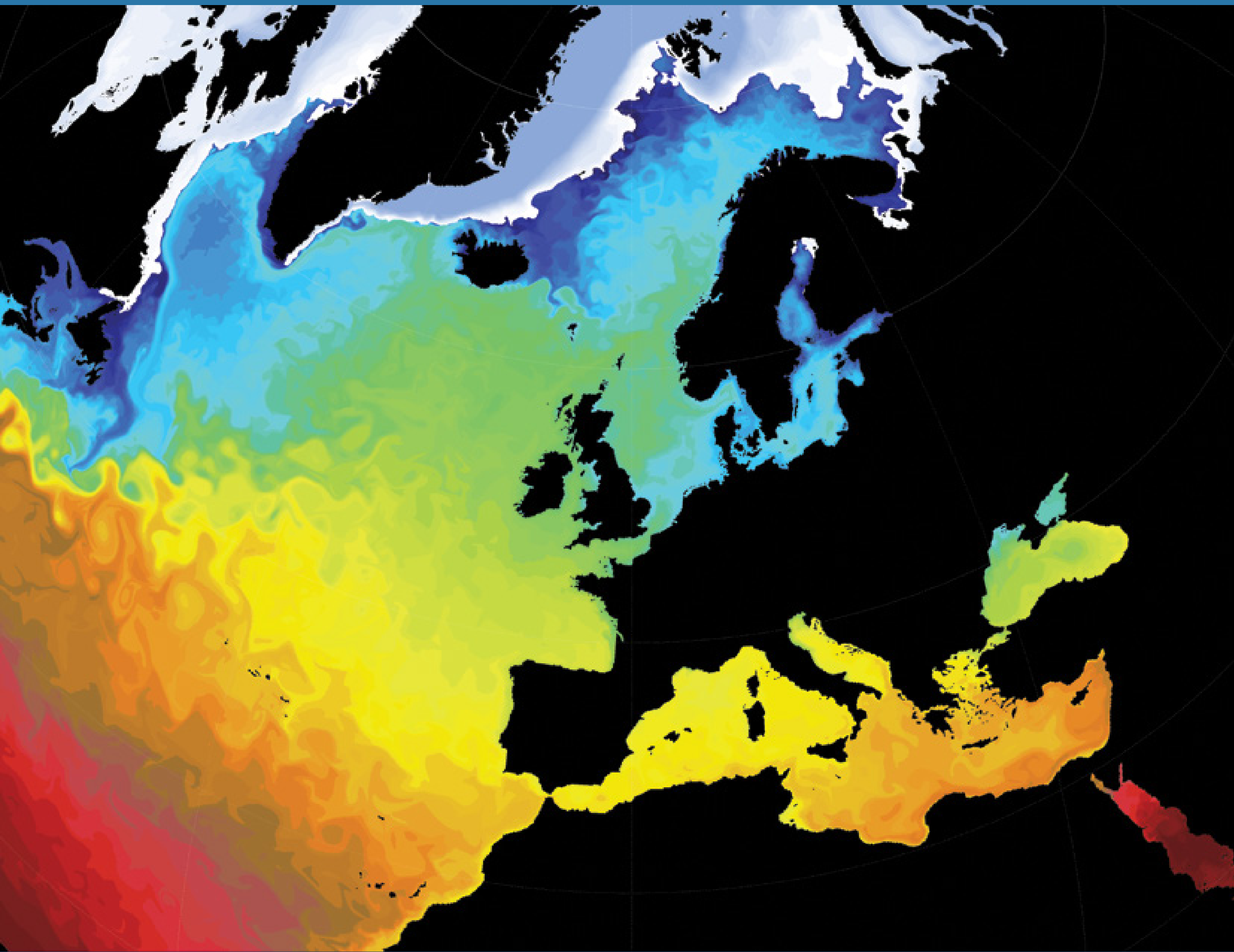
Marine sustainability in an age of changing oceans and seas



Report by the European Academies' Science Advisory Council (EASAC) and the Joint Research Centre (JRC) of the European Commission

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Cover illustration: Sea Surface Temperature in European Seas (5 day mean SST with sea-ice cover from the beginning of January 2004) from the NEMO 1/12 degree model courtesy of National Oceanography Centre, UK/Marine Systems Modelling/Andrew Coward.
The temperature of the seas around Europe underscore the importance of the sea for the livelihood of the European societies.

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Preface

EASAC, the European Academies' Science Advisory Council, provides science-based advice to European decision-makers. It does so very often by producing reports or statements that synthesise a subject in a form suitable for a wide audience and focused on questions that are relevant to policymaking. After over 50 reports and statements by EASAC on issues concerning the environment, energy and biosciences, the present report is the first dealing with marine issues.

The Joint Research Centre (JRC) of the European Commission provides EU policies with evidence-based scientific and technical support throughout the whole policy cycle, including to other Commission services, EU institutions and Member States. This includes support for marine, maritime and fisheries policies.

The report is the result of fruitful collaboration between EASAC and the JRC. It was prepared by a working group of experts drawn from the European national science academies, which was supported by the JRC. It is hoped that the report will prove useful in the further development and implementation of European Union marine and maritime policy as well as the organisation of supporting science needed to inform and guide these policies.

The last 10 years have seen a growth in marine and maritime policymaking within the European Union with a key feature being the concept of the ecosystem approach to guide sustainable use of the seas. In view of this increasing focus on coherent marine and maritime policy and governance within the EU, as well as globally, the EASAC Council decided in December 2013 to conduct a study on the issue of marine sustainability together with the JRC. This decision particularly acknowledged the need to provide advice from the point of view of the European science academies on this new direction of marine policy and to highlight the particular challenges that this poses to the organisation of science.

The report has the aim of contributing to the governance challenge of how to integrate the various aspects of marine policy (fisheries management, biodiversity conservation and marine environmental protection) as part of a coherent ecosystem approach. It considers how current science knowledge on marine ecosystems and the organisation of science can support an integrated approach to management of the seas. The report looks at a number of key aspects for sustainable development in changing oceans and seas, and particularly highlights the key scientific challenges in addressing these issues. The report presents both recommendations from science for policy development, and recommendations on policy for science.

The health of the oceans and coastal seas is vital for the future well-being of all of Europe, indeed of all humankind, and sustainable management of this sensitive and fast-changing component of the global ecosystem is essential.

Jos WM van der Meer
EASAC President

Vladimír Šucha
JRC Director General

Summary

Introduction

Oceans and seas are essential components of the biosphere. Marine sustainability and human society are intrinsically interlinked. The oceans are crucial for global food security, human health and regulation of climate. The livelihoods of over 3 billion people worldwide depend upon services from marine and coastal biodiversity. Under the EU's blue growth strategy, new marine goods and services, such as marine renewable energy, marine biotechnology and marine minerals, are seen as important sources of employment, economic security and sustainable development.

Over the past 10 years there has been increasing focus on marine and maritime governance both within the European Union and beyond. The fundamental challenge that European policymakers must address is how to achieve a sustainable use of the oceans that ensures that marine goods and services are available for future generations, while meeting the demands of human population growth and economic growth.

Policy development and implementation for marine sustainability

Whilst we focus in this study on marine and maritime policies, it must be highlighted that ocean absorption of increased atmospheric heat and carbon dioxide resulting from human activities will significantly deepen the challenge of achieving marine sustainability. An intensification of climate change and acidification of the oceans can be expected to have stark consequences for marine biodiversity and productivity at regional and global scale.

The EU's integrated maritime policy (IMP) and marine strategy framework directive (MSFD) already express a determination to use an ecosystem approach for the integrated management of human activities. This provides a key means of fostering marine sustainability. Ecosystem-orientated perspectives are commensurate with the inherently interconnected character of physical, biogeochemical and ecological processes in the sea and human interactions with them. However, the scientific understanding of marine systems is constantly evolving and there remain considerable uncertainties in the basic characterisation of marine ecosystem structure and function and in key physical and biological drivers. Policymaking and policy implementation must recognise these uncertainties and drive efforts to address them.

An effective implementation of the MSFD will be key for ensuring sustainable use of the seas through its use of an ecosystem approach and emphasis on ecosystem health, expressed through the concept of good environmental status (GES). The first steps in implementing the MSFD must be built on and used to strengthen the development of the IMP and the implementation of the EU directive on marine spatial planning.

The revision of the common fisheries policy must be used as base for securing an end to overfishing both within EU waters and beyond and to minimise harmful impacts of fishing on marine ecosystems. Growing populations will demand more food from the seas and further steps are needed to improve the ecological efficiency of marine harvest.

Marine protected areas (MPAs) are currently used as conservation tools under the EU nature directives, but so far most attention has been on benthic habitats. The networking of MPAs on the basis of pelagic connectivity has been little explored as a means to enable recovery of fish stocks and to support GES at sea-basin scale.

EASAC and the JRC make the following recommendations for the further development and implementation of policy for marine sustainability:

Climate change

(i) Carbon emission mitigation is a prerequisite for the sustainability of marine ecosystems. We, therefore, **emphasise** that European policymakers must use all opportunities to drive the transformation to a carbon-free economy by advancing carbon emission mitigation measures, enforcing carbon emission reductions and stimulating alternative technologies.

Implementing ecosystem-based management

(ii) We **urge** that the ecosystem approach is applied in a holistic manner to strengthen the EU's integrated maritime policy through concerted application of the common framework of goals for good environmental status under the MSFD. This framework for ecosystem health should be used to achieve a closer integration of EU marine environment, maritime, marine fisheries and marine nature policies.

(iii) We **recommend** that ecosystem-based marine and maritime governance under the integrated maritime policy and the MSFD is developed through sustained commitment to a step-by-step adaptive implementation, which:

- makes use of the best available current scientific knowledge about marine ecosystems and their dynamics, and tools for understanding influences critical to ecosystem health;
- is embedded in awareness of uncertainties and limitations in characterising marine ecosystem structure and function and key physical and biological drivers;
- recognises the complexity and interconnections in the sea and the limitations in developing scenarios of environmental change;
- does not delay management action on account of uncertainty but makes appropriate use of precaution to avoid unintended impacts;
- has real scope and incentive for innovation and improvement taking advantage of constantly evolving scientific knowledge and capabilities;
- gives increased attention to the role of pelagic habitats and systems in generating functional change within marine ecosystems, including using the concept of cells of ecosystem functioning in the definition of spatial management areas.

Impact assessment and maritime spatial planning

(iv) We **recommend** an integrated implementation of the MSFD, the marine spatial planning directive and nature directives that provides for coordinated planning and management of the seascape. Spatial and operational management of activities should be based on the goals for ecosystem health at the sea-basin scale developed under the MSFD. Policymakers and scientists need to work together to define what level of disturbance constitutes too much disturbance. This must also take into account the connectivity of the marine system within and between Member States' marine waters.

(v) We **recommend** that independent analysis is needed to inform policy choices that promote specific resource uses or societal behaviours that are linked to the oceans. The uncertainties inherent in these choices should be identified at an early stage and continually reviewed taking into account information from research and development activities. Policies such as those on deep-sea mining and marine renewable energy development need to be informed by ongoing analysis of the impacts of different policy options that internalise environmental costs and uncertainties and build in new learning.

Towards increased and sustainable ocean harvest

(vi) We **strongly recommend** that the revised common fisheries policy is used to bring current fisheries exploitation to sustainable levels by ending overfishing and minimising the harmful impacts of fisheries on marine ecosystems. Scientific advice on fisheries management and stock recovery needs to be followed.

(vii) To anticipate demands for increased food biomass from the sea that will come from human population growth, we **recommend** greater commitment to policy development and knowledge building on how to improve the ecological efficiency of ocean harvest. This includes exploring the potential for ecologically efficient aquaculture and sustainable seafood from species groups from the lower levels in marine food webs.

Networks of marine protected areas

(viii) We **highlight** that networks of marine protected areas need increased attention as tools within overall ecosystem-based management, including at sea-basin scale. This requires a substantially increased commitment to understand water movements and ecological connections between ecologically important and vulnerable areas. This knowledge needs to be built into the development of networks of MPAs, which can play a strong role in securing good environmental status.

Organising and focusing marine science to support marine sustainability

European Union research and technological development programmes contain much important marine science. Horizon 2020 continues this tradition with a strong emphasis on research to support EU policymaking in marine and maritime governance. The integrated maritime policy has recognised through its 'Marine knowledge 2020' initiative that improved marine knowledge is key to fostering innovation in the marine and maritime economy. These efforts must be continued to realise the ambitions for EU marine data infrastructures and the systematic management of marine data. Horizon 2020 should be used as a key mechanism for improving marine knowledge to support the MSFD and IMP. To support integrated marine and maritime governance, a fundamental shift in marine science towards holistic and integrative research is needed. This must combine continued work to characterise and understand ecosystem structure and functioning, with the means to characterise ecosystem health and provide scenarios of the environmental, economic and societal impact of different choices in human use.

EASAC and the JRC make the following recommendations for organising and focusing marine science to support marine sustainability:

Building knowledge on increasing the ecological efficiency of ocean harvest

(i) We **recommend** that a major research initiative is urgently initiated into ecosystem-orientated approaches to ocean harvest that can address the demands for increased food biomass from the oceans to meet demographic and economic development. This research should build knowledge to inform options for increasing the overall ecological efficiency of ocean harvest and thereby the sustainable yield from the ocean. These options include examining the potential of sustainable seafood biomass from lower levels in the marine food webs and developing ecologically efficient aquaculture.

Building an integrated knowledge base for marine sustainability

(ii) We **recommend** the implementation of a sustained European strategy for marine ecosystem observation that incorporates biological observations alongside ongoing physical and chemical programmes. This will fulfil the goals of understanding the state of the environment and its component ecosystems needed to define GES under the MSFD. Biological observations, representative of all trophic layers, should be based on a sustained, long-term network of time series, including observatories at coastal marine research stations, within marine protected areas, and along ocean transects. Oceanic observation sites where the effects of global changes are monitored in a systematic fashion should form an important part of this strategy.

(iii) We **recommend** that habitat mapping takes into account not only the seabed habitats in the benthic domain but also the habitats in the water column and their dynamics that generate much of the functional changes within marine ecosystems.

(iv) We **recommend** that the large and diverse datasets assembled by EU data infrastructure projects need to be tested to support knowledge building across research and operational activities. Concerted efforts are needed to open up access to marine data, so that the benefits of these infrastructures can be realised. Substantial support is needed for efforts to improve the quantity and quality of biodiversity data, such as those relevant for the MSFD, which are scarce in comparison to other data types.

Science support for marine sustainability

<u>Research set-up</u>

(v) We **recommend** that organisational structures for stimulating and funding European marine research programmes should be coordinated to reflect the interconnectedness of the sea with a slim administrative structure ensuring effective governance of the programmes and effective cooperation between the projects, the European Commission and national authorities. Shared funding from European Union and national resources should secure:

- the possibility to perform research at an international level;
- effective selection mechanisms ('one-stop evaluation') of international programmes based on quality; and
- the sustained viability of national marine research by the Member States.

<u>Research priorities</u>

(vi) We **recommend** that the key priorities for holistic and integrative research include:

- consolidating the scientific description and characterisation of marine biodiversity, including extending habitat mapping to address habitats in the water column and their dynamics;
- building comprehensive and coherent ecosystem-based indicators that recognise interactions between species, habitats and ecological processes and contribute towards a complete realisation of the concept of GES under the MSFD;
- quantifying marine species interactions and how they adapt to changing conditions in marine environments, including benthic-pelagic coupling;
- developing end-to-end integrated models that characterise socioeconomic benefits from the sea, the supporting ecosystems and biodiversity and the human and natural pressures that threaten them;

- building scenarios to explore future responses of marine ecosystems under anthropogenic and natural forcings and that help to define the controls and limits of ecosystem resilience;

(vii) To support efforts to mitigate the effects of climate change we also highlight the need to support research that cautiously considers the potential of marine experimental geoengineering.

Human capacity building

(viii) We **recommend** that greater attention needs to be given to developing human expertise in the combination and integration of individual marine sciences to support data interpretation. This requires:

- enhanced training of specialists in key disciplines and steps to ensure their retention as a valued part of the marine science structure.

- focused training of graduate scientists capable of interdisciplinary integrative marine science.

