and consequences of its loss

Biodiversity in the ocean provides a wide range of direct benefits to humans (ecosystem services) in the form of fisheries, clothing, medicines, oxygen production, climate regulation, breakdown of pollutants and contaminants, to name just a few (Snelgrove et al., 1997). In many cases, a particular ecosystem service links to a single species, such as commercial fishery, or a particular type of organism that yields a natural product. Similarly, ecologists recognize keystone species, those individual species that exert disproportionate influence relative to their abundance in an ecosystem such as sea stars (starfish) in the rocky intertidal. In these instances the loss of that one species has clear ramifications for the ecosystem and, in some cases, for humans. Loss of genetic diversity may also create problems, for example, following loss of genetic traits such as adaptations to cope with cold temperatures or disease.

Increasingly, researchers ask whether species diversity actually matters to the delivery of these ecosystem services, as well as many ecosystem functions (e.g. nutrient cycling, photosynthesis, habitat provisioning) that support these services. Numerous examples illustrate critical roles for individual species, but few studies have demonstrated whether the totality of species in an environment really matters (but see Danovaro et al., 2008), and whether loss of species necessarily compromises ocean function unless that

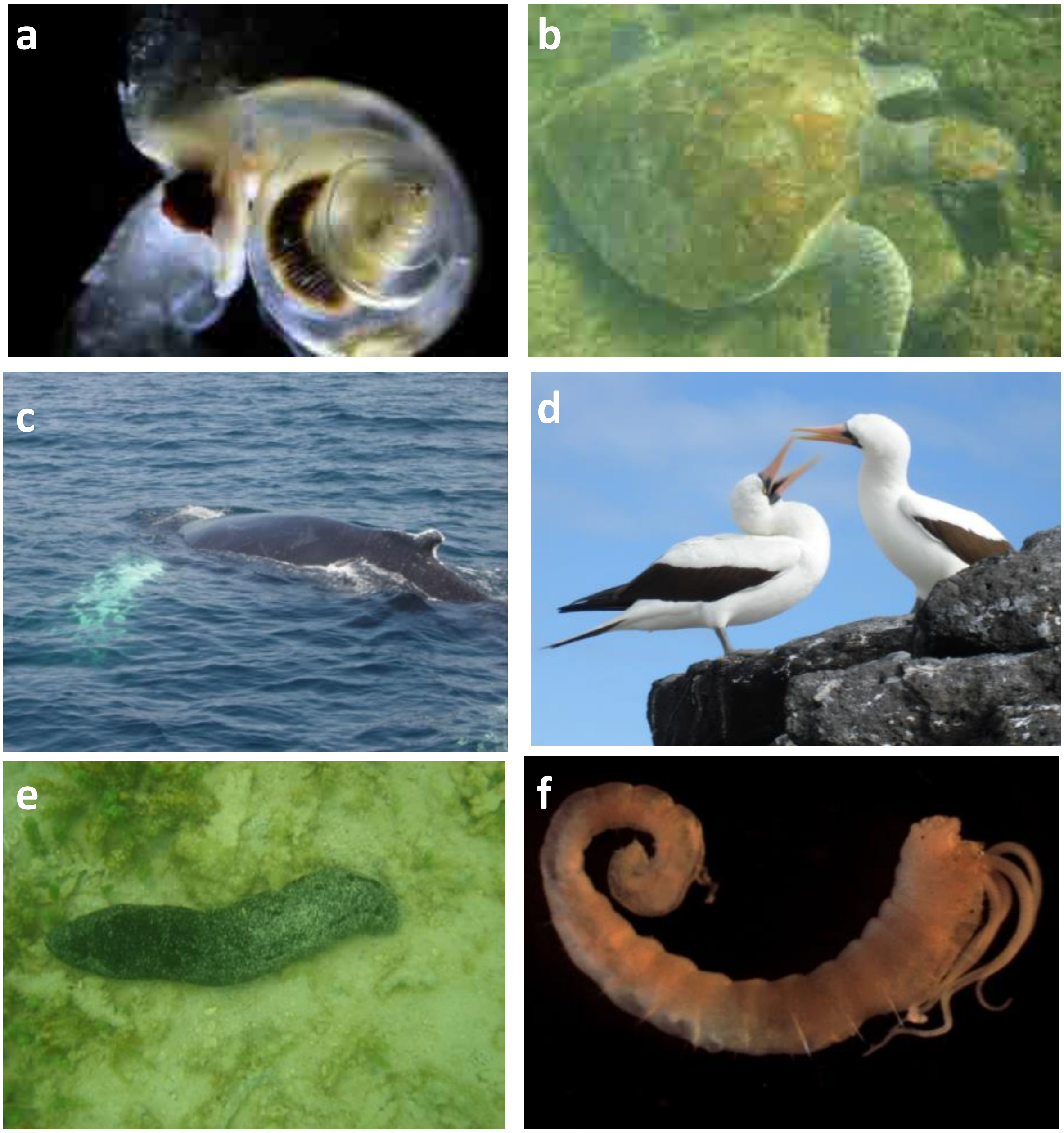

Figure 7.1. Marine animals vary hugely in size, form and function. For example: a) planktonic pteropods drift in ocean currents, feeding on small plankton. Their thin carbonate shells make them particularly vulnerable to ocean acidification. Migratory species that live in surface waters include: b) Galapagos green turtles that feed on eelgrass and macroalgae; c) Humpback whales off Newfoundland that feed on plankton and small fish; and d) Nazca booby, which feeds on marine fish. On the seafloor, e) Galapagos sea cucumbers live on the bottom and ingest sand as they deposit feed. Smaller, macrofauna (44-400 microns) such as f) ampharetid polychaetes live within sediments and ingest sediment grains and organic material. Photo credits (a) Nina Bednaršek/NOAA, (b), (c), (d) (e) P. Snelgrove, (e) N. Campanya i Llovet.