(ix) We **recommend t**hat a European Marine University is established as a virtual institution charged with leading the development of enhanced graduate education, training and research in interdisciplinary integrative marine science. The European Marine University should coordinate a coherent and sustained Europe-wide curriculum and develop harmonised goals for marine science. In support, we recommend that a specific focus of the Erasmus Mundus cooperation and mobility programme should be an interdisciplinary graduate marine research programme that focuses on the issues specified in this report.

Science in society

(x) We **recommend** that efforts are intensified to develop ocean literacy in Europe building on the work of the European Marine Science Educators Association. This work must be used to enhance public understanding of the importance of the ocean to humankind as the basis for a better appreciation of the environmental costs of economic development.

(xi) We **highlight** that to support this:

- improved information is needed on the current knowledge of ocean issues in the European population to guide ocean literacy and citizen science initiatives;

- outreach from EU and national research needs to be given more attention during funding decisions, with more emphasis placed on the development of communication and outreach skills.

1. Introduction

1.1. Oceans, seas and coastal areas are essential components of the global ecosystem. The oceans cover more than two thirds of the Earth's surface, contain 97 % of the planet's surface water and support 50 % of global primary production, hosting a huge biological diversity. Oceans are the primary regulator of the global climate and an important sink for greenhouses gases and provide us with water. Oceans are crucial for global food security and human health. Over 3 billion people worldwide depend on services from marine and coastal biodiversity for their livelihoods. Maintaining healthy and productive ocean ecosystems is therefore essential for achieving sustainable development.

1.2. Marine ecosystems are under increasing pressure from human activities and growing populations. The global human population is projected to increase from 7.2 billion in 2012 to 9.6 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2013). Human uses of the sea have both intensified and diversified over the course of the last century and, with technological development, a range of new interests in the use of marine goods and services has emerged. Society has also increasingly recognised the value of marine biodiversity and marine landscapes as locations to secure human health, and of the oceans' role in climate regulation. Strategies for marine and maritime governance need to respond to a range of natural and human-induced changes taking place today including rising sea temperatures, ocean acidification, depletion of fish stocks, habitat destruction, altered biodiversity and species distribution with consequent trophic effects, eutrophication and increasing hypoxic zones, and the increased dispersal of various anthropogenically produced substances. There is an increasingly complex range of challenges in preserving and maintaining healthy, resilient and productive oceans and ensuring that future generations continue to benefit from marine goods and services.

1.3. Our understanding of the seas and oceans is far more limited than that of our terrestrial habitat. We are only beginning to appreciate the role that the oceans play in the Earth's climate system, to tackle the threats to our marine environments, to value the benefits afforded to society by the sea and to understand the consequences for our health and well-being if these are lost. To address the challenges we face, a fundamental shift is needed in the way we approach marine science, both within Europe and globally, towards integrated and holistic research that supports ocean management, protection and conservation of marine ecosystems and a sustainable use of the oceans and seas.

Sustainable development

1.4. The concept of sustainable development emerged from the UN Conference on the Human Environment in Stockholm in 1972, which led to the establishment of the United Nations Environment Programme (UNEP), as well as the creation of a plethora of multilateral environmental agreements (MEAs). In 1987 Gro Harlem Brundtland, the then Prime Minister of Norway, defined sustainable development as: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1972).

1.5. The scope of sustainable development governance has expanded considerably with the conceptualisation that has emerged being one that integrates economic and social development with environmental protection. Progress across all these so-called pillars of sustainable development in a consolidated manner is seen as critical to its achievement. Ensuring that economic and social development occurs within and respects the limits of environmental sustainability is a profound challenge.

1.6. The adoption of a sustainable development goal (SDG) to conserve and sustainably use the oceans, seas and marine resources for sustainable development by the UN General Assembly in September 2015 ([1]) is a valuable step in framing international cooperation and the promotion of sustainable use of marine resources at a global level. The importance of specific targets and instruments within the SDG for oceans and coasts has been highlighted by Visbeck et al. (2014). It should be recognised that the concept of marine sustainability is not new; in 1992 Hsü and Thiede addressed the sustainable use of the seafloor.

1.7. Over the last 20 years, marine governance has moved beyond the sectoral management of marine activities that emerged during the second half of the 20th century to promote a holistic and integrated approach to management of the seas recognising that the collective human footprint on marine ecosystems needs managing. A key aspect has been the embedding of the ecosystem approach concept, originally defined internationally under the UN Convention on Biological Diversity, in regional seas management through the North Sea Conferences, OSPAR, the Helsinki Commission (Helcom) and the Barcelona Convention. The ecosystem approach (also referred to as ecosystem-based approach and ecosystem-based management) requires an integrated management of human activities that promotes conservation and sustainable use in an equitable way. It requires the best available scientific knowledge about both the structure and function of the ecosystems, and their dynamics, in order to identify and take action on critical influences on the health of marine ecosystems. Thereby sustainable use of ecosystem goods and services should be achieved through the maintenance of ecosystem integrity. Concepts such as integrated coastal zone management and maritime spatial planning have also emerged. A comprehensive review of marine governance has been provided by the German Advisory Council on Global Change (2013).

1.8. Integrated management approaches for marine sustainability have now become a key focus of European Union policy and legislation. The EU integrated maritime policy espouses a holistic approach to the sustainable growth of the maritime sector through its blue growth agenda. The environmental pillar of the policy is provided by the EU marine strategy framework directive (MSFD) requiring Member States to work in an integrated way to achieve the target of good environmental status (GES) by 2020. An EU directive on marine spatial planning was adopted in July 2014.

1.9. Marine governance and the use of marine goods and services has a strong global perspective. Approaches outside Europe can affect our use of goods and services in Europe and the quality of European seas and vice versa. During 2015 the United Nations General Assembly welcomed the first output from the UN Regular process for global reporting and assessment of the state of the marine environment ([2]). This summary of the first global integrated marine assessment has been developed as a scientific basis for decisions at the global level on the world's oceans and seas, and a framework for national and regional assessments and management decisions.

1.10. The seas around Europe (see Box 1.1) each have their own oceanographic and biogeographic character and encompass a diverse array of ecosystems. These different seas each fall to a different extent within European Union governance mechanisms and coordinated ocean management in each of the sea basins is at a different stage of development. Contrasting approaches may be merited in each sea basin for both science and governance, but pan-European efforts to provide a consistent framework are appropriate.

Rationale for an EASAC study

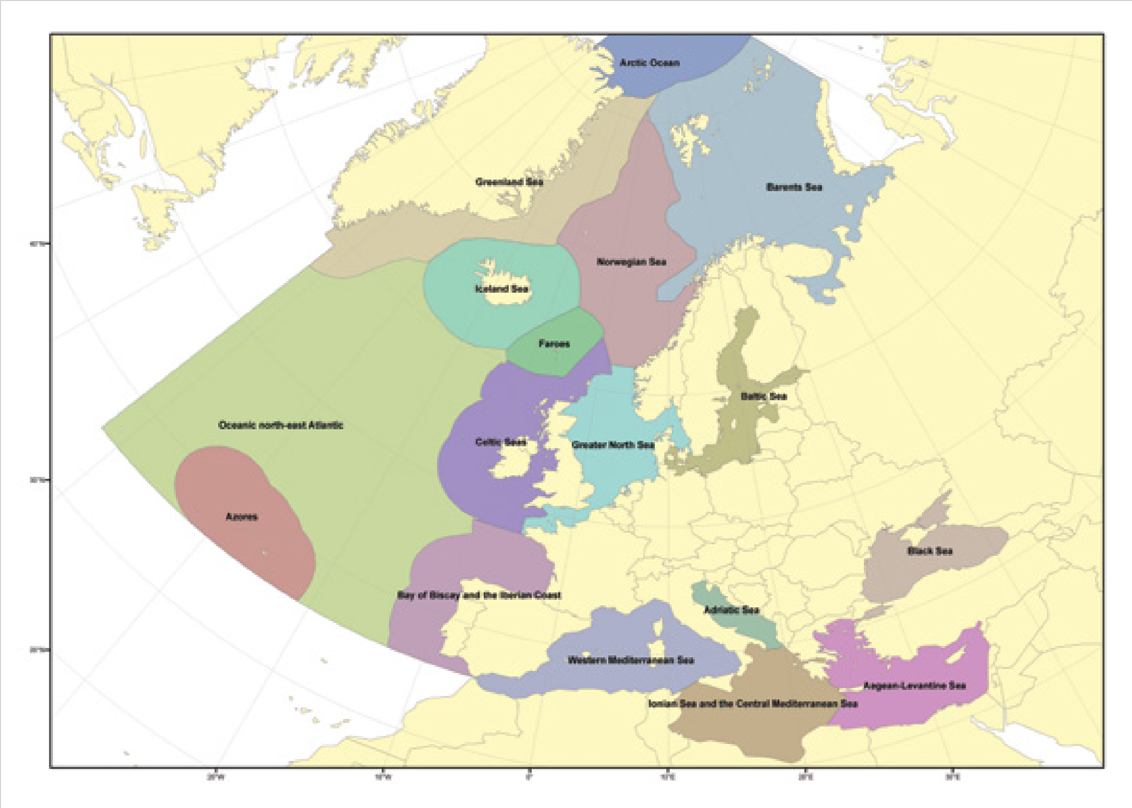
1.11. This EASAC report has been generated as the output of a Working Group on Marine Sustainability convened by EASAC in 2013 in response to the increasing focus on coherent marine and maritime governance in the EU, as well as globally. It has the aim of contributing to the governance challenge of how to integrate the various aspects of marine policy as part of a coherent ecosystem approach by considering how current science knowledge on marine ecosystems and the organisation of science can support an integrated approach to management of the seas. The study looks at a number of key aspects for sustainable development in changing oceans and seas (fisheries management, biodiversity conservation and marine environmental protection) and in particular considers the key scientific challenges in addressing these issues.

1.12. We first examine how the ecosystem approach to management can be developed in tandem with marine science to ensure a sustainable management of the seas (Chapters 3 and 4). We consider how long-term management of the demand for biomass from the sea may need to adapt, to ensure sustainable use integrated with other services (Chapter 5). Networks of marine protected areas are being increasingly used as a

([1]) United Nations Sustainable Development Summit 25-27 September 2015.

([2]) http://www.un.org/ga/search/view_doc.asp?symbol=A/70/112

Box 1.1: The seas around Europe embrace a range of physical and biogeographic characteristics and governance arrangements (map based on ICES ecoregions; source: ICES/EEA)



In the northern seas (Arctic, Barents, Norwegian) the annual cycle of sea ice formation and fresh water input, and the turnover of the thermohaline circulation play a key part in driving highly productive ecosystems. The shelf seas to the west of Europe (Faeroes, Celtic Seas, Greater North Sea, Bay of Biscay and Iberian Biscay Shelf) are driven by temperature, current and seasonal oscillations and upwelling of water along the continental margins. As the seas become more enclosed (Greater North Sea, Mediterranean Sea), the effect of discharges from land-based catchments becomes more important. The enclosed seas (Baltic Sea, Black Sea) are mainly catchment driven and sensitive to the effects of land-based inputs such as nutrients, leading to eutrophic and, in some places, oxygen-depleted conditions.

The EU Member States have direct responsibility for more than half of the regional seas surrounding the European continent, but the seas come under differing degrees of EU governance. Around the North Sea, Baltic Sea and Celtic Seas a majority of coastal states are EU Member States (seven of eight, eight of nine and three of three respectively). Around the Mediterranean Sea and Black Sea, EU Member States are a minority (eight of 21 and two of six respectively) with a greater variety of economic and institutional development and stability. Activities in the seas to the north are governed by non-EU coastal countries or through multilateral agreements (e.g. Arctic Council, North East Atlantic Fisheries Commission (NEAFC), OSPAR) and are outside direct EU governance mechanisms.

conservation and restoration tool and the report considers how science can inform the optimal development of these networks (Chapter 6). We then consider issues around the organisation of science to support current policy directions: the need for long-term observations and sound stewardship of data resources (Chapter 7). Finally the report considers the optimal coordination of national and European marine research, the need to develop the right human capacities and the need to build current work on public outreach to ensure that European society can pursue an informed interaction with the sea and oceans (Chapter 8).

1.13. The report proposes a series of recommendations aimed at the practical implementation of governance for marine sustainability and the optimisation of scientific support. These recommendations are intended to inform European Commission and national government work towards sustainable development and an integrated management of marine activities that equates to a sustainable use of the seas.

Climate change mitigation is a prerequisite

1.14. Global environmental change in which the ocean services play a key role through climate regulation and carbon dioxide absorption provides the context for all management of human interactions with the oceans (Box 1.2). The oceans' services come at a price (Stocker, 2015). With an intensification of climate change, stark consequences for marine biodiversity and productivity can be expected which will further constrain many human populations and activities. The ecological and economic impacts of marine acidification have many uncertainties but they could be severe. Carbon emission mitigation is a prerequisite for the sustainability of marine ecosystems. We strongly urge European policymakers to use all opportunities to drive the transformation to a carbon-free economy by advancing carbon emission mitigation measures and enforcing carbon emission reduction. Without the implementation of carbon emission reduction programmes, efforts towards marine environmental protection and sustainable management will very likely fail.

Marine litter

1.15. We also recognise that there are many further pressing issues for ocean science and governance that this report does not address. One issue that has been high on the political agenda during the preparation of this report has been marine litter and especially the flow of plastic debris into the marine environment (United Nations Environment Assembly, 2014). We recognise the important steps to formulate initial actions and to promote key research to further responses to this issue and will look with interest at the outcome of the first steps in this important work (Box 1.3).

Box 1.2: Climate change and ocean acidification

Climate change and ocean acidification are significant threats to marine ecosystems within the seas of Europe and will ultimately affect human well-being.

Atmosphere and oceans are closely coupled, with the ocean playing a significant role in regulating global and regional climate and weather patterns and absorbing heat from the atmosphere. Anthropogenic emissions of greenhouse gases are recognised to have contributed to an unprecedented warming of the climate system since the mid-20th century (IPCC, 2013). Ocean warming accounts for the storage of more than 90 % of the energy accumulated over the last four decades and redistributes it from one region to another on time scales ranging from years to several decades. Annual sea surface temperatures in the North-East Atlantic for the period 1999–2008 were warmer than in the period 1971–2000 across the whole of the North-East Atlantic. Sea temperatures in the North Sea have warmed the most, increasing by 1 to 2 °C over the past 25 years. In the Arctic, both the maximum (March) and minimum (September) sea-ice extent decreased by around 2.5 % and 8.9 % per decade, respectively, in the period 1979–2009. In 2015 the maximum winter sea-ice extent recorded was the lowest on record (National Snow and Ice Data Centre, 2015). Climate is an important factor driving changes in the distribution, abundance and seasonality of marine biota, including fish stocks. Evidence suggests that the range of many species is changing under a warming climate (Poloczanska et al., 2013). The changes in distribution and abundance, which are expected to continue in the near future, have been sufficiently abrupt and permanent to be termed 'regime shifts', with ecosystems reorganising rapidly in terms of changes in predator-prey relationships. Spread of non-indigenous species is also occurring, with mass mortalities of some species having occurred in the Mediterranean as a result (Coll et al., 2010; Rivetti et al., 2014).

Increased concentrations of atmospheric carbon dioxide (CO^2) also make the oceans more acidic. The ocean is currently absorbing roughly 25 % of emitted fossil fuel CO^2. There has been an average global decrease in ocean surface water pH of 0.1 units since the start of the industrial revolution which reflects a 26 % increase in acidity. Surface waters in polar seas and upwelling regions are increasingly at risk of becoming undersaturated with respect to calcium carbonate. Significant rates of acidification have been measured at several locations in the Arctic Ocean, which is particularly vulnerable to ocean acidification (AMAP, 2014). In the Nordic Seas, for example, acidification is taking place over a wide range of depths—most rapidly in surface waters and more slowly in deep waters. Decreases in seawater pH of about 0.02 per decade have been observed since the late 1960s in the Iceland and Barents Seas (AMAP, 2014). This ocean acidification also impacts the energy balance, physiology and behaviour of many marine organisms. For example, during natural ocean acidification events identified in the geological past, many marine calcifying organisms became extinct (Secretariat of the Convention on Biological Diversity, 2014). Predictions of ecological and economic impacts of marine acidification have many uncertainties but they could be severe, affecting the many biologically mediated processes that transport carbon from the ocean surface to the depths with potentially serious impacts through reduced diversity and abundances of various key species that underpin the current functioning of marine ecosystems (Nagelkerken and Connell, 2015).

Box 1.3: Marine litter

Marine litter is now recognised as a persistent problem affecting the seabed, the water column and coastlines. It poses risks to a wide range of marine organisms through ingestion or entanglement. Those risks threaten economic impacts for local authorities and for a number of economic sectors, for example aquaculture, tourism and fishing. OSPAR monitoring in the North Sea has shown that beaches have an average of 712 litter items per 100 m (OSPAR Commission, 2010), but areas where ocean currents converge have substantially higher concentrations. Monitoring of plastic on the seafloor has only just commenced. Some 65 % of items monitored on beaches are plastic, degrading very slowly over hundred-year time scales and prone to breaking up into small particles (microplastics). The widespread presence of microplastics (dimensions in millimetres or smaller), either from use in products (such as exfoliants or industrial abrasives) or resulting from the fragmentation of larger pieces, and their potential uptake by filter-feeding organisms is of increasing concern, given the capacity of plastic particles to absorb, transport and release pollutants. Microplastics are accessible to a wide range of organisms at least as small as zooplankton, with potential for physical and toxicological harm (Law and Thompson, 2014), such as limitations in growth and ecological efficiency. The consequences of plastic enrichment in the food web are still largely unknown and their investigation is a major research need. The main sources of litter from land include tourism, sewage, illegal dumping and open waste disposal sites. The main sea-based sources are shipping and fishing, including abandoned and lost fishing gear. Following inclusion in the list of GES descriptors in the MSFD, marine litter is now the subject of Regional Actions Plans adopted by the European regional sea conventions. EU framework research is also addressing this issue through projects such as CleanSeas, MARLISCO and NANOPLAST ([3]).

([3]) CleanSeas (http://www.cleansea-project.eu/drupal/?q=en/node/2 (accessed 14.1.2015)), MARLISCO (http://www.marlisco.eu/ (accessed 14.1.2015)) and NANOPLAST.

2. Policy and science context

EU policy context

2.1. The European Union and its Member States are party to a range of international conventions with goals relevant to marine and maritime governance. European policy and legislation for the sea (see Table 2.1) operates and takes reference from The United Nations Law of the Sea and the processes and institutions related to it ([4]), the Convention on Biological Diversity and the International Maritime Organisation, among others.

2.2. EU regulation of a number of marine activities has long been operated through separate sectoral policies, such as fisheries management, chemicals management and waste and waste water management. The common fisheries policy was introduced in the 1970s as a sector-specific policy aimed at both managing and making sustainable European fishing fleets and conserving fish stocks as a common resource. The common fisheries policy has undergone several revisions with the most recent revision taking effect in 2014 recognising that catch limits between 2015 and 2020 should be set for ensuring sustainable and harvestable fish stocks in the long term.

2.3. The European Union has also long been involved in marine policy efforts to protect and conserve the marine environment, having engaged early as a contracting party to European marine regional conventions such as OSPAR, Helcom, the Black Sea Commission and the Barcelona Convention. Since the late 1990s these organisations have begun to seek to apply the ecosystem approach as a key element of their strategies for marine governance.

2.4. In recent years, the European Union has started to develop its own framework of specific marine policies. The marine strategy framework directive (MSFD) adopted by the European Council in May 2008 introduces a new paradigm for European ocean management with the ambitious aim of achieving a good environmental status (GES) in European seas across a broad range of environmental descriptors, centred on biodiversity and ecosystem functioning. The MSFD represents the environmental pillar of the broader EU integrated maritime policy, endorsed by the European Council in December 2007. This embraces all marine-related issues, reinforcing cooperation and effective coordination at the different decision-making levels with a view to reconcile the apparently conflicting needs of protecting the ecosystem integrity of European seas and exploiting their natural resources. In addition, the launch of a marine and maritime research strategy (European Commission, 2008) as part of the European Research Area underlines the importance of pursuing scientific and technical efforts across all disciplines of the marine and maritime sectors. We applaud these developments and envision wider European approaches in these fields.

([4]) Commission on the Limits of the the Continental Shelf, International Seabed Authority, Department of Oceans and Law of the Sea, Regular Process for Global Reporting and Assessment of the State of the Marine Environment.

Table 2.1: Main European Union policies and directives relevant to marine sustainability

European Union policies and directives	Aim
Integrated maritime policy	To provide a more coherent approach to maritime issues, with increased coordination between different policy areas
Common fisheries policy	To ensure that fishing and aquaculture are environmentally, economically and socially sustainable and that they provide a source of healthy food for EU citizens
Marine strategy framework directive (MSFD) (2008/56/EC)	To take measures to achieve or maintain good environmental status (GES) in the marine environment by the year 2020 at the latest
Marine spatial planning directive (2014/89/EU)	To establish a framework for maritime spatial planning aimed at promoting the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources.
Water framework directive (2000/60/EC)	To achieve good surface water status (including good ecological status) for water bodies by 2015 at the latest (covers coastal and transitional waters)
Habitats directive (92/43/EEC)	To contribute towards ensuring biodiversity through the conservation of natural habitats and of wild fauna and flora
Birds directive (2009/147/EC — amended version 79/409/EEC)	Conservation of all species of naturally occurring birds in the wild state
Invasive alien species regulation (1143/204)	To prevent, minimise and mitigate the adverse impact on biodiversity of the introduction and spread of invasive alien species.

2.5. The overarching policy framework provided by the integrated maritime policy focuses on issues that do not fall under a single sector-based policy and issues that require the coordination of different sectors and actors. Of these, blue growth (European Commission, 2012), which provides the relevant components of the Europe 2020 strategy, is a long-term perspective to support sustainable growth in the marine and maritime sector as a whole. It aims to: identify and tackle challenges (economic, environmental and social) affecting all sectors of the blue economy; highlight synergies between sectoral policies; and study interactions between the different activities and their potential impact on the marine environment and biodiversity. In undertaking this, a fundamental component is both to foster research and innovation and to monitor and analyse the environmental impacts of blue growth industries (e.g. coastal tourism, desalination, offshore wind energy, tidal energy). 'Marine knowledge 2020' and maritime spatial planning (and coastal zone management), as pillars of the integrated maritime policy, provide the knowledge base around which blue growth activities should be developed. Furthermore, these pillars provide the necessary interface between the environmental policies (e.g. MSFD) and the maritime exploitation of the seas and oceans. The blue growth economy in the EU is expected to grow to employ 7 million people by 2020.

European Union support for marine science

2.6. Science has played an important part in supporting the development of sector-oriented management approaches. Assessments of fish stocks form a key basis for management advice for fisheries. Ecotoxicological research has informed the identification and management of hazardous substances. Conservation ecology has provided advice on habitat degradation to inform conservation policy. However, more interdisciplinary approaches are needed to decipher the effects of combined stressors on organisms, populations and systems, leading to integrated approaches to management.

2.7. The European Union supports and encourages marine science across the European Research Area through its framework programmes for research and technological development. The most recent of these programmes is Horizon 2020, running from 2014 to 2020. Several EU research projects address issues considered in this report [5]. The European Union also finances coordination and support actions for its framework programmes, such as the Euro-Oceans, MarBEF and Marine Genomics Networks of Excellence, which have now been merged to form EuroMarine+ to initiate more transdisciplinary science approaches. EuroMarine+ now aims to provide a rich and diverse source of the best expertise and innovation available in European marine research that can respond rapidly to societal needs and environmental demands. A range of EU LIFE projects have provided support actions to update and develop EU marine environment policy and implement the MSFD (Barratt et al, 2014).

2.8. The Galway Statement on Atlantic Ocean Cooperation (May 2013) initiated a transatlantic ocean research alliance between Canada, the United States and the European Union to address key scientific, environmental,

(5) For example, DEVOTES, VECTORS, CoCoNet and MIDAS.

governance, policy and societal challenges of mutual concern, including better ecosystem assessments and forecasts, a deeper understanding of vulnerabilities and risks, including those related to global climate change and its impacts (e.g. sea-level rise, shifts in biogeography of commercially important species) and anthropogenic impacts including those related to resource exploitation (e.g. fisheries, deep-sea mining).

European marine science networks

2.9. In addition to these EU science initiatives, EASAC recognises that there are many marine science networks and coordination initiatives working across Europe (see Table 2.2) as well as internationally, for example within the framework of the International Oceanographic Commission. In particular, the EASAC Marine Sustainability Working Group agreed that, as a basis for its own work, it should endorse the European Marine Board position paper 'Navigating the Future IV' (2013). 'Navigating the Future IV' provided a compendium of marine science policy briefings that together set out a blueprint for the next phase of seas and oceans research in Europe. To ensure coherence with policy developments, several of these briefings focused directly on societal challenges. The paper also demonstrated the key role of marine science and technology in supporting blue growth in sectors such as marine biotechnology, marine energy, aquaculture, fisheries and deep-sea mining.

Table 2.2: Selected marine science networks and coordination initiatives of relevance to European marine policy

	Purpose	Membership
European Marine Board	To develop common priorities to advance marine research and bridge the gap between science and policy	Leading national marine research centres and organisations in European countries
International Council for the Exploration of the Sea (ICES)	A global organisation that develops science and advice to support the sustainable use of the oceans, including European fisheries and environment advice	20 member countries from the North Atlantic region from both Europe and North America
Mediterranean Science Commission (CIESM)	Integrates a broad spectrum of marine disciplines, encompassing geophysical, chemical and biological processes, along with high-resolution mapping of the sea bottom	23 member countries from the Mediterranean region
Joint programming initiative Healthy and Productive Seas and Oceans (JPI Oceans)	To provide a long-term integrated approach to marine and maritime research and technology development in Europe	All EU Member States and associated countries that invest in marine and maritime research
SEAs ERA (2010-2014)	To establish a framework for maritime spatial planning aimed at promoting the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources.	
(funded by the EU FP7 ERA-NET Scheme)	Towards integrated European marine research strategy and programmes	Leading marine RTD funding organisations in 18 countries
EuroMarine	To give voice to the entire European marine scientific community and to promote cutting-edge science by supporting identification and initial development of emerging scientific topics, issues and methods	Leading marine science institutes across Europe
European Network of Marine Research Institutes and Stations (MARS Network)	A foundation created by European marine research institutes and stations	65 European laboratories, institutes or university departments primarily devoted to fundamental marine science and possessing coastal research facilities

3. Ensuring effective ecosystem-based management

Marine systems are inherently interconnected

3.1. The oceans and seas are a single interconnected system with component ecosystems that function at a range of spatial scales. Connections and interactions between the different parts of the sea and between the different components of marine biology have long been recognised. C. Petersen (1860-1920) studied the ecology of benthos to understand the ecology of fish, so as to provide better scientific advice to fisheries management. Science continues to reveal new connections in the sea. For example, interactions between warming sea temperature, ocean acidification and plankton are among the most recently identified (Reid et al., 2009).

3.2. Marine ecosystems are complex, and the biodiversity inhabiting them is huge and dynamic, with patterns and being controlled by the interplay between physical, biogeochemical and ecological processes. Consideration of these interactions and exchanges is crucial to the development and management of human interactions with the sea.

3.3. The different ecological components are often linked. Plankton, benthos and nekton need to be considered as part of a spectrum since many species, through their life cycles, can have phases in these different compartments and, thus, play different ecological roles during their life.

3.4. The water column and the seabed operate as a coupled integrated ecosystem; likewise, coastal habitats and benthos are closely linked. Habitat types in the water column, fronts, eddies, gyres, downwelling and upwelling currents, thermohaline stratification and circulation are often not stable and exist only during particular seasons, or under particular conditions. Upwelling and cascading phenomena, among others, often link coastal systems to deep-sea systems. Upwelling brings nutrients towards the coast and, together with terrestrial runoff, makes phytoplankton blooms happen. Downwelling brings oxygenated water into the deeper parts of the ocean, preventing anoxia.

Adaptive development of an ecosystem approach is needed

3.5. The aspiration to use an ecosystem-based approach under the marine strategy framework directive (MSFD) recognises these connections. From a global perspective the MSFD is unique and, if effectively implemented, has the potential to shift the way we manage European seas. The directive focuses Member States of the European Union on the effects of marine regulation through binding them to a measure of health in marine ecosystems. This is good environmental status (GES) [6], which is defined by reference to 11 descriptors of normative status (see Box 3.1). Each Member State is required to define strategies for managing human activities so as to ensure GES, working where necessary in coordination with neighbouring Member States sharing the same sea region.

[6] Good environmental status is defined as the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations.

Box 3.1: Main issues covered by the MSFD descriptors for good environmental status (see Annex 1 to Directive 2008/56/EC)

1. Biodiversity is maintained.

2 Non-indigenous species do not adversely alter the ecosystem.

3. Populations of commercial fish stocks are healthy.

4. Marine food webs: elements of foods webs ensure long-term abundance and reproduction.

5. Eutrophication is minimised.

6. Sea-bed integrity ensures functioning of the ecosystem.

7. Permanent alteration of hydrographic conditions does not adversely affect the ecosystem.

8. Contaminant concentrations have no pollution effects.

9. Contaminants in seafood are at safe levels.

10. Marine litter does not cause harm.

11. The introduction of energy (including underwater noise) does not adversely affect the ecosystem.

3.6. This is extremely challenging and sets a new benchmark in requirements for comprehensive and integrated marine scientific support. The question of how to characterise marine ecosystem health in a consistent way as a basis for maintaining ecosystem goods and services sits at the heart of the MSFD. While much progress has been made in understanding marine ecosystems, the relationship between biodiversity and marine ecosystem functioning is far from being resolved (Boero and Bonsdorff, 2007) and this will limit the possibilities for characterising ecosystem health and its interaction with human uses.

3.7. The first stages of the implementation of the MSFD have already taken place. EU Member States established in 2012 a first characterisation of the conditions that represent GES in their waters and defined related targets and indicators. The European Commission's assessment of this first implementation step (European Commission, 2014) highlights the lack of coherence between Member States' approaches. It is clear that the work has also been done in a quite pragmatic way based around existing sector-specific policies. Many science needs and uncertainties have been recognised, including conceptual and factual tools to measure the new indicators and targets (McQuatters-Gollop, 2012), agreed approaches to aggregation and integration of indicators (Borja et al., 2014) and how to define targets for the issue of food webs ([7]). There is, as yet, little in the way of an ecosystem perspective considering the underlying physical, biogeochemical and ecological interactions between ecosystem structure and functioning that provide the context around the indicators and the related targets to be achieved. Research and modelling to build this contextual understanding around the defined indicators is of fundamental importance.

3.8. While the directive provides the basis for an ecosystem-based approach, there is a potential risk that the partial approaches applied so far could become too enshrined in national legislative systems, and there is resistance to innovation when new scientific knowledge and capabilities become available. National governments and the European Commission must properly ensure an adaptive implementation which is progressive over the 6-year cycles of the directive's implementation, and moves beyond the initial steps by taking advantage of new scientific developments. The outputs of the EU framework programme research project DEVOTES (8) (2015-2016) will be important, among other projects, in this context by considering cumulative, synergistic and antagonistic impacts from human activities within the context of climatic variation.

3.9. As noted by the European Environment Agency (EEA) (2014) there is no single correct spatial scale at which an ecosystem-based, holistic approach should be implemented. The appropriate scale should be determined by the connections between ecosystem features and human activities. Pelagic features are often disregarded in the identification of functional units for management. For example, they have not been recognised so far in the habitats directive. Although episodic, they are very important in generating change within marine ecosystems and greater attention to the definition of patterns of occurrence might allow for a more optimal spatial management of marine resources (Box 3.2). We refer in this report to 'cells of ecosystem functioning' (Boero, 2014) as a conceptual approach for defining spatial units of the pelagic system. Coupling with global change will be important to model the complexity of responses in the pelagic system. Different issues require different scales of analysis and interpretative understanding.