loss represents a keystone or commercial species. Despite surprisingly few documented global marine extinctions, many examples illustrate local extinctions (Dulvy et al., 2003) and potential loss of genetic diversity. Furthermore, the poor state of knowledge on marine biodiversity in remote (e.g. deep sea) and/or undersampled (e.g. coral reefs), marine environments that face increasing habitat loss through human pressures point to potential global extinction of species totally unknown to science (Snelgrove, 2010).

Human activities that directly or indirectly affect species distribution by harvesting (e.g. commercial species), or alteration of marine environments (e.g. ocean acidification, ocean warming) may produce cumulative impacts that reduce ecosystem complexity and species number (Halpern et al., 2008). Species resilient to one form or intensity of impact may be vulnerable to cumulative impacts because the combined impact of several pressures on an ecosystem often exceeds the sum of individual impacts. Biodiversity change may also reduce resilience of ecosystems to climatic and non-climatic drivers. These changes may reduce the services ecosystems provide.

Earth's history illustrates the reason for concern about ongoing human impacts on biodiversity and the marine environment, given that past mass extinctions reorganized ecosystems and species diversity (Cardinale et al., 2012). Major carbon cycle perturbations associated with ocean warming, ocean acidification, and hypoxia events are considered to be likely major drivers of many mass extinctions (Clarkson et al., 2015; Hönisch et al., 2012).

Gaps in biodiversity knowledge

Even for better known groups of organisms such as fishes, a full 25% of species may remain undescribed by scientists, and recent estimates suggest that as much as 90% of multicellular marine taxa may still be undiscovered (Mora et al., 2011). Scientific knowledge of biodiversity relates inversely with size, with far lesser knowledge of small organisms. Indeed, one microbial expert suggested that the ocean may harbour more than a million different types of microbes, the vast majority of which remain undocumented and whose very existence has only begun to emerge through the molecular biology revolution. These glaring gaps point to concerns that go well beyond extinction of species prior to scientific recognition of their very existence. Why do so many different species live in the ocean and what would be the ramifications of their loss? Are many species redundant, so that another species will assume the role of another that disappears? Which species can adapt to rapid ongoing environmental change? For the most part, we have little to no capacity to answer those questions.

Pelagic environments

Open ocean pelagic (i.e. water column) environments contribute immensely to sustaining life on Earth, driving cycling of nutrients, food, and oxygen, influencing climate and weather. Pelagic organisms span from extremely diverse unicellular organisms such as phytoplankton and bacteria (Fig. 7.2) to marine mammals (Fig 7.1), including the largest animals on Earth, the blue whale. Phytoplankton and some types of bacteria carry out most of the photosynthesis (primary production) and thus form the base of the food webs for most of the ocean. Fast growing, low diversity phytoplankton species in polar and subpolar waters or during intense blooms of diatoms or other groups in temperate waters contrast the slow growing and species-rich phytoplankton in nutrient-poor tropical-subtropical regions (Fig. 7.2).

High productivity closer to land and in regions where deep, nutrient-rich water upwells to the surface supports high abundances of pelagic invertebrates and fish, including very productive pelagic fisheries (Angel et al., 1993). The biodiversity, complexity and size spectrum of phytoplankton community largely determine the trophic organization and species diversity of pelagic ecosystems, including the food availability for the higher trophic levels (zooplankton, fish), the metabolic activities, nutrient remineralization and export of organic matter. Few long-term or detailed studies on seasonal changes in phytoplankton diversity exist and we still know little about how changing diversity affects productivity and functioning of marine food webs. We do know that excess nutrient runoff in highly populated coastal regions causes hypoxia (reduced oxygen) and other problems, in tandem with habitat destruction and over-exploitation by fisheries. Increasing evidence shows rapid environmental change resulting from ocean warming, ocean acidification, and other pressures such as marine litter and fisheries. These activities often cause mortality and alter many biodiversity components including non-target species. For example, jellyfish outbreaks often occur in coastal ecosystems with low or compromised diversity, related to these and other drivers, such as aquaculture and introductions of non-indigenous gelatinous species.