The ecosystem-based approach to management of human activities must be all-embracing

3.10. Ecosystem-based management should provide a consistent framework to evaluate the ecological efficiency of all the different uses of the sea based around a framework of consistent goals for ecosystem

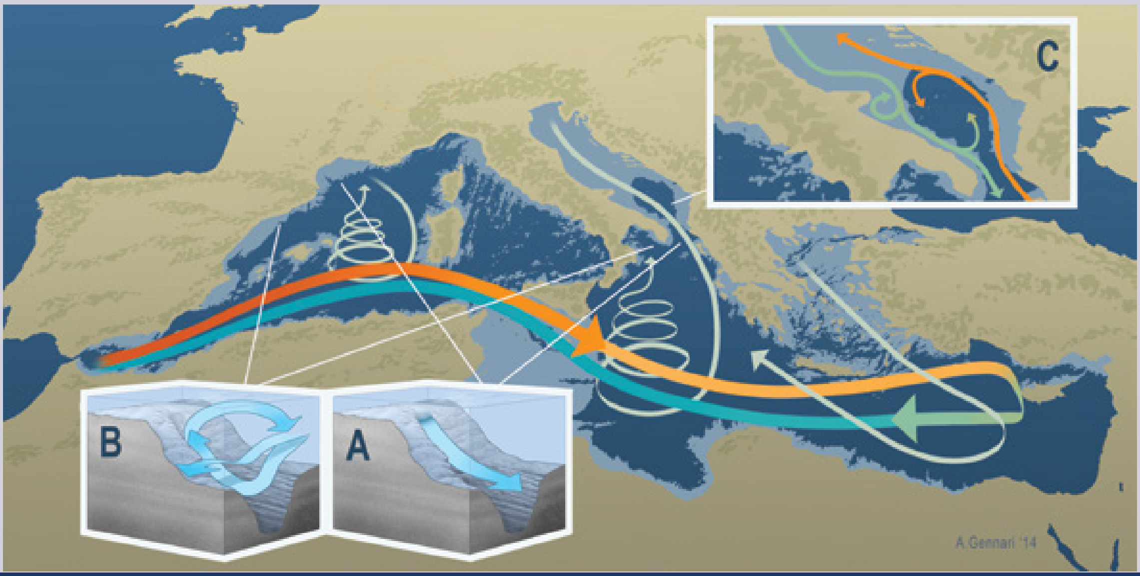
([7]) MSFD Descriptor 4 for determining good environmental status: All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.

([8]) DEVelopment Of innovative Tools for understanding marine biodiversity and assessing good Environmental Status (http://www.devotes-project.eu/ (accessed 14.1.2015))

Box 3.2: The importance of the water column for ecosystem function (artwork by Alberto Gennari, for the EU CoCoNet project)

In the marine environment, the EU habitats directive focuses only on the benthic realm and does not address the water column, the largest meta-habitat of the planet. The water column connects benthic habitats and itself comprises a suite of habitats. The features of the water column are not homogeneous, either in time or in space. There are portions of the water column that are more connected with each other than with other portions. Their homogeneity contributes to the connection of benthic habitats and, altogether, these tightly connected spaces can be considered as cells of ecosystem functioning, both at benthic and pelagic scales.

Large-scale circulation patterns, such as the Gibraltar current in the Mediterranean Sea, are coupled with regional scale patterns, such as the circulation triggered by the cold engines of the Gulf of Lions and the Northern Adriatic (**A**) (sometimes replaced by the North Aegean cold engine). At a smaller scale, the sea bottom topography and the coastline define sub-regional dynamics that do have coherent features: marine canyons are characterised by upwelling currents that trigger phytoplankton production (**B**), nourishing the coastal systems (coupled with terrestrial runoffs), whereas coastlines can enhance the formation of gyres and eddies (**C**) that define specific functions due to concentration phenomena. The definition of cells of ecosystem functioning, and of their interconnections, is mostly hypothetical and has yet to be tested experimentally, due to lack of integrative approaches linking the current regimes and the functioning of ecosystems at various temporal and spatial scales.



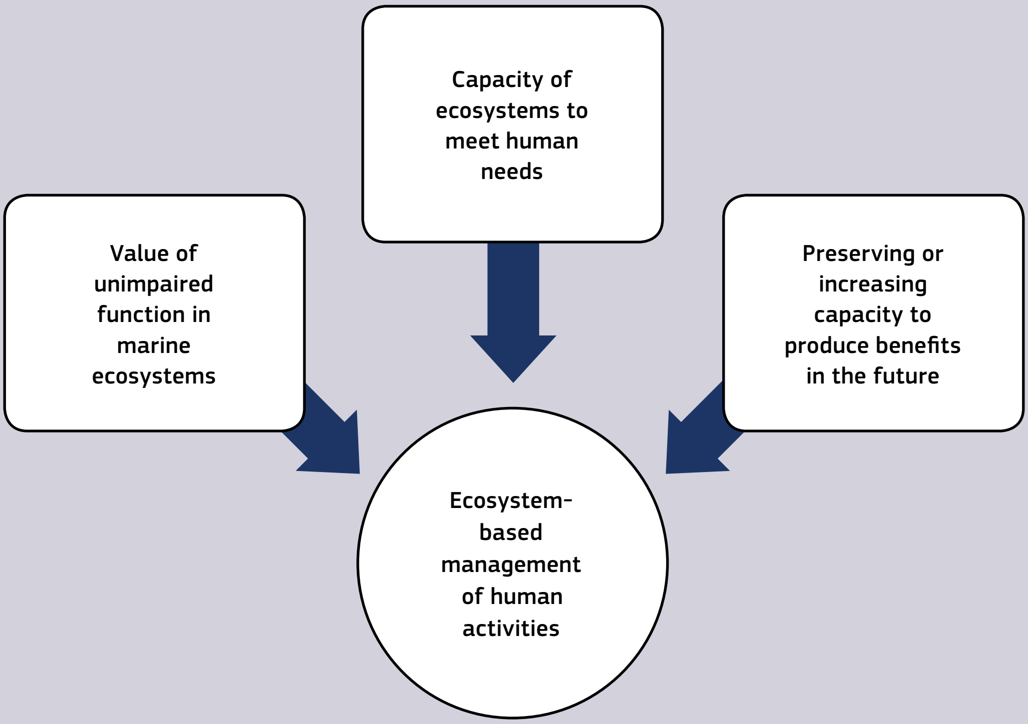
Source: Alberto Gennari, for the EU Project CoCoNet.

health within which human uses are managed (see Box 3.3). This framework should be used to promote innovation in these uses over the mid to long term, so as to ensure sustainability. Long-term economic, social and environmental sustainability that meets the demands of growing populations may require substantial policy adaptation informed by research.

3.11. The MSFD should be used as the framework for the closer integration of fisheries management, under the common fisheries policy, within goals for sustainability of the marine ecosystem as a whole. There are no good scientific reasons for treating fishing as a separate or dominant activity with its own conceptual framework. It is to be welcomed that commercial fish stocks are included as part of the MSFD alongside biodiversity, food webs and sea bed integrity which are also subject to fisheries pressure. This should be used as the framework for the integration of fisheries management within overall ecosystem goals. Fish play varying roles as components of marine ecosystems through their life cycles. A tuna, for instance, starts its life as a small planktonic larva, then grows into a juvenile stage that, eventually, reaches the adult size. The same species thus plays very different roles throughout its life cycle. Ecosystem indicators and scenario-building activities for fisheries should be part of the framework for integrated management of other activities. Scientific collaboration is beginning to bridge this gap.

3.12. Local and regional dimensions of ecosystem-based management need to be recognised reflecting the diversity of European seas and the different arrays of pressures acting in different part of Europe. Changes to the ocean from climate change and ocean acidification which will affect the resilience of marine ecosystems need to be accommodated within the evaluation of changes resulting from other pressures. Climate change will influence the different European regional seas in contrasting ways (see Box 3.4). Understanding the complex effects of combined environmental changes on marine ecosystems and their constituent organisms remains a key knowledge gap.

Box 3.3: Key principles for ecosystem-based management of human activities



Scientists must integrate the disciplines

3.13. Marine policy and legislative developments have been echoed by strong requests for integrated and synthetic approaches to marine sciences in the research calls issued by European funding agencies. Science has too often addressed this challenge by reducing complex systems into simpler units and by analysing these in isolation from one other. This results in the setting of conceptual compartments that do not reflect the real world. An example of this approach being the single fish stock that is currently used in fisheries management and that takes limited account of climate impacts and interactions between species. The first phases of

Box 3.4: Effect of climate change in European regional seas

The question of how global change impacts on different parts of Europe requires the integration of scientific knowledge at a variety of geographic scales. Climate change is expected to impact the physical conditions differently in each European regional sea especially in northern countries (EEA, 2014). The challenge of 'what good status or health is or means' (Borja, 2014) has been discussed in terms of: (i) temperature and sea-level rise; and (ii) acidity and their implications for functioning of ecosystems, but very little attention has been given to the larger-scale, complex biophysical interrelationships which couple the land–ocean–atmosphere interactions at the regional or European scale. The Baltic Sea, the Mediterranean and the Black Sea are fundamentally catchment-driven systems in contrast to the oceanically influenced North East Atlantic Ocean and the Greater North Sea. Global change will treat European areas very differently. In the north, it is impacting terrestrial ecosystems and the hydrological cycle in the catchments and thus calls for information from terrestrial change to changes in the sea. The land (farmland, lakes, rivers, forests) affects the coastal waters and their well-being in terms of allochthonous inputs of dissolved and particulate organic matter (DOM/POM) together with other dissolved substances including nutrients, toxics and microplastics. Our current understanding of, for example, the role of DOM/POM in the 'health' of marine waters is far from complete. Traditional limnology has treated brownification and sediment growth as internal loading issues in lake systems. Understanding of how the problems arising from DOM/POM alterations and how climate change-related stressors should be managed needs to be developed. The same is true for other substances. The northern seas call for the integration of terrestrial systems management with management of the sea. In the south of Europe, the Mediterranean Sea is acting as a miniaturised ocean and its biota are rapidly changing as the temperature increases: non-indigenous species of tropical affinity are becoming prevalent and indigenous species are undergoing mass mortalities (Rivetti et al., 2014). See Boero (2014) for a description of future scenarios in the Mediterranean Sea.

the MSFD have divided biodiversity into birds, mammals, fish, shellfish, and habitats as a pragmatic step to deal with its complexities. In the further implementation of the MSFD these aspects need to be linked together, for example through elaboration of the concept of food webs already included in the descriptors of GES. Reductionist approaches are certainly crucial in attaining sufficient levels of knowledge without being overwhelmed by the complexity of the observed systems, but eventually the shift from analysis to synthesis is necessary, especially for management and protection.

3.14. To support this fundamental shift it is necessary to move towards effective holistic and integrative research. New methodologies combining bioecological aspects, including human-related aspects, with physico-chemical information in a holistic, integrated manner are essential to inform ecosystem-based management. These approaches need to be built on the outcomes of the existing approaches that provide the basis for higher levels of understanding.

Ecosystem modelling will describe, providing scenarios and probabilities

3.15. Theoretical ecology has usually been developed with mathematical models that include a network of links among variables. This approach, in theory, is conducive to producing scenarios about the behaviour of the systems. Complex systems, including marine ecosystems, are nonlinear and chaotic, being extremely sensitive to initial conditions and, thus, inherently unpredictable in the medium to long term. A new level of complexity in modelling systems is needed, taking into account the history of the components and the variability of processes responding to external forcing and so being prognostic to future developments, within reasonable constraints. The EU's seventh framework programme for research and technological development (FP7) project VECTORS ([9]) is relevant here, being focused on exploring current and future ecological, social and economic consequences of change in the marine environment relevant to the ecosystem approach.

3.16. The current adoption of management strategies and plans that seek to be integrative must recognise that representing the complexity of marine ecosystems effectively remains a substantial scientific challenge. This challenge calls for focus on investment, scientific endeavour and human capacity building in the decades to come. Management of the seas must not fail to recognise the inherent uncertainties in marine ecosystems and must maintain the potential to embrace innovation in the theoretical frameworks that describe the structure and the understanding of these complex systems. Conceptual models that capture a wide range of perceptions of how marine ecosystems function may enhance dialogue between scientists from different disciplines and non-scientist stakeholders and can capture the dimensions of societal values and governance, as well as information on natural systems and economics.

Recommendations

3.17. Integrated ecosystem-orientated management approaches are commensurate with the inherently interconnected character of physical, biogeochemical and ecological processes in the sea. The ecosystem approach should be applied in an absolutely holistic manner to strengthen the EU integrated maritime policy. A unified and consistent framework of goals for good environmental status should be developed under the MSFD that encompasses all existing human uses and all components of the marine ecosystem. This ecosystem approach framework should be used to achieve a closer integration of fisheries management under the common fisheries policy, EU maritime policies and environmental policies and thus guide the management of existing human uses and development of future uses. While much progress has been made in understanding marine ecosystems, the relationship between biodiversity and marine ecosystem functioning is far from being resolved and this limits the possibilities for characterising ecosystem health and its interaction with human uses. A long-term step-by-step adaptive approach to ecosystem-based marine management is needed, that:

- makes use of the best available current scientific knowledge about the ecosystem and its dynamics, and of tools for understanding influences critical to ecosystem health;
- is embedded in an awareness of current uncertainties and limitations in the state of scientific knowledge and capabilities, and recognises the complexity and interconnections in the sea and the extent to which science can develop scenarios of environmental change;
- has real scope for and possibility to innovate and improve by taking advantage of constantly evolving scientific knowledge and capabilities emerging from research.

3.18. Greater attention is needed to the importance of the pelagic features in generating functional change in marine ecosystems. Information on pelagic features should be used to characterise cells of ecosystem functioning, which should become a key criteria in the definition of spatial management areas.

([9]) Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors (VECTORS) (http://www.marine-vectors.eu/ (accessed 14.1.2015))

4. Managing the environmental impact of human activities

Regulation of the impact of human activities has evolved in a fragmented way

4.1. Human uses of marine goods and services are diversifying and intensifying. Long-standing uses, such as fishing, waste disposal, sand and gravel extraction and maritime transportation, are being joined by a range of new interests including energy production from waves and wind, storage of greenhouse gases, algae production, ocean mining, use of genetic resources and development of new food sources.

4.2. Human activities are also extending their reach into the deeper waters of the Mediterranean, the North-East Atlantic and the Arctic. Technological advances mean that oil production and fishing are becoming a more realistic proposition in deeper waters and new industries that make use of the resource of these areas, such as deep-sea mining, methane and hydrates as energy reserves and the exploration of marine genetic resources, are coming into the frame for regulatory assessment. It has been suggested that blue biotechnology has an expected yearly growth rate of 5 to 10 % and deep-sea minerals extraction could eventually represent up to 10 % of the world's minerals.

4.3. Regulation of the environmental impacts of a number of human activities has long been operated through separate EU sectoral policies, such as fisheries management, chemicals management and waste and waste water management. Oil and gas industry regulation has been within the mandate of regional sea organisations, such as OSPAR and the protocols of the Barcelona Convention. A range of other public and private projects considered as having significant effects on the environment are evaluated under the EU environmental impact assessment directive (2011/92/EU ([10])). Provisions under Article 6 of the habitats directive (92/43/EC ([11])) are also relevant in applying to the effects of plans or projects on features protected through the Natura 2000 network ([12]). The strategic environmental assessment directive (2001/41/EC ([13])) applies to a wide range of public plans and programmes (e.g. on land use, transport, energy, waste, agriculture). Regulation of deep-sea activities in the area beyond the national jurisdiction of coastal states will fall under the International Seabed Authority.

4.4. With this plethora of approaches, different sectors respond in many different fashions to uncertainty and the application of the precautionary principle. Ecosystem-orientated approaches need to be used to guide the management of the multiplying human demands for marine space and resources.

([10]) Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment.

([11]) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

([12]) There has been work in some countries (e.g. Germany, Sweden, United Kingdom) to consider fisheries activity within the scope of this provision.

([13]) Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment.