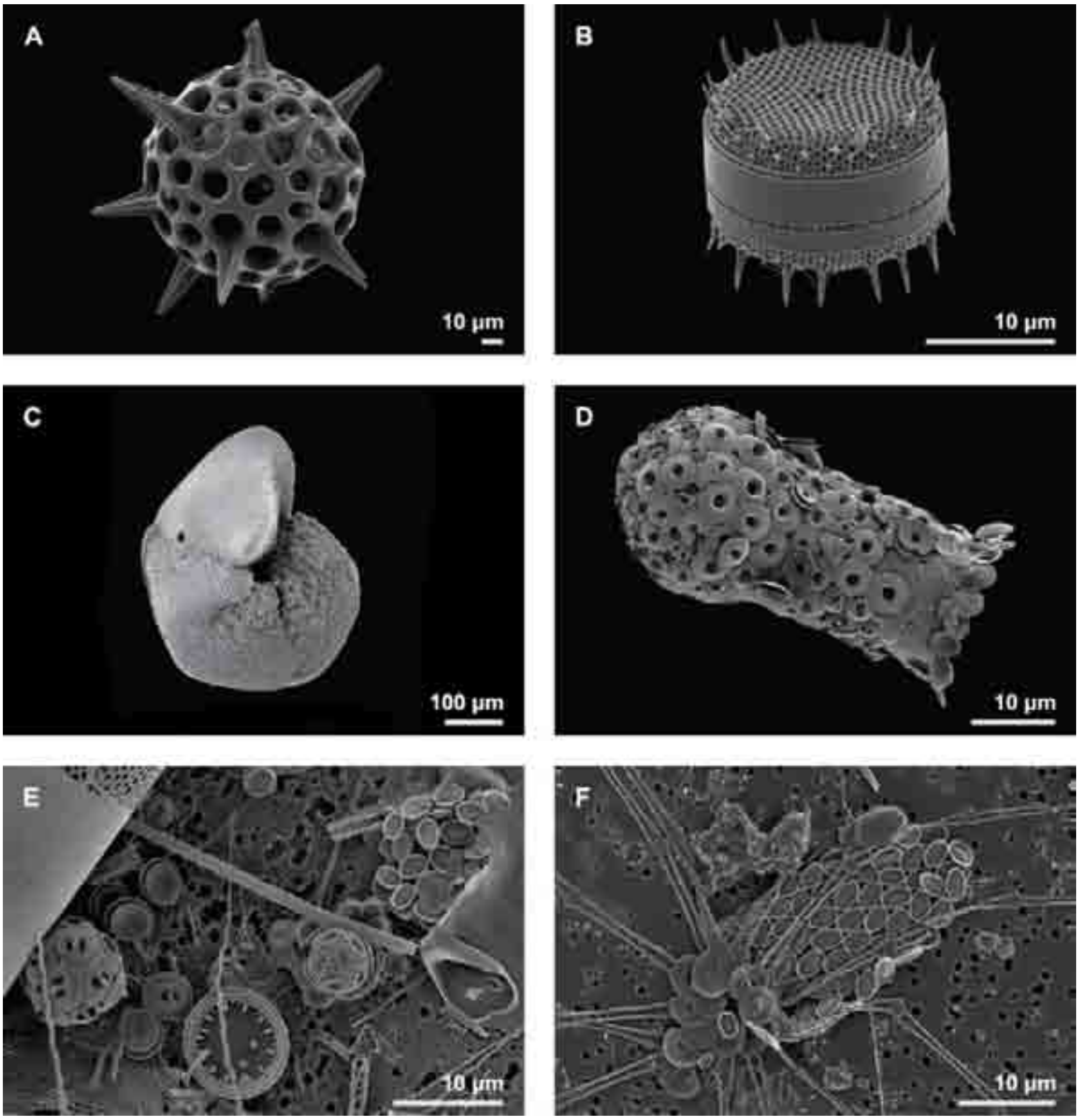

Figure 7.2 Electron micrographs illustrating the range of diversity and size of planktonic organisms. A) radiolarian (siliceous zooplankton); B) diatom (siliceous phytoplankton); C) planktonic foraminiferan (calcareous zooplankton); D) tintinnid (ciliate cell) with a vase-shaped shell (loricae) consisting mostly of protein but can incorporate small mineral particles, such as coccolith plates of coccolithophores; E) different phytoplankton groups and species; and F) coccolithophores (calcareous phytoplankton). Several of these groups (foraminifera, coocolithophores) are likely to be vulnerable to ocean acidification because of their calcareous structures. All photos P. Ziveri.

Rapidly increasing atmospheric CO_2 emissions globally has warmed the ocean, increased ocean acidity (reduced pH), reduced oxygen in large areas, and increased stratification of ocean layers (Hoegh-Guldberg & Bruno, 2010). These changes are expected to shift phytoplankton communities and favour smaller plankton typical of low-production open-ocean waters. Ocean acidification already affects some planktonic species and could reduce biodiversity and production (Ziveri et al., 2014). Major knowledge gaps exist regarding impacts of climate change and ocean acidification on communities, response to multiple drivers, and how phytoplankton may evolve and adapt in a future ocean.

Seafloor environments

Seafloor environments support a wide range of diversity and abundance from the rocky intertidal to the abyss (Fig. 7.3). Near-shore environments span from often productive and low-diversity coastal environments (rocky intertidal, mangroves, salt marshes, seagrasses), regulated largely by variable physical processes, to less productive subtidal rock, sand, and muddy bottoms, to highly diverse and productive coral reefs with complex biological interactions. With increasing depth and the total disappearance of light, typically between 200 and 1000 metres depth, productivity generally declines sharply with depth, with the notable exceptions of hydrothermal vents and cold seeps supported by chemical emissions from the seafloor rather than sunlight and photosynthesis (Snelgrove, 2010). These chemosynthetic environments support a unique, but low diversity fauna, but represent some of the most productive environments (and highest biomasses per unit area) in the ocean. Shallow water volcanic carbon dioxide vents and their acidic waters provide an opportunity to understand long-term responses of coastal ocean life to increases in CO_2 levels. These sites show a lowering of ecosystem complexity and species diversity with increased acidification (Hall-Spencer et al., 2008). Sediments cover much of the deep seafloor, and support a diverse but low abundance community that depends on photosynthetic production raining down from the sunlit surface layers. Several lines of evidence suggest highest diversity in tropical seabed environments with declines poleward (Tittensor et al., 2010), a pattern that appears more complicated in deep-sea systems where some studies point to a mid-latitude diversity peak.