Marine spatial planning needs to be coordinated as the means of ensuring good environmental status

4.5. Recent EU marine legislation, such as the marine strategy framework directive (MSFD) and the marine spatial planning directive, provides the opportunity of adopting more holistic approaches to achieve a sustainable use of the sea. Marine spatial planning is the central approach of the EU's blue growth strategy. It aims at promoting a rational utilisation of marine resources so as to facilitate the growth of maritime economies. Policy documents explain blue growth as based on sustainable development and the ecosystem approach (European Commission, 2012), but it remains to be seen how this can be implemented in practice.

4.6. As a first step, the marine strategies under the MSFD and marine spatial planning need to be implemented by Member States as a coordinated and integrated planning for the seascape, bringing the plethora of means for regulating marine activities into a consistent overall framework. Integration is a profound challenge, given the fragmentation into different management regimes, but ecosystem goals provided by good environmental status (GES) need to be applied uniformly as a common framework to guide the sustainability of marine activities. This should be underpinned by a progressively updated knowledge base of integrated information and expertise, capable of expressing current knowledge and uncertainty.

4.7. The MSFD targets and indicators that have been defined so far have not been formulated with a close emphasis on how to assess impacts for the planning of activities at an appropriate spatial scale. Goals at sea-basin scale must guide a much stronger integration of the MSFD approach with the systems for regulating activities and planning. Transnational planning and environmental appraisal of activities need coordination at a regional sea scale, taking into account the connectivity of marine systems and the potential for transboundary and cumulative effects and impacts within European seas. Networks of MPAs based on connectivity should be an integral part of the organisation of marine space.

4.8. This unified framework needs also to capture the influence of social behaviours and economic sectors on ecosystem goals, and express and communicate uncertainties across a range of data on different disciplines. Economic evaluation within an ecosystem approach must internalise the costs of impacts on biodiversity and ecosystem services. The Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) was established in April 2012 and is envisaged to become the leading intergovernmental body for assessing the state of the planet's biodiversity, its ecosystems and the essential services they provide to society. The EU should ensure that marine issues are given due emphasis in the work of the IPBES.

Sustainable use of the marine environment needs sustained fundamental science to guide it

4.9. Many countries have strong advisory science capabilities that support the regulatory environmental appraisal of new enterprises (e.g. offshore wind farms or new areas of aggregate extraction). These official capabilities are not isolated and need to draw on, and be fertilised by, the best available science emerging from universities and research institutions.

4.10. The application of marine strategies and spatial plans to achieve a sustainable use of the seas depends upon well-founded scientific knowledge on marine ecosystems as the setting for marine activities. The relationship between human society, environmental pressures, their impacts and the resulting state of the environment is conceptually described but is sparsely populated with empirical data. While the current state of knowledge allows us to predict some impacts with reasonable certainty, considerable expert judgement is needed when extrapolating to analyse impacts on biodiversity at the population level of species or at sea region scale. Given the expanding human use of the seas, it is absolutely critical that societal choices through policy, regulatory and planning regimes are informed by science-based knowledge. Science must play a key role in informing choices over: (i) the expansion of existing activities into new marine areas; (ii) the introduction of new activities and pressures into the sea; (iii) the potential for cumulative effects of pressures from human activities and (iv) the definition of the limits of ecosystem resilience.

4.11. Our understanding of the linkages between climate change and anthropogenic disturbances needs to be improved. The reduced resilience of marine systems as a result of climate change and ocean acidification needs to be factored into impact assessment.

4.12. Cumulative impacts can lead to poor environmental status even if the values of all the physical and chemical descriptors are below their limits. Although cumulative or in-combination impacts are recognised in the environmental impact assessment (EIA) directive, habitats directive and GES, tools for supporting their assessment are still in development, for example Micheli et al. (2013) or Coll et al. (2012). These tools require substantial integration of data methods for representing the sources of uncertainty. Empirical information on how ecosystems respond to different combinations and intensities of drivers is still scarce and assumptions and safety factors used to accommodate uncertainties for individual impacts multiply in combination. Substantial scientific efforts are needed to support the collation and combination of data and to develop effective and authoritative methodologies for integrative science that handle and express uncertainty in a way that can be communicated effectively to policymakers and society, who in turn need to be guided on the use of these tools.

4.13. Certain issues in environmental appraisal can become controversial and can become potential stumbling blocks between regulators, their scientific advisors, developers and stakeholders. Independent scientific experts from scientific institutions can provide a source of scientific appraisal for informing decision-making, but this needs calibration to ensure consistency between sectors. For transnational and transboundary projects, international scientific networks are a potential means of coalescing and expressing scientific opinion between national experts, but are relatively little used.

Early warning independent assessment of the impacts of policy choices is needed

4.14. Environmental appraisal of policy choices is not a specific requirement of the strategic environmental assessment directive and yet it is applied in some European countries as standard practice. Early warning independent assessment of policy choices is an element of good practice that should be more widely applied, particular where these choices favour particular resource uses, promote societal behaviours or are likely to lead to transnational cumulative effects. A dichotomy of approach is apparent between understanding impacts and facilitating technology. For example, research on the environmental effects of both marine energy exploitation and marine mining has increasingly lagged behind the developing technology and is urgently needed (Inger et al., 2009).

4.15. Targets for renewable energy have led some countries to embark upon relatively large-scale development of offshore renewable energy. Major gaps in knowledge for marine renewable development have involved uncertainties about abundances, life cycle and behaviour of marine biota in proposed development areas. This information needs to be combined with knowledge of environmental stressors, such as physical presence and the dynamic effects of energy devices, energy removal effects and acoustic and electromagnetic fields, which can result in single or multiple impacts on ecosystems in the vicinity of energy devices over different timescales (Boehlert and Gill, 2010).

4.16. An example of the challenge of integrated management is provided by considering the impact of noise on marine mammals. With the development of marine renewable energy production much attention is currently being given to the effects of impulsive noise from pile-driving during the construction of offshore wind farms. This is only one of the activities that can displace marine mammals. For example, there is some evidence that seismic exploration using air guns (Stone and Tasker, 2006) and shipping activities also disturb harbour porpoises (Nabe-Nielsen et al., 2014). The cumulative effect of all these activities will be to displace harbour porpoises from a proportion of their habitat. That proportion will change both in size and location through time. This displacement essentially reduces the amount of habitat available for the harbour porpoise population and, therefore, the overall carrying capacity of the sea, as long as disturbance continues. While there are limits for the number of harbour porpoises that can be caught as by-catch, there is as yet no corresponding process to reach a decision on disturbance limits for harbour porpoises (or other marine mammals). There is no firm consensus on what constitutes too much disturbance. Early and ongoing evaluation of such strategic development is needed as part of marine planning guided by such concepts, especially in the light of the consideration of underwater noise in the 11th descriptor of GES.

4.17. While marine renewable energy developments are at the present time likely to remain within exclusive economic zones (EEZ), there is significant interest in mining for minerals in deep-sea areas (> 200 m) to source metals including silver, gold, copper, manganese, cobalt and zinc. These minerals are present in high concentrations in manganese nodules on the deep-sea sea floor, cobalt crusts around seamounts and polymetallic sulphide deposits around deep-sea hydrothermal vents. The majority of these areas of interest lie in areas beyond national jurisdiction (ABNJ). Concerns over the capacity of the present system of ABNJ governance to deliver sustainable management of deep sea non-living resources in these areas have meant that much of the discussion on these issues at international level has been dominated by legal and policy questions. Yet there are significant scientific questions around such developments that need to be factored into European Union engagement in the relevant regulatory forum and the wider societal debate about resource use. There are huge technological challenges but also a relatively limited knowledge of the potential environmental impacts of deep-sea mining, both because the sector is still in the early stages of development and because scientific knowledge of the marine ecosystems in these areas is limited. Only 0.0001 % of the deep sea has been sampled biologically (European Marine Board, 2013). While the presence of some of the target features is known, their extent, frequency, sensitivity and functional role in the ecosystem are in some cases barely characterised and our knowledge is based upon relatively few well-studied examples. The full societal value of the deep sea is only beginning to be understood and choices around opening up new mining or developing more effective reuse of metals already in the technosphere appear relatively little discussed.

4.18. In the case of gas hydrates, research on one study site, Hydrate Ridge at the Cascadia convergent margin in the North-East Pacific, has advanced the fundamental understanding of cold seepage and gas hydrate formation and behaviour as no other effort at a comparable study site. Research from Hydrate Ridge provides the basis for the evolving understanding of the risks of pursuing methane hydrates as energy reserves, as well as the destabilisation of natural hydrates as a result of climate change (Suess, 2014).

4.19. Effective decision-making on sustainable and environmentally sound regulation of these activities must be informed by the best available science, but it must also be recognised that uncertainties will be inherent in any impact prediction due to limited knowledge. Ramirez-Llodra et al. (2011) have highlighted that legal and policy frameworks for the exploitation of deep-sea resources must take into account that progress among relevant stakeholders will be unsynchronised. Operators with economic interests in deep-sea resources will usually move more quickly than scientists, managers and legislators, but deep-sea research scientists should have a key role to play in advising on impact assessments in the deep seas. Effective stewardship of deep-sea resources will require continued exploration, research, monitoring and conservation measures, working in tandem with one another. Deep-sea mining is the subject of the FP7 MIDAS project (Managing Impacts of Deep-seA reSource exploitation) which will investigate the environmental impacts of extracting mineral and energy resources from the deep-sea environment with a view to providing information relevant to best practice.

Recommendations

4.20. We recommend an integrated implementation of the MSFD, the marine spatial planning directive and nature directives that provides for a coordinated planning and management of the seascape. Spatial and operational management of activities should be based on the goals for ecosystem health at the sea-basin scale developed under the MSFD. Policymakers and scientists need to work together to define what level of disturbance constitutes too much disturbance. This must also take into account the connectivity of the marine system within and between Member States' marine waters.

4.21. Support for fundamental science to inform marine regulation is crucial. This needs to continue work to characterise biodiversity and ecosystem functioning as the setting for marine development in order to provide a basis with which to extend descriptive scenarios for the impacts of developments. Biodiversity and ecosystem functioning are the pillars of GES in the MSFD.

4.22. Policy options that favour particular resource use, promote societal behaviours or have potential to lead to cumulative transnational impacts (marine renewables) need independent early warning and ongoing analysis. Policies such as those on deep-sea mining and marine renewable development need to be informed by systematic analysis of the impacts of different policy options that internalise environmental costs and uncertainties.

5. Towards an increased and sustainable ocean harvest

Key societal challenges increase the pressure on the marine living resources

5.1. According to the ‘UN 2012 revision of the world population prospects’ the human population is projected to increase from 7.2 billion in 2012 to 9.6 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2013).

5.2. The human trophic level has increased (i.e. a higher proportion of meat in the diet) since 1961 (Bonhommeau et al., 2013) and a further increase is likely, along with projected economic growth in China and India.

5.3. A key challenge is how to increase food production to meet the demand of an increasing population. The Earth’s land areas produce 98 % of all food (Duarte et al., 2009) and the human utilisation and pressure on land is much higher than for the ocean (Vitousek et al., 1986; Pauly and Christensen, 1995).

5.4. The ceilings for increased food production appear more severe on land than in the ocean (Duarte et al., 2009) and, consequently, attention to the increased utilisation of marine living resources seems inevitable. Under current practice, overfishing is a serious concern with 39 % of assessed commercial fish stocks in the North East Atlantic and 88 % in the Mediterranean and Black Seas considered overexploited (EEA, 2014). A recent modelling study suggest that the biomass of predatory fish in the world oceans has declined by two thirds over the last 100 years (Christensen et al., 2014) and the status of many other commercially exploited fish stocks is not regularly assessed. A major challenge is therefore to find ways to increase the ocean harvest and at the same time combat overfishing and other unsustainable ocean use.

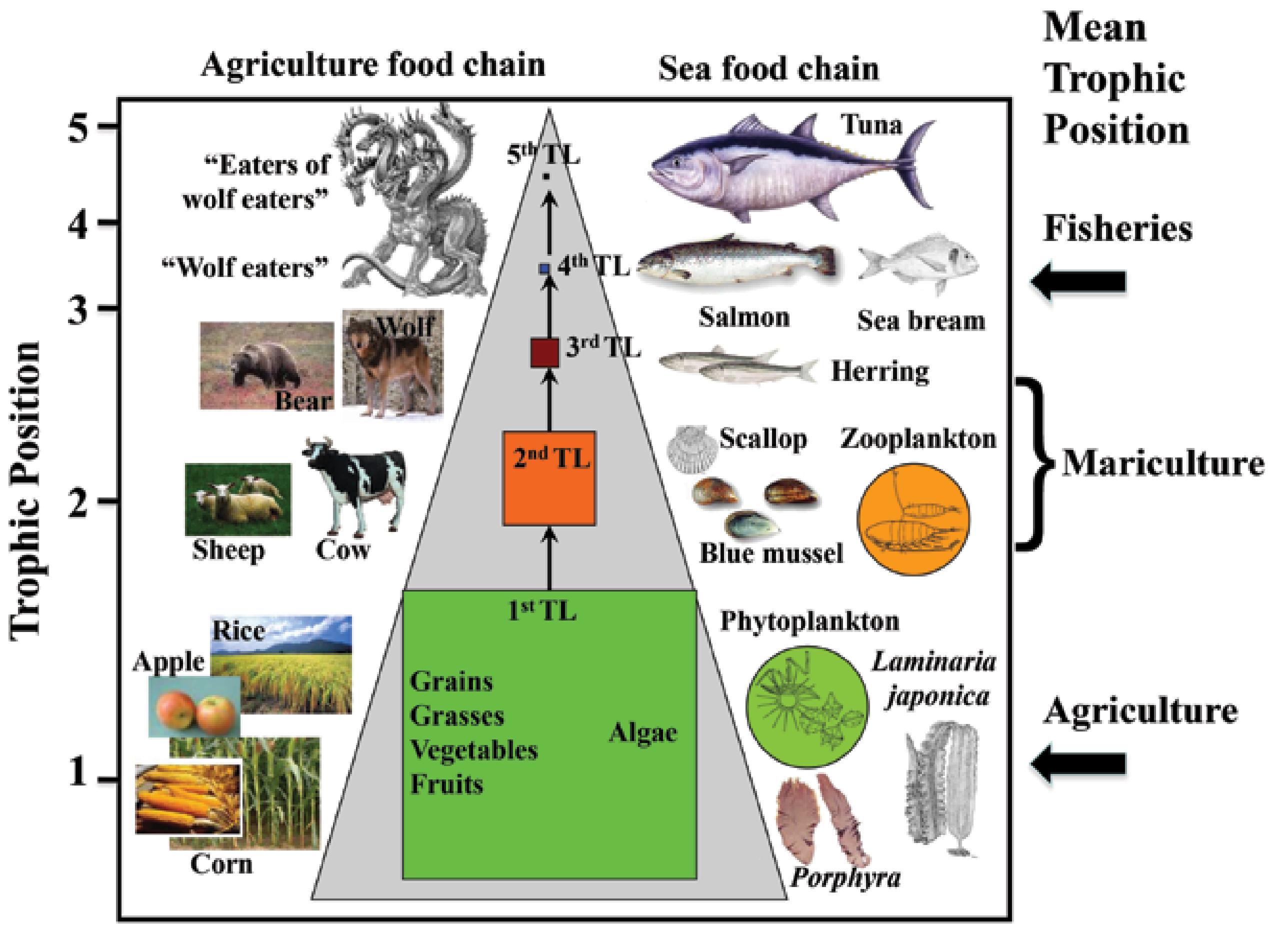
5.5. Current EU strategies for sustainable growth for the bioeconomy focus on bringing exploitation of fisheries to sustainable levels, promoting sustainable and competitive aquaculture and reducing the EU’s heavy dependency on seafood imports from outside it (European Commission, 2012). An effective implementation of controls on discards in the latest revision of the common fisheries policy will take some time.

5.6. Bringing current fisheries exploitation to sustainable levels by ending overfishing and minimising the harmful impacts of fisheries on marine ecosystems is a fundamental prerequisite. Scientific advice on fisheries management and stock recovery needs to be followed. However, in the longer term sustainable ecosystem-based use of living marine resources may require considerable innovation and a move away from traditional approaches.

Compared to land, the ocean appears underutilised as a food provider for the human population

5.7. The global primary production has been estimated at 104.9 109 tonne carbon yr^{-1} with roughly equal contributions from land and ocean (Field et al., 1998).

Figure 5.1: "A comparison of the trophic positions of agriculture and mariculture products", redrawn from © Carlos M. Duarte et al. Will the Oceans Help Feed Humanity?, BioScience (2009) 59 (11): 967-976 doi:10.1525/bio.2009.59.11, Fig. 4, with the kind permission of Oxford University Press. For reproduction or use of this material, permission must be sought directly from the copyright holder.



The global fishery landing corresponds to 10^7 tonne carbon yr^{-1} (by assuming a wet weight (WW) to carbon (C) ratio of 10), i.e. 0.02 % of the estimated oceanic primary production.

5.8. Because the current fishery occurs high in the food chain (Figure 5.1), and the ecological efficiency between trophic levels is considered low (commonly assumed to be approximately 10 %), it can be approximated that the current fishery is based on a primary production that is roughly 400 times higher than the fishery landing (note, however, that this number is extremely sensitive to inaccuracies of the assumption of 10 % efficiency). This primary production is 8 % of the total oceanic primary production (Pauly and Christensen, 1995; Watson et al., 2014). The corresponding terrestrial utilisation is higher and was estimated at 40 % in 1986 (Vitousek et al., 1986), but is probably higher today due to approximately 30 years of human population growth and a concurrent increase in the human trophic level (Bonhommeau et al., 2013). This higher degree of utilisation, however, is not the prime reason why the terrestrial system provides more biomass for the human population than the oceans.

5.9. Although the oceans' primary production equals that of the land, marine food contributes only 2 % to the human food supply (Duarte et al., 2009). There are at least three reasons for the large discrepancy between land and ocean as human food provider:

(a) Compared to the land, there is a severe lack of direct observations of marine living resources. Major biotas and biomass components of the ocean are still unknown and consequently the knowledge base needed to move towards a more efficient and sustainable ocean use is underdeveloped. For example, it remains uncertain whether the global fish biomass (including non-harvested mesopelagic fishes) is 1, 10 or even > 10 billion tons wet weight (Irigoien et al., 2014).

(b) Fishery landings are commonly used as the primary proxy for abundance due to the lack of adequate observation systems. The question of whether catch reflects abundance is a matter of continued controversy among fishery biologists (e.g. Pauly, 2013; Hilborn and Branch, 2013) and this hampers progress in sustainable use of the ocean.

Box 5.1: Overall ecological efficiency of the ocean harvest

The ecological efficiency (E_i) can be defined as the production (P_i) at one trophic level (i) divided by the production (P_{i-1}) at the level below (i-1).i.e. $E_i = P_i/P_{i+1}$. This efficiency varies between trophic levels and between ecosystems, but is frequently assumed to be 0.1 (i.e. 10 %). Here we define the overall ecological efficiency of the ocean harvest (E_H) as the total ocean harvest (H) divided by the total oceanic primary production (P_1). Thus the annual ocean harvest of 100 mill tonnes wet weight, which corresponds to 10 million tonnes carbon, and the annual oceanic primary production of 50 billion tonnes correspond to an overall ecological efficiency, E_h = 0.0002, i.e. 0.02 %, which suggests a low overall utilisation of the oceanic productivity. This might appear to be in conflict with previous reports of the degree of human utilisation of ocean living resources; for example, Pauly and Christensen (1995) estimated that the global fishery landing requires 8 % of the total oceanic primary production giving the impression that we are very much closer to an upper limit for the ocean harvest. This percentage, however, is based upon the present practice of fishing relatively high up in the food chain, which is the main reason for the low overall ecological efficiency of the current ocean harvest.

(c) Ocean harvest is primarily based on hunting at a high level in the food chain. This has a very low overall ecological efficiency (approximately 0.02 %, see Box 5.1). Some fisheries are comparable to hunting 'wolf eaters' (trophic levels above top predators) (Figure 2) and consequently even at a minor yield (in terms of food for the human population) overfishing is not surprising from an ecological point of view.

The apparent paradox of concurrent overfishing and underutilisation

5.10. Despite the low yield from the oceans, there is no doubt that overfishing is a serious concern for many stocks and regions. It is likely that increased sustainability through protection and conservation of the exploited stocks alone will reduce, rather than increase, the overall ecological efficiency of the harvest and consequently diminish the role of the ocean as a food provider.

5.11. The debate around overfishing gives the strong impression that the ocean is overexploited as a source of human food. This is true only if we continue to harvest at much higher trophic levels than on land.

5.12. Harvesting at lower trophic levels would have the effect of increasing the ecological efficiency of the harvest. To illustrate this, if 8 % of the oceanic primary production is used through harvesting at the herbivore level (e.g. mussels), the hypothetical herbivore harvest would be 4 000 million tons wet weight compared to the 100 million tons wet weight achieved through current fishery practices. The overall ecological efficiency of the herbivore harvest equals 0.8 % in comparison to the 0.02 % for the current fishery harvest.

Increased sustainable harvest — the way forward

5.13. The question of how to increase the role of the ocean as a human food provider while ensuring a sustainable use of marine living resources can theoretically be addressed in two ways: (i) by harvesting from a lower level in the food chain and (ii) by developing ecologically efficient mariculture.

5.14. **Harvesting lower in the food chain.** Harvesting lower in the food chain is theoretically a possible action in order to (i) release direct exploitation pressure and overfishing at higher trophic levels and (ii) increase the biomass harvest from the ocean. One suggestion, which relates to fishing at a lower average trophic level, is the 'balanced fishery' concept (Garcia et al., 2012). The idea is to distribute a moderate mortality from harvesting across the widest possible range of species in an ecosystem. With harvesting spread over more species, groups and sizes (and thereby over several trophic levels), yields are likely to be higher and the impacts of fishing, for example population extirpations (local extinctions) and biomass depletion, lower. This is a distinctly different concept from that of 'fishing down the food chain', which has previously been used to describe a forced change in fish stocks and fishery catches caused by the fishery itself (Pauly et al., 1998), i.e. starting with removal of the largest fishes and proceeding with next largest and so forth inevitably leading to successively smaller fish (which tend to be at a lower trophic level than large fish) in the sea as well in the harvest. Whether this fisheries-induced change occurs remains a matter of dispute due to the controversy over how well catch data reflect abundance (Pauly, 2013; Hilborn and Branch, 2013; Branch et al., 2010).

5.15. Harvesting lower in the food chain obviously involves several challenges. First of all, and noted above, we lack fundamental knowledge, including abundances, about major lower trophic level biomass components such as production of krill, copepods and mesopelagic fishes. At an appropriate point approaches will need to be developed to promote and educate the public to engage with alternative sources of protein.

5.16. **Ecologically efficient mariculture**. Duarte et al. (2009) argue that a greater contribution of the oceans as a human food provider must involve mariculture development. Essentially, mariculture must innovate: (i) to close the production cycle in order to abandon its current dependence on fish oil and fish meal derived from forage fisheries catches; (ii) to enhance the production of edible macroalgae and filter-feeder organisms; (iii) to minimise environmental impacts; and (iv) to increase integration with food production on land, such as transferring water-intensive (due to freshwater shortage on land) components of the human diet (i.e., production of animal protein) to the ocean. The aquaculture industry has a vital role to play in the search for a more sustainable mariculture.

Recommendations

5.17. The revised common fisheries policy must be used to bring current fisheries exploitation to sustainable levels by ending overfishing and minimising the harmful impacts of fisheries on marine ecosystems. Scientific advice on fisheries management and stock recovery needs to be followed. While much needed, these efforts appear insufficient to increase the sustainable yield from the ocean. To anticipate the demands for increased food biomass from the sea that will come from human population growth, we recommend greater commitment to policy development and knowledge building on how to improve the ecological efficiency of ocean harvest while at the same avoiding overfishing of predatory fish.

5.18. A major research initiative is needed to develop scientific understanding of the potential to increase the overall ecological efficiency of the ocean harvest and thereby the sustainable yield from the ocean while moving away from current fishing practice and the related depletion of fish stocks. An ecosystem approach aiming for increased overall ecological efficiency of the harvest needs to be explored. The current overall ecological efficiency of the global fishery landing amounts to 0.02 % of the total oceanic primary production. From a theoretical point of view it appears feasible to increase this yield, by at least one order of magnitude, with lesser impact on marine ecosystems than current fishery practice imposes. This needs to be informed by concerted research to improve knowledge on biomass components such as mussels, krill, copepods, mesopelagic fishes and squids.

5.19. Blue growth and increased biomass might facilitate the next food revolution in human history. However, the potential for progress is currently hampered by adherence to historical hunting practices and associated overfishing, inadequate knowledge of major oceanic biota and biomass components, and the lack of an ecosystem-oriented management scheme that targets increased ecological efficiency of the ocean harvest. Although these challenges cannot be overcome with research alone, a blue sustainable food revolution would require a major research endeavour not previously undertaken in the oceans.

6. Networking of marine protected areas within an ecosystem approach

Marine protected areas cover a broad range of designations

6.1. Marine protected areas (MPAs) are promoted as a tool for marine conservation, but also have potential to contribute to ecosystem-based management. Most MPAs are biologically important areas that deserve protection through effective management. Conservation objectives are set, with protection at a higher level than the surrounding area. MPAs are usually areas where human activity is strongly regulated or even not allowed at all (as in a no-take zone), but current legal definitions of MPAs embrace a range of objectives in relation to species, habitats and ecological processes, for example:

(a) protecting, conserving and restoring;

(b) preventing degradation and damage;

(c) protecting and conserving areas that best represent the range of features.

6.2. As in terrestrial national parks, MPAs often comprise areas that contain charismatic expressions of biodiversity, either at habitat or species level. The uniqueness of the expression of biodiversity is often the main reason for protection. MPAs are usually designated due to structural reasons, such as the beauty and uniqueness of what they contain, but their function is rarely independent from much wider spaces.

6.3. Alongside conservation aims, MPAs are often expected to enhance fisheries, with an emphasis on the benefits for living resources in the vicinity of the protected area (Gell and Roberts, 2003). Fish populations in MPAs often increase in size through enhanced reproduction, with the spillover benefits beyond the protected area enhancing fisheries yields. Fisheries biologists and ecologists, however, rarely propose MPAs as an instrument to regulate fisheries, advising other types of management, such as periods of closure over vast areas, restrictions of gear efficiency and increase of minimal sizes.

6.4. Other aims of MPAs include socioeconomic benefits, such as enhanced income for local populations due to increased tourism, triggered by the enhanced profile of an area designated as an MPA. MPAs are also expected to lead to environmental restoration of degraded areas. They also offer opportunities for use as field laboratories for marine scientists and, furthermore, should enhance the marine literacy of their visitors.

6.5. A focus on protected areas, disregarding the surrounding environment, fails to consider the openness of marine systems. The features of a given site are strictly linked to the conditions of other sites, according to source-sink theory. The connections between coherent portions of the marine environment define networks of MPAs through use of ecological criteria.

Effective networking of MPAs requires a better understanding of connectivity

6.6. Networks of MPAs are considered in the Convention on Biological Diversity, the European regional sea conventions and Natura 2000. In the marine strategy framework directive (MSFD), networks of MPAs are recognised as a means of providing conservation of the diversity of the constituent ecosystems at a regional level. Networks of MPAs contributing to ecosystem-based marine spatial management are recognised as an optimal way of safeguarding biodiversity assets.

6.7. Dense coastal populations and demand for marine space typical of European seas are the main reason for networking a suite of small MPAs to meet regional protection, conservation and restoration objectives. The creation of MPA networks provides for expanding good practices of environmental management across much larger areas than the single networked MPAs that, in this form, can be used within a marine spatial plan area. Restriction of human activities within an overall network area will not be as strict as in the MPAs.

6.8. Ecological coherence is the key criterion for networking of MPAs (Olsen et al., 2013). Although concepts such as representation of features and replication are seen as a part of ecological coherence, from a functional perspective the essential concept for good design of a network of MPAs is connectivity, i.e. the connections that occur through current regimes between the various MPAs in the network. The connections are realised, for example, by the exchange of propagules, eggs, larvae, resting stages, juveniles or adults. MPA network design and management must reflect what is already happening in nature (Figure 6.1).

6.9. Oceanographic circulation is thus the key measure of connectivity, since currents connect different parts of marine systems. While currents connect, however, the biotic realisation of such connections occurs when the propagules settle at a place conducive for their survival (Berline et al., 2014). Connectivity between MPAs is necessary to ensure both the persistence of local populations and the export of propagules outside their boundaries.

6.10. The presence of a network of suitable habitats is thus another condition for the realisation of connectivity. Vagility of species is an important issue, since species might produce propagules with a vast array of dispersal potentials. The mosaic of these conditions (oceanography, habitat, propagule features of particular species) determines a gradation of interconnections within a putative network area. A compromise is thus to be searched for, so as to consider the highest number of possible connections across the widest range of species.

6.11. The identification of spatial units of coherent ecosystem patterns and processes (e.g. the cells of ecosystem functioning described in Box 3.2) helps in designing networks of MPAs. Marine canyons, for instance, are often the drivers of upwelling currents that bring deep waters towards the coast, injecting nutrients that then trigger phytoplankton production. Surface currents then disperse the products of this high production that originates from the presence of a canyon, acting as a unit of ecosystem functioning. Other very important cells of ecosystem function include sites of deep water formation and current regimes such as eddies and gyres, which act as concentrators and/or distributors of important ecosystem functions, based upon primary production.

6.12. The habitats directive does not currently take into account the water column as a habitat, focusing on the benthic realm. This shortcoming needs to be corrected to facilitate effective MPA network design, because the functional properties of pelagic systems are extremely important in ecosystem functioning. Identification and mapping of pelagic as well as benthic features will become crucial for integrated coastal zone management and for maritime spatial planning. Currently, the marine habitat mapping of European waters is far from complete, and the very concept of cells of ecosystem functioning is in its infancy. In the absence of better information on water column processes the coherence of MPA networks is being considered by pragmatic approaches with high uncertainty levels.

6.13. Designing the networks according to ecological principles provides a sound basis with which to work towards GES throughout a given network area. The FP7 project CoCoNet ([14]) is identifying groups of interconnected MPAs in the Mediterranean and Black Seas as a basis for potential networks of MPAs.

MPAs should be used as observatories within an overall ecosystem monitoring system

6.14. Understanding whether EU or European regional sea networks of MPAs are coherent will be optimally supported by an EU-wide network of monitoring stations and observatories for evaluating the status of biodiversity within MPAs.

6.15. Marine protected areas are the ideal places to monitor the conditions of biodiversity, with reference to the first descriptor of GES under the MSFD. Comprehensive species and habitat inventories are a prerequisite for proper monitoring of the status of biodiversity, and periodic checks of inventories must be undertaken in order to detect change. Similar long-term series should also be carried out outside MPAs, so as to make control observations available. Biodiversity monitoring should cover not only the presence of species but also their

([14]) Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential (CoCoNet) (**http://www.coconet-fp7.eu/index.php/about-coconet** (accessed 14.1.2015)).

phenology, since the timing of reproductive periods, usually linked with seasonal cycles, can serve as a proxy for climate change.

6.16. Effective ecologically based design, management and monitoring of MPAs, contributing to the biodiversity-based aspects of good environmental status, calls for a better understanding of the links between biodiversity and ecosystem functioning. Developments in human capacity building to support both integrative and taxonomic analysis are essential.