Seafloor ecosystems provide a wide range of functions from the shoreline to the deep sea (Snelgrove et al., 1997). In shoreline environments these functions include primary production (e.g. kelps, benthic algae), secondary production (fisheries, trophic support), nutrient recycling and carbon mineralization (e.g. salt marshes, mangroves, sediments), habitat provisioning for other species (e.g. coral reefs, kelps) and numerous other functions. The roles of different environments vary greatly; coral ecosystems cover a small proportion of Earth, but support extremely high levels of primary and secondary productivity. Deep-sea ecosystems, despite comparatively low rates of activity, recycle considerable organic matter and nutrients because they cover 65% of the Earth's surface.

Because of their proximity to human activity, shoreline and continental shelf environments face the greatest pressures from human impacts (Roberts, 2010). Historically, fishing outweighed other pressures in altering ecosystem function and structure (e.g. diversity, abundance), generally through habitat destruction from trawling, and overfishing top predators and altering food webs. However, in recent years climate change has increasingly driven anthropogenic change. For example, many experts attribute the increasing prevalence of bleaching of coral reefs over the last few decades to ocean warming and increased nutrient supply. These changes have led to predictions that much of the diversity and function of coral reefs could largely disappear within the next 20 to 50 years (Pandolfi et al., 2003).

These changes point to critical knowledge gaps on marine biodiversity and how it may change in the near future. Clearly we must advance knowledge of marine biodiversity and how changes in biodiversity may alter future delivery of ecosystem functions and services. We must also develop strategies to try to mitigate those changes in order to enhance ocean sustainability into the future. Documenting global biodiversity and the ramifications of biodiversity loss for ecosystem functions and services represent core activities for the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). However, as noted above, that task will be particularly challenging in poorly documented, species rich environments such as coral reefs and deep-sea sediments, and for smaller organisms.

Whether pelagic or seafloor habitat, we still cannot predict exactly how human activities and related environmental changes drive fish and invertebrate communities. Nonetheless, there is some consensus that without careful management, impacts on biodiversity will endanger some of the most vulnerable human populations and marine habitats around the world, as well as threaten food security and other important socioeconomic aspects (such as livelihoods).

Figure 7.3 Examples of seabed environments include shallow-water low productivity habitats such as: a) the high energy intertidal in the Galapagos Islands; b) the muddy sandflats of Roscoff, France, and high-productivity habitats such as c) diverse Mediterranean algal reefs (coralligenous assemblages) and d) Galapagos mangals, as well as diverse deep-sea low productivity habitats such as cold water corals and deep-sea muds. Photo credits (a), (b) and (d), P. Snelgrove; (c), A. Ferrucci; (e) and (f) P. Lawton/A. Metaxas/P. Snelgrove/ROPOS

Priority research questions

Will the ocean continue to provide key functions and services irrespective of biodiversity status and species composition? Can we afford to lose species and, if so, which ones? Can we identify and sustain hotspots of biodiversity and function and, if so, through what strategies? How can we best identify ecological redundancy in species? How can we best identify hotspots of diversity and function with finite resources? What strategies can help to ensure the sustainability of these hotspots (e.g. MPAs, many small, few large)? How do multiple human pressures such as climate change and fishing disturbance act in concert – are they additive, multiplicative?