Recommendations

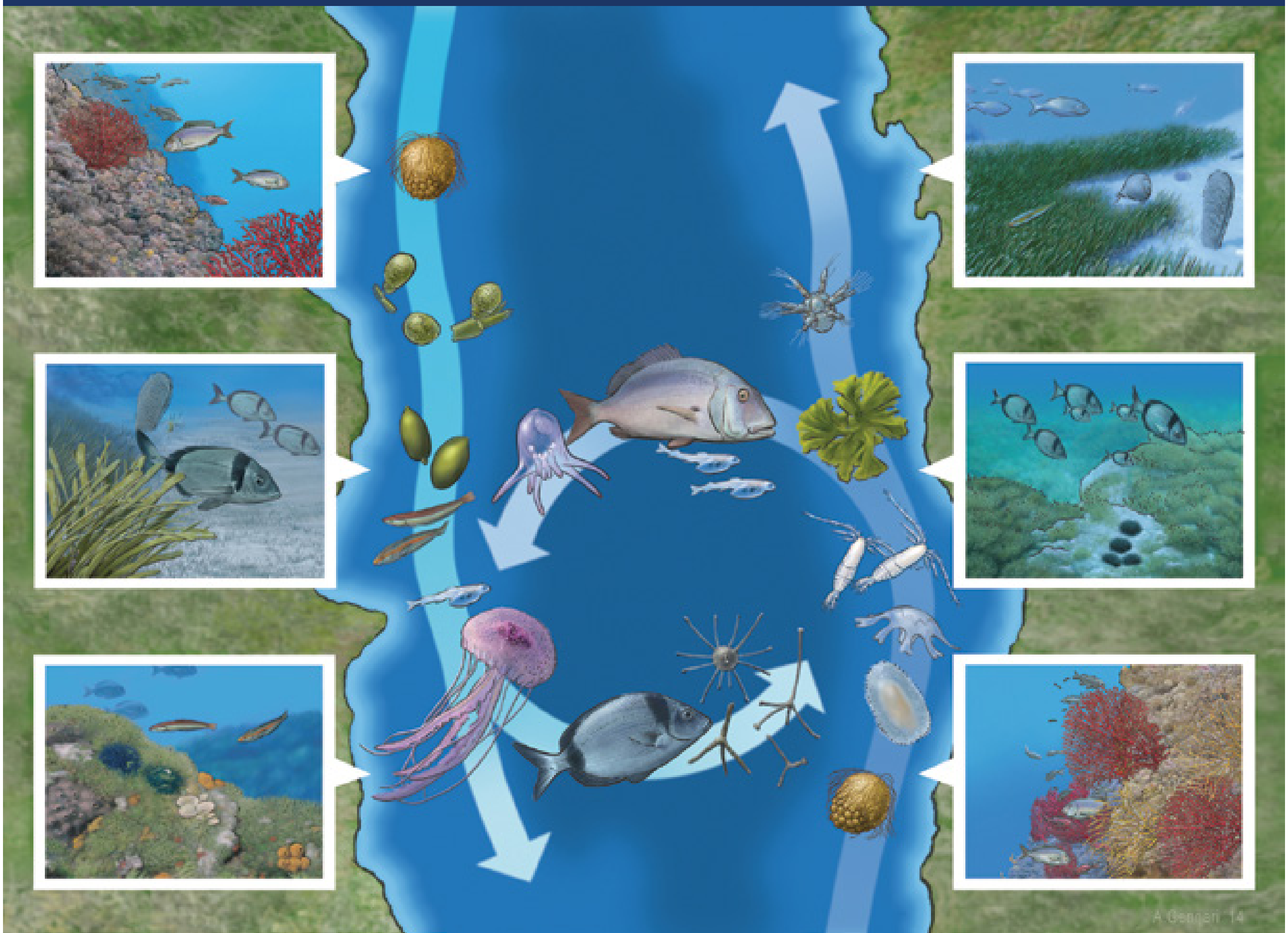
6.17. Increased attention needs to be given to the effective use of networks of MPAs as tools within ecosystem-based management, at sea-basin scale. Oceanographic connections are crucial to design networks of MPAs, with much wider objectives than the single MPAs.

6.18. The design of networks of MPAs should be strongly directed by connectivity based upon cells of ecosystem functioning whose components have a higher degree of interconnections than with the components of neighbouring cells. This requires substantially increased efforts to understand water movements and ecological connections between ecologically important areas. This knowledge needs to be built into the development of networks of MPAS, which can play a strong role in securing good environmental status.

6.19. To support this, habitat mapping needs to take into account habitats in the water column and their dynamics.

6.20. Marine protected areas should be used as biological observatories within the overall marine monitoring system, integrating the currently existing ones considering just physics, chemistry and biogeochemistry.

Figure 6.1: Currents connect habitats through propagule transport (artwork by Alberto Gennari, for the EU CoCoNet project)



Source: Alberto Gennari, for the EU Project CoCoNet

7. Building an integrated knowledge base for marine sustainability

Environmental change and biodiversity assessment require a flexible observational strategy

7.1. Many EU Member States have well-established systems for monitoring the quality of the environment covering mainly physico-chemical variables and information on primary producers. This is also the focus of the Marine Environment Monitoring Service of the EU's Copernicus programme. The development of dedicated sensors for use with satellite technology and the expansion of automated observations through moorings, gliders and ship-based sensors enables automated measurement of a range of environmental conditions, from temperature to the concentration of various types of chlorophyll. These approaches provide essential information on physical and chemical conditions (as well as some information on biogeochemistry) and mean that some areas of European seas are very intensively monitored. Within these routinely measured parameters there is a bias in the operational maturity of the systems, with the systems for physical observations being more mature that those for chemistry and even more than for biogeochemistry. Now the vision for an ecosystem-based approach to management, including good environmental status (GES) with respect to biodiversity and ecosystem functioning under the marine strategic framework directive (MSFD) provides concrete requirements that more attention be given to bioecological data collection, for which there are few automated instruments. Managing activities to regulate biodiversity or the efficiency of food webs requires observational information on the bioecological components of the ecosystem and approaches that are adaptable and responsive to change.

7.2. While the monitoring of a predefined set of variables is necessary, observation strategies and scientific studies need to take a more adaptive approach than traditional monitoring tactics, to account for change. Regime shifts, which can be considered more likely in a period of rapid change, imply that new actors enter the stage, or that variables usually assumed to be more or less constant start to behave in novel ways, determining new conditions (see Box 7.1).

A long-term network of observatories is needed

7.3. Fulfilling the goals of understanding the environmental and ecosystem status in European seas requires the establishment a sustained long-term European marine observation strategy. This strategy should merge network biological observations at observatories and through observing systems with existing monitoring of physical and chemical variables. Long-term monitoring should be used to inform understanding of variability on all time scales (intra-annual, interannual, decadal) which provide understanding of present-day environmental changes and improves our ability to anticipate future changes. The key components of this biological observation network should be as follows:

(a) observations at marine protected areas as the reference points where biodiversity is expressed in

Box 7.1: The importance of observation for detection of regime shifts

When monitoring for fishery yields began to retrieve more jellyfish than fish, this was disregarded (Riisgård, 2012). Understanding of the processes leading to this regime shift from a fish to a jellyfish ocean would have been considerably enhanced if the quality and quantity of jellyfish had been monitored from its first observation. Jellyfish are also not included in monitoring protocols for marine conditions, which has impeded understanding of a now widely recognised regime shift. The absence of jellyfish records in the scientific literature prompted denials that the phenomenon was taking place, due to lack of evidence. Meanwhile, the media reported extensively about it. If an observational approach had been in place, the rise of the jellyfish would have been recorded since its onset, allowing for better understanding and management of this phenomenon. An observation system would have immediately perceived the presence of jellyfish. It is imperative that those observing the quality of the environment are prepared to perceive changes, to investigate them and to register their values.

the best possible shape and against which the rest of the observation network should be matched;

(b) observations at the network of marine stations distributed along Europe's coast, such as those involved in the European Network of Marine Research Institutes and Stations (MARS Network ([15])) (for example, Plymouth, Kristineberg, Helgoland, Naples, Lubiatowo). These marine stations have accumulated knowledge, data and expertise but their potential as distributed observatories and infrastructures for assessing the impact of climate change on biodiversity and marine ecosystem functioning has not been harnessed. Marine stations, either inadvertently or by design, are repositories of long-term observations and datasets necessary for documenting global changes (National Academies of Science, 2014);

(c) offshore observations by oceanographic vessels and ships of opportunity, such as the Continuous Plankton Recorder survey.

7.4. The geographic scope of the infrastructure and observatories should include representative sites in both coastal and open ocean systems. The establishment of oceanic observation sites where the effects of global changes are monitored in a systematic fashion is also urgently needed. These sites should be located in the North Atlantic outside of the main flow of the North Atlantic thermohaline circulation so that global change-related issues in the deep ocean can be detected more distinctly. The site should be served by a European scientific entity with the necessary scientific qualifications to guarantee long-term monitoring of the physical, chemical and biological properties of the ocean according to consistent methods. One of this organisation's tasks would also be to develop principles of monitoring the marine protected areas (MPAs) and it should be provided with sufficient funding to establish a monitoring programme for a selected suite of MPAs. Similar observatories should be placed in the deepest parts of the Western and Eastern Mediterranean Seas, to monitor key processes such as water renewal and deep water formation

7.5. Networking of marine stations with research centres should be promoted to spark innovation and to share best practices, protocols, and platforms for data archiving and retrieval. Such networking has the potential to open new arenas of scientific inquiry, education and outreach. It can capture social and intellectual capital to tackle major questions by attracting a wide range of scientists and promoting multidisciplinary collaboration.

7.6. Currently, these 'observatories' *sensu lato* are sustained by national funds. In order to have a coherent coverage the EU should sustain networks. The European Marine Biological Resource Centre (EMBRC) might be the first nucleus of this, together with Lifewatch. But the network should be better coordinated and more inclusive, coupling marine stations with marine protected areas.

Private sector use of the sea has a role to play in monitoring and observation

7.7. The increasing use of European seas by industry presents an opportunity to increase society's knowledge of the seas. The infrastructure being installed in the sea has the potential to offer platforms for new autonomous monitoring systems. This requires the full engagement of industry and is an opportunity that should not be squandered. There are good examples from the development of the oil industry where the benefits of data collection and an open attitude to the data's use has been realised (e.g. Metocean).

European action on marine observation needs coordination

7.8. There are risks in a lack of coordinated action across Europe, since individual states might act with different timings, rationales, care and expertise. A European observation system must be operated at the level of all European seas and, if possible, into the Arctic and in coordination with the other side of the Atlantic. As a priority a common rationale of what an observation point must do in order to provide an accurate description of the features of marine ecosystems should be agreed, based on the descriptors of good environmental status (GES). These data become useful once they

([15]) http://www.marsnetwork.org

are comparable and reliable. The network of observatories should have a common operational protocol. An important aspect concerns designing 'interfaces' in the overall system, i.e. between operational systems such as Copernicus with monitoring from the marine strategic framework directive (MSFD) and common fisheries policy. In parallel, sustained investments in the development of new technologies to fulfil these requirements and in expertise in holistic and integrated analysis are essential. A framework for ocean observing has been proposed by the UNESCO task team for an integrated framework for sustained ocean observing (2012).

Knowledge generation requires a systematic management of marine data through a unified European data infrastructure

7.9. Good management of marine data is a vital part of supporting knowledge transfer to the next generation and thereby ensuring the sustainable management of our seas. Systematic management of our marine datasets is needed to ensuring that data are available for analysis, synthesis and interpretation that cumulatively builds our understanding of the state of marine ecosystems and the drivers of change. Our ability to robustly model the future changes in the global ocean system and how they will impact human activity needs to be informed by reliable data indicating how the system works now and how it worked in the past.

7.10. When viewed at a European scale, marine data tend to be generated in a highly fragmented way by many diverse disciplines and yet the importance of marine data transcends national boundaries and single stakeholder groups. Potential for integrating data from different disciplines is essential for the type of integrated analysis needed to effectively support ecosystem understanding Many EU Member States have national marine data centres and some are moving towards networks and infrastructures but approaches are inconsistent. Technologies and concepts for data infrastructures are rapidly developing. Open Data, Open Science, eScience and increasing machine-to-machine communication using application programming interfaces (APIs) offer possibilities for the rapid exchange and assimilation of data. Real-time delivery of large, multivariate oceanographic and biological datasets, with increasing temporal and spatial resolution, will demand a new approach to data stewardship from storage and open access, to integration and standardisation (European Marine Board, 2013).

7.11. The EU INSPIRE policies (Directive 2007/2/EC etc.) are pursuing improved accessibility of public data and information and the transformation of the current fragmented arrangement of systems into one interconnected and interoperable structure. The 'Marine knowledge 2020' initiative includes the Copernicus Marine Environment Monitoring Service (Regulation 377/2014), the European Marine Observation and Data Network (EMODnet [16])) and the EU Fisheries Data Collection Framework (Regulation 199/2008). Taken together these policies and initiatives should provide a concrete foundation for improved data infrastructures that support marine sustainability and they clearly need to be be followed. Testing, adaptation and a coordinated implementatation over the long term are needed, so that researchers, industry and public authorities are able to make more effective use of marine datasets, thus improving understanding and to enhancing sustainable use.

Design principles for data infrastructures

7.12. There is wide agreement that data infrastructures need to encompass the following design principles:

(b) collect data once and facilitate their use many times through open access;

(c) develop data and metadata standards across disciplines as well as within disciplines;

(d) process and validate at different levels (national, regional, global);

(e) build on existing efforts where data communities are already self-organised;

(f) accompany data with statements on ownership, accuracy and precision;

(g) develop a decision-making process that is user driven;

(h) recognise that marine data are a public good, and discourage cost-recovery pricing from public bodies.

Knowledge generation requires open and available data

7.13. Open data should be normal practice and should embody the principles of being accessible, assessable, intelligible and usable (The Royal Society, 2012). Open data will enable current barriers to assembling and using data, such as lack of permission to access data and restrictions imposed on end-use of data, to be overcome.

7.14. Making marine data freely accessible to the scientific community for analysis is not exclusively a technical issue but depends heavily on the commitment and enthusiasm of data providers and organisations that fund data collection. For example, greater availability of fisheries data to scientists is an important consideration under the EU Fisheries Data Collection Framework (DCF). Data availability depends not only on the willingness of scientists to provide 'their' data but also on the political will of stakeholders (in the case of the DCF, e.g. the Member States) to fully collaborate with data collection and dissemination schemes. Reluctance

(16) http://www.emodnet.eu/

to provide data, be it by scientists or stakeholders, must be taken into account when developing strategies for open access data collection frameworks. Steps to address the limitation of access to certain data types need to be taken at a political and legislative level.

7.15. In parallel, efforts to improve data accessibility can be strengthened when linked to well-defined purposes (e.g. specific research, scientific research). It is critical that public accessibility of data should be a high priority and a fundamental principle in all publicly supported or publicly relevant projects throughout Europe, whether funding is from European Commission, Member States or private sector sources.

Accessible, reliable and interoperable data

7.16. The design of data infrastructures should prioritise discovery, that is making the data easy to find, as well as facilitating access and promoting use through ensuring data interoperability. The reliability of biodiversity information needs to be flagged and analysis improved as a matter of urgency. Hardisty et al. (2013) described the grand challenge for biodiversity informatics as being to develop an infrastructure to allow the available data to be brought into a coordinated coupled modelling environment to be able to address questions relating to our use of the natural environment (Hardisty et al., 2013). This can only be done if we know the reliability of those biodiversity data we have and improve the quality of those we collect.

7.17. Hardisty et al. (2013) recommended that data encoding should, as a basic principle, allow analysis across multiple scales, i.e. from nanometres to planetary scales, and from nanoseconds to millions of years. Attaining the goal of global, European and regional sea scale ocean modelling for marine sustainability will require a combination of data from specific monitoring sites, from integrative time series which link such specific sites, such as the Continuous Plankton Recorder, and with regional scale data from remote sensing. In addition, new approaches will be needed, for example where our understanding of model organisms can be employed in the analysis of eDNA to support novel functional models of marine ecosystems that complement organism-based or trophic level-based existing models. Databases on a next-generation scale will be required to manage next-generation bioinformatics data.

Information technology choices should reflect technological trends and future demands

7.18. The field of information and communication technologies will be an increasingly crucial component of the marine data management infrastructure. The choice of information technology should consider technological trends and the possible future demands from such initiatives as Open Data, Open Science, eScience, the Transatlantic Ocean Research Alliance and Ocean Observation Systems.

7.19. Many existing international data-sharing programmes are based on centralised data resources serviced by data portals and online geographic information systems (GIS). A modern approach is the concept of a 'hub and spoke' internet architecture that enables a distributed data resource. This approach, combined with web-based message brokering, data mediation and machine-readable technologies, makes a network of distributed data centres appear as a cohesive cloud-based data store ([17]).