Biodiversity underpins the health of the planet and directly impacts society, pointing to an urgent need to clarify the role of biodiversity in sustaining life, cultural heritage and ecosystem services. To address the monitoring, protection, and sustainable development of the marine and coastal environment we must enhance international cooperation to support regional comparative studies, data sharing, complementary approaches that reduce redundancy of effort, and development of effective indicators of change.

Developing and developed countries will both benefit greatly by increasing collaboration at regional (e.g. North Sea, Mediterranean, Japan/East Sea) and broader (e.g. North Atlantic, western Africa, Southern Ocean) scales that cross international boundaries and recognize the interconnectedness of the global ocean. Despite increasing concern internationally on marine conservation, biodiversity change continues with declines in use and non-use values associated with species diversity and unique ecosystems. Deteriorating or vanishing ecosystems will bring high costs to society. Sustainable development and reduction of fossil fuel consumption to limit ocean warming, acidification and reduced oxygen can help to avert ecological problems. Marine Protected Areas and similar interventions can also help to maintain diversity and function.

Proposed G7 actions

- Organize international working groups to coordinate research efforts to evaluate effects of ecosystem loss on ecosystem functions and services, and advise on local to global solutions to address these risks
- Catalyze efforts to develop a global network of marine protected areas by bringing together experts on MPA strategies from developed and developing countries and from tropical, temperate and polar environments in order to share lessons learned and best practices
- Support and improve data sharing and standardization tools such as the International Ocean Biogeographic Information System (www.iobis.org) and World Register of Marine Species (WoRMS, www.marinespecies.org).

8. Marine ecosystem degradation

Key messages

- Marine ecosystem degradation involves the loss of benefits to society; it can occur as a result of natural causes or human activity.
- Impacts of climate change, including ocean acidification, are inherently global. Widespread local activities can also have cumulative global effects. The many components of both kinds of impacts interact.
- The rate of marine ecosystem degradation is accelerating due to economic growth and population growth.
- Improved assessments of ecosystem state should be based on integrated, interdisciplinary observations that include biodiversity and ecosystem functioning.
- Further international policy action is needed to reduce the drivers of marine degradation, improve marine literacy and develop a global approach to marine conservation.

What is ecosystem degradation?

Marine ecosystems are degraded whenever the goods (e.g. food, raw materials, drugs) and services (e.g. climate regulation) we obtain from them are reduced.

Marine ecosystem degradation occurs both at structural level, with alterations of biodiversity (i.e. the variety of species pools in various habitats and ecosystems), and at functional level, with alteration of ecosystem functioning (i.e. the interactions between the living and the non-living components of ecological systems that guarantee high levels of production at all trophic levels, from primary producers, plants and algae, to top predators such as sharks, marine mammals and large fish).

Are marine ecosystems degraded?

Marine ecosystems have always been changing. It is crucial, however, to assess if observed changes are due to human activities or if they are due to natural phenomena, such as El Niño and the North Atlantic Oscillation, that are probably unrelated to our action.

At the 21st Conference of the Parties of the UN Framework Convention on Climate Change (UNFCCC COP21), 198 countries recognized the impact of human activities on climate, based on the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Emissions of carbon dioxide and other greenhouse gases are not only altering climate regimes, but also causing oxygen depletion and ocean acidification, with detrimental effects on the health of the ocean (Gross, 2016).

Climate change is global, with clear trends in changes to the physics and chemistry of the ocean that together lead to changes in the structure and function of marine ecosystems. The new states of marine ecosystems are less conducive to provide the goods and services that greatly contribute to human well-being (Waters et al., 2016).

Many local activities are so widespread that their impact on the ocean has become global. These include overfishing (both legal and illegal); unsustainable aquaculture; transport of non-indigenous species that become established at new locations as invasive species, altering the functioning of the ecosystems; alteration of food webs; eutrophication leading to harmful algal blooms and bottom water hypoxia; alteration of sea floor integrity with destructive fishing gear (such as trawling) and deep sea mining; permanent alteration of hydrographic conditions due to the construction of infrastructures such as harbours, coastal defences and dams; chemical pollution with contamination of food webs and sea-food; discharge into the sea of plastic and other types of litter; and the introduction of any kind of energy (sound, temperature, electricity, etc.) over the limits of tolerance of sensitive species.

These impacts often act in synergy, with combined consequences that are more than additive – and that cannot therefore be determined from experiments that investigate one impact at a time. Evident symptoms of global marine ecosystem degradation, besides acute ones linked to local situations, are: impoverishment of fish stocks, leading to trophic downgrading (i.e. removal of large top predators and prevalence of species that occupy lower positions in trophic networks; Fig. 8.1) and increasingly frequent jellyfish blooms (Roux et al., 2013); unsustainable aquaculture based on feeding with other, smaller fish from over-exploited natural populations; invasions of alien species that alter ecosystem functioning; habitat destruction, with direct impacts on the physical features of substrates; contamination of ecosystems, with introduction of contaminants in the water and their accumulation in food webs; and mass mortalities due to high temperatures, oxygen depletion or acidification, resulting in widespread defaunation and dead zones (McCauley et al., 2015; Rivetti et al., 2014).

Figure 8.1 Decrease in fish size and abundance for a range of species as shown by 'trophy' photographs from West Keys, Florida in 1957 (top), early 1980s (middle) and 2007 (bottom). From McClenachan (2008); *re-use permission requested.*

Due to the above, the answer to the question 'are marine ecosystems degraded?' is 'yes': marine ecosystems are losing the ability to provide human benefits at a very fast pace, due to evident changes in both biodiversity and ecosystem functioning. The causes are many, and interact with each other.

Past trends of ecosystem change

Marine ecosystem degradation, as described above, became significant since the Industrial Revolution of about 200 years ago (Worm et al., 2006; Yasuhara et al., 2012). There is, however, likely to have been some older, but comparatively minor degradation, related to earlier times, including native people and ancient dynasties.

Global analyses show that marine ecosystem degradation began significantly earlier in Europe and North America (~1800s) compared with Asia (post-1900) due to about 100-year earlier industrialization in European and North American countries (Yasuhara et al., 2012; 2015).

All lines of evidence including time-series fishery data , historical documents, archaeological remains and paleontological/sedimentary records consistently indicate increasingly rapid ecological degradation over the past 100-200 years (Jackson et al., 2001; Lotze et al., 2006; Worm et al., 2006; Britten et al., 2012; Lotze & McClenachan, 2014), with irreversible modifications (Buchanan, 2014).

Marine ecosystem degradation accelerated globally in the late 20th Century due to post-World War II economic growth and population growth, with associated urbanization, chemical fertilizer use, introduction of other pollutants, advanced fishing gears, and factors associated with climate change (Hoegh-Guldberg et al., 2007; Yasuhara et al., 2012).

Proposed G7 actions

The G7 nations are encouraged to take the necessary actions to:

- Better assess the state of marine ecosystems with the implementation of observation strategies that consider biodiversity and ecosystem functioning. Current observatories mostly focus on physical, chemical, and biogeochemical features of the ocean: they tend to disregard both biodiversity and ecosystem functioning. Existing observation systems must be upgraded and more strongly linked to policy-making, in order to have a constant check of the global situation, and be able to bring about management interventions whenever signs of significant degradation of ecosystems become evident (Boero et al., 2015).
- Identify the sources of stress and remove or buffer them. Most stressors derive from land-based activities, and the solution of our marine problems resides on land.
- Consider marine systems as a single synthetic object, linked to terrestrial ones, with implementation of the ecosystem approach, maritime spatial planning, and integrated coastal zone management within a single, co-ordinated strategy based on holistic principles. Do not analyse the impact of any activity in isolation from other impacts; consider synergies.
- Promote technological innovation that considers the solution of environmental problems (e.g. reduce the use of plastics, reduce the use of fossil fuels, promote efficiency in resource use, eliminate waste).
- Internalize environmental costs in cost-benefit analyses of any human enterprise (currently they are mostly externalized).
- Promote international legislation aimed at solving global environmental problems. Countries should not cause deterioration of the environment of other countries; i.e. it is necessary to avoid the impact of national activities acquiring a global dimension. This principle is valid from carbon emissions to plastic and contaminants discharge. Global warming is altering the 'cold engine' in the sub-polar North Atlantic, the driver of the Great Oceanic Conveyor, with a probable impact on global current regimes, leading to big changes in the functioning of oceanic ecosystems (and also further altering climate). Responsibilities are reticulated, as are the changes, so it is important that all states agree on general principles, as they did at UNFCCC COP21.
- Assess sustainability by including the loss of natural capital in all cost-benefit analyses, and matching it against the growth of economic capital.
- Promote ocean literacy in school curricula; we cannot respect what we ignore. Education is our future.

- Marine Protected Areas (MPAs) should be instituted to preserve biodiversity hot spots. Nevertheless, the management of ecosystems, aimed at preserving their functions, requires a global approach to conservation that cannot be restricted to MPAs. All marine waters should reach a Good Environmental Status.

Advanced countries such as the G7 nations have benefitted greatly from the use of natural capital on a worldwide basis, thereby increasing their economic capital. It is therefore appropriate that G7 countries should take a global leadership role in ocean conservation, providing a major contribution to the removal of causes of marine ecosystem degradation – hence restoring not only the quality of their own environment, but also for that of developing countries, less able to afford conservation and remediation measures. The current situation does not require further proof that human impact on marine ecosystems is unacceptably large, and increasing. The task now is to decide how to reverse this trend, requiring global-scale decisions, commitments and implementation.

The solution of these problems necessarily requires greater scientific and technical effort: well-trained researchers need to extract sound scientific knowledge from the big data collected by, and stored in, highly sophisticated information systems. Based on this knowledge and understanding, policy-makers will then be able to use their wisdom and judgement to decide how best to restore both the beauty and functionality of nature – reversing the tendency towards an uglier and less productive world – whilst also safeguarding ocean biodiversity for the next generation (Thiede et al., 2016).

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Abbreviations

Excluding those abbreviations that are only mentioned once when they also given in full.

CBD	Convention on Biological Diversity
CO_2	Carbon dioxide
CoNISMA	Consorzio Nazionale Interuniversitario per le Scienze del Mare (Italy)
COP	Conference of Parties
CNR-ISMAR	The Marine Sciences Research Institute of the Italian National Research Council
CNRS-INSU	Centre National des Sciences de l'Univers - Institut National de la Recherche Scientifique (France)
CSIR	Council of Scientific and Industrial Research (India)
DNA	Deoxyribonucleic acid
EEZ	Exclusive Economic Zone
EU	European Union
FT-IR	Fourier transform infrared spectroscopy
G7	Group of Seven: Canada, France, Germany, Italy, Japan, UK and USA
GEOMAR	Research Centre for Marine Geosciences (Germany)
GOOS	Global Ocean Observing System
IAPSO	International Association for the Physical Sciences of the Ocean
ICES	International Council for the Exploration of the Seas
ICSU	International Council for Science
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPRC	International Pacific Research Centre
IOC	Intergovernmental Oceanographic Commission of UNESCO
ISA	International Seabed Authority
IUGG	International Union for Geodesy and Geophysics
MARPOL	International Convention for the Prevention of Pollution from Ships
NASA	National Aeronautics and Space Administration (USA)
NOAA	National Oceanographic and Atmospheric Administration (USA)
NSF	National Science Foundation (USA)
OMZ	Oxygen Minimum Zone
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
pH	Logarithmic measure of the hydrogen ion concentration in aqueous solution
PICES	North Pacific Marine Science Organization
RCP	Representative concentration pathway
REE	Rare earth elements
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SPC	Secretariat of the Pacific Community
UK	United Kingdom of Great Britain and Northern Ireland
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WMO	World Meteorological Organization