7.20. By using a similar approach to distributed data, it would be possible for Europe to provide a marine science data store that would be in keeping with the objectives of EMODnet and that would complement EMODnet services. The adoption of this distributed data architecture and the utilisation of the Open Source technologies mentioned previously could establish a template for machine to machine interoperability between the data hubs of national ocean data centres around the world.

Active processes for assessing data are essential

7.21. Active use of data resources and infrastructures in assessment and analysis is both essential for knowledge generation and a critical part of their effective management and development. Strengthened investments in data infrastructures need to be complemented by their application to address a wide and innovative range of analyses. A significant component of data infrastructure projects should address the marketing of the products and services they develop, specifically to attract users from outside the project-funded community. Virtual laboratories are one means of allowing researchers to exploit databases for analysis and to contribute analytical methods.

Recommendations

7.22. A sustained European strategy for ecosystem observations is needed which incorporates biological monitoring with ongoing physical and chemical programmes to fulfil the goals of understanding the state of the environment and its component ecosystems, as required by the MSFD in the definition of GES. Biological observations, including lower levels of marine food webs, should be based on a sustained, long-term network of time series, including observatories at coastal marine research stations, within marine protected areas and along ocean transects. Oceanic observing sites where the effects of global changes are

([17]) NOAA has implemented a distributed data architecture to provide data via a WEB API. It was done by leveraging the features of established Open Source/Standard Earth science-based technologies such as THREDDS, OPENDAP, NETCDF, ERRDAP and OGC. As a result of this endeavour NOAA has made globally available its store of marine science data to not only the scientific community but also to the mainstream software development community via a familiar web/cloud-based machin-readable WEB API.

monitored in a systematic fashion should be form an important part of this strategy.

7.23. Knowledge generation through monitoring, observation and research science requires the systematic management of marine data through a unified European data infrastructure, with data accessible, available and usable. Continued efforts are needed to ensure the realisation of current EU ambitions for marine data infrastructures and systematic management of marine data.

7.24. The large and diverse datasets assembled by these EU data infrastructure projects need to be tested to support knowledge building across research and operational activities. Concerted efforts are needed to open up access to marine data, so that the benefits of these infrastructures can be realised. This needs to be coupled with substantial support for efforts to improve the quantity and quality of biodiversity data, such as those relevant for the MSFD, which are scarce in comparison to other data types.

8. Science for marine sustainability

8.1. RESEARCH SET-UP

8.1.1. The integrated policy and integrated ecosystem-based approaches to management have been well recognised in all EU strategies, including the seventh environment action programme, the Europe 2020 biodiversity strategy, the integrated maritime policy and the common fisheries policy. As recognised in the preceding sections a better operationalisation of this approach is needed. This requires a better conceptual underpinning on the one hand, and an explicit consideration of the sustainability of proposed management practices on the other.

8.1.2. Integrating knowledge across different ecosystem components (land, air, water) and linking physical, chemical and biological aspects when assessing the status of marine systems is crucial for accurate evaluation of problems on a European level. The need for holistic, long-term, cross-sectoral and resource-efficient approaches to tackle the problems with marine resources will require, in addition, integration with human and social sciences, as has been stressed in a number of recent European documents (Borja, 2014; EEA, 2014; European Marine Board, 2013).

8.1.3. The fact that the oceans are connected systems that do not operate according to national boundaries or human organisational structures means that marine research in Europe needs to be structured accordingly. This requires international coordination and ecosystem-focused programmes that address scientific questions in an interdisciplinary way, taking into account stakeholder requirements. We recommend that balanced organisational structures that include all those most important partners from a wide field of expertise should be used to stimulate and fund European marine research programmes. Key features include:

(a) targeted research efforts addressing holistic scientific questions, oriented to the entire marine system;

(b) marine research that embraces intra-disciplinary aspects, including engineering, law, economics and sociology where this is needed to realise an ecosystem-based approach;

(c) a slim, but effective, administrative structure with direct interface between the European Union administration and the respective research team ensuring effective governance of the programmes and effective cooperation between the projects, the European Commission and national authorities;

(d) shared funding from EU and national resources that secures: (1) the possibility to perform research at an international level; (2) effective selection mechanisms ('one-stop evaluation') of international programmes based on quality; and (3) the sustained viability of national marine research in the Member States through constraining the administrative burden;

(e) infrastructures to cope with the demand for large and diverse sets of data and information;

(f) human capacities both in individual disciplines and in their combination and integration to support data interpretation.

8.1.4. Marine policy and legislative developments have been echoed by strong requests for integrated and synthetic approaches to marine sciences in the research calls issued by European funding agencies. To support this a fundamental shift is needed to develop holistic and integrative research that supports sustainable ocean management and combines continued work to characterise ecosystem structure and functioning with the means to characterise ecosystem health and provide the environmental, economic and societal scenarios of different choices in, and approaches to, human use. There is a range of unidisciplinary and multidisciplinary science needs to enable the effective application of the ecosystem approach:

(a) to consolidate the scientific description and characterisation of marine biodiversity, including extending habitat mapping to include habitats in the water column and their dynamics;

(b) to build comprehensive, consistent and coherent ecosystem-based indicators to fully implement the concept of good environmental status (GES) under the marine strategy framework directive (MSFD);

(c) to quantify marine species interactions and how they adapt to changing conditions in marine environments, including benthic–pelagic coupling;

(d) to develop end-to-end/integrated models (encompassing socioeconomic sciences) that characterise the human benefits from the sea, the ecosystems and biodiversity that support these and the human and natural pressures that threaten them;

(e) to build scenarios to explore the future responses of marine ecosystems (including biogeochemical cycling and food web interactions) under anthropogenic and natural forcings based on palaeoinformation, marine observations and ecosystem models and define the controls and limits of ecosystem resilience;

(f) to inform ecosystem-orientated approaches to ocean harvest, including examining the potential to target use of biomass at a lower level in the food chain and options for developing ecologically efficient aquaculture (see Chapter 5);

(g) to cautiously consider the potential of marine experimental geoengineering (see Box 8.1).

8.1.5. Europe has a wealth of marine science capability within its universities, research institutions and scientific agencies that can help to address these questions. It must be martialled and supported accordingly, so that a paradigm shift towards integrative research can be achieved. Current trends in higher education give most focus to single disciplines favouring the training of strongly specialised scientists. These skills are still much needed, but there is an even greater need for integrative scientists, able to bridge the highly specialised research fields (see Chapter 8.2).

Box 8.1: Marine experimental geoengineering

A range of geoengineering techniques have been proposed to mitigate the effects of increased atmospheric CO^2 and increased atmospheric temperatures. The scope of geoengineering depends on the definition used. Techniques that have been classed as geoengineering range from carbon capture and storage in geological structures, carbon sequestration using marine algae and iron fertilisation through to sunlight reflection methods and the use of seawater to enhance cloud reflectivity (Vivian, 2013). Geoengineering has attracted a degree of controversy due to scientific and ethical concerns around some large-scale interventions and concerns that its consideration will distract efforts to curb emissions and adapt to climate change. These concerns have been examined further by Reynolds (2015). It is, however, important that research continues to address the potential applicability of the various proposed techniques as well as to identify their risks and uncertainties in an open and responsible way in order to inform consideration of the social, ecological and economic effects. Those experiments that have been conducted to date have yielded valuable information about how biological processes in the ocean control climate.

8.2. HUMAN CAPACITY BUILDING

8.2.1. European research funding structures and priorities have a direct link to the development of human capacity. The training of the next generation of marine specialists must provide them with the capacity to deliver science to support marine sustainability. The challenging questions for marine sciences are now centred on understanding systems and their interactions. Future marine scientists need to be able to integrate analysis across disciplines while at the same time having strong capacities and understanding of traditional disciplines. Marine scientists and technologists of the future will also need to be trained communicators, who can engage, educate and inform society's choices.

Human capacity building in key skills

8.2.2. Recent European research funding programmes have been concentrated on supporting research infrastructures or on outcome-focused applied science, which aims to provide scientific support to a knowledge-based societal development. With this focus the development of human capacities and skills has not been well supported and the reservoir of key expertise in certain disciplines has declined. Boero (2010) has highlighted the demise in taxonomic expertise (see Box 8.2) that has resulted from an overwhelming focus on investment in new technologies without sufficient recognition that a combination of novel and traditional ways to study biodiversity is essential. This diversity must be better recognised in funding actions through an approach that balances investment in infrastructure with investment in development of human capital, to provide scientific capacity for describing and characterising species recognition.

Support needs to be given to the development of capacities to undertake integrative science

8.2.3. As we have commented elsewhere in this report, there is a need for a shift in the development of integrative science to support long-term, resource-efficient approaches to ensuring sustainable use of marine ecosystems. This has been stressed in a number of recent European documents (Borja, 2014; EEA, 2014; European Marine Board, 2013). Human pressures on marine ecosystems are cumulative and their consideration increasingly complex, but the key issues of over-exploitation, climate change and loss of biodiversity persist. While a truly holistic approach must be both acknowledged and required in funding decisions to achieve the ecosystem approach, this requires infrastructural development combined with the training of appropriately skilled graduates.

8.2.4. Atmospheric sciences provide a good example of the balance of data gathering and data interpretation; without the capacity to interpret data the potential advances for society are limited. Science education and training must identify ways of building the capabilities of the next generation of marine scientists and engineers to work at a systems level, applying multidisciplinary knowledge to address complex marine issues that cut across scientific, environmental and social systems. This includes developing both problem-orientated and outcome-focused marine science.

8.2.5. There are some significant interpretative challenges in areas such as ecosystem function, trophic dynamics, biogeochemistry, biodiversity, climate change and adaptation studies, which cut across all disciplines. All of these issues call for improved investment in capacities for understanding and interpretation of complex processes across systems. The evaluation of the status of marine systems at regional level requires the integration of knowledge of different ecosystem components and the linking of physical, chemical and biological aspects at differing scales (Borja et al., 2014). The framing of investigative questions, approaches and methodologies can differ quite markedly between disciplines and opportunities for cross-disciplinary training will be difficult to establish due to this mismatch. Training of scientists needs to give renewed focus on developing cross-disciplinary capacities as well as developing the capability to link to disciplines beyond the traditional marine sciences, such as law, economics, sociology and the maritime industry. For example, ecosystem modellers need to link with biogeochemists and biologists; marine ecologists need to link with fisheries scientists; marine spatial planning at its best will require a multidisciplinary approach integrating sociological, economic and ecological components (Qiu and Jones, 2013; Stelzenmüller et al., 2013). Collaborative research funded by EU and national agencies encourages cross-disciplinary science within the context of projects but there remains a challenge to advance the agenda within sustained educational structures.

8.2.6. The educational landscape that currently produces our professional marine experts in Europe is quite complex and fragmented. The European Marine Board (2013) has noted a range of potential barriers to increased cross-disciplinary training of graduates including focusing of studies on the specialities of supervisors, lack of alignment of faculties and schools and inertia due to loss of scientific control in large partnerships.

8.2.7. We recommend that a virtual European Marine University is established to focus the development of cross-disciplinary graduate training and to foster the coherence of marine expertise in Europe. The university should be assigned with leadership in developing enhanced education, training and research in interdisciplinary integrative marine science as a coherent and sustained Europe-wide curriculum. This curriculum should build upon the best available educational structures and practices in the Member States and set a framework for the kind of studies that are envisaged for educating the next generation of European scientists. There should be a clear commitment to build a strong link with the EU policy framework and to achieve technology transfer. One blueprint could be the Interdisciplinary Faculty (INF) at Rostock University, whose members originate from the faculties of natural sciences, agriculture, law, business, medicine and technical engineering. All members of the INF have a double status and the student programmes match both requirements, one from the classical discipline and the one from the INF. Such an initiative could be mirrored across Europe, honouring double degrees where appropriate. Another example is the University of the Arctic, which promotes issue-based cooperation with networks of institutions that are flexible enough to respond to topical issues. Likewise a European Marine University could stimulate international cross-disciplinary projects and spearhead the development of more harmonised research interfaces between marine science disciplines. A European Marine University could also lead the development of a more harmonised set of goals for marine science including promoting the development of communication and outreach skills amongst the marine science community.

8.2.8. In support, a specific focus should be developed within the Erasmus Mundus ([18]) cooperation and mobility programme for interdisciplinary, graduate marine research programmes with a core focus on the issues specified in this document. The programme shall consider proposals on interdisciplinary topics, where up to 10 PhD students from different disciplines and universities all over Europe combine their specific PhD thesis themes to a given overarching topic. A series of such PhD graduate programmes is aimed to attract the best students from Europe and bridge the intellectual gaps between a wide scope of disciplines.

8.2.9. The European Marine Board recently established a Working Group on Marine Graduate Training to identify some of the key issues and challenges faced by educators and make recommendations on how to improve marine higher educational training in Europe. Addressing key skills disciplinary shortages, developing a new generation of system-oriented scientists and enhanced training in communication are important aspects of this.

Box 8.2: The state of taxonomy

Taxonomy is one of the oldest branches of biology and the Linnaean system of classification established in the 1750s is still in use today. However, taxonomy is today experiencing an unprecedented rate of change, driven particularly by advances in methodology due to the molecular revolution, and by changes in the way taxonomy is disseminated, due to the revolution in information technology. At a time when taxonomic expertise is in great demand for documenting and monitoring changing patterns of species diversity, it is ironic that the pool of expert taxonomists is shrinking (House of Lords Science and Technology Committee, 2008) and it is difficult to attract younger scientists into the discipline because of poor career prospects. Successful monitoring of GES under the MSFD depends upon the availability of taxonomic expertise so the training of the next generation of taxonomists should be a high priority.

([18]) Erasmus Mundus is a cooperation and mobility programme in the field of higher education that aims to enhance the quality of European higher education and to promote dialogue and understanding between people and cultures through cooperation with third countries. In addition, it contributes to the development of human resources and the international cooperation capacity of higher education institutions in third countries by increasing mobility between the European Union and these countries. Erasmus Mundus is managed by the Education, Audiovisual and Culture Executive Agency (EACEA).

8.3. FROM SCIENCE TO SOCIETY

8.3.1. Sustainable development of marine and coastal resource use requires partnership between governments, industry, scientists and public stakeholders. The internalisation of environmental costs and their relation to economic benefits within blue growth can only be effective if there is a recognition of ocean issues within society. Scientists and educators have a critical role to play in communicating the state of knowledge on marine ecosystems and uncertainties, and in fostering appreciation of the oceans' influence on the biosphere and society, as well as society's influence on the oceans. For many the oceans are out of sight, remote and hostile, so this requires the unseen to be made real and vital: a challenging task.

8.3.2. The EU's MSFD and integrated maritime policy both gave scarce acknowledgement to the need to engage society as a key to achieving their aims. However, a number of recent initiatives have raised awareness of the profile of ocean literacy amongst European policymakers. In 2012, a first European Ocean Literacy Conference took place, facilitated through the establishment of a European Marine Science Educators Association (EMSEA). The EMSEA is partner to a number of international initiatives, such as the ocean literacy initiative of the United States National Oceanic and Atmospheric Administration (NOAA). The inclusion of ocean literacy as one of the themes for greater trans-Atlantic collaboration in the Galway Statement on Atlantic Research Cooperation was a step forward in the policy arena. In 2014, the European Maritime Day hosted a themed panel discussion on ocean literacy.

8.3.3. Some of the key challenges in developing ocean literacy include:

(a) training the next generation of marine scientists to share their scientific knowledge with the general public;

(b) introducing formal educators to some of the knowledge rules and norms of the scientific community and building ecological studies into school currricula where this is not already done;

(c)stimulating partnerships between informal science educators (museums, science centres, aquaria, etc.) and marine scientists to share experience of best available practice in outreach;

(d) including more ocean issues as a cross-cutting issue in the formal programmes of all school levels, including undergraduate courses, such as law, economics and technology.

8.3.4. A workshop on defining an ocean literacy agenda for Horizon 2020 and transatlantic cooperation was held in 2014 (European Marine Board, 2014). This workshop developed recommendations for how mechanisms and initiatives to support marine science outreach and education should be included in Horizon 2020 and beyond to ensure that knowledge generated through EU research programmes is transferred in an efficient way to those who benefit from it. These included recommendations for including criteria on ability to engage relevant stakeholders and outreach to the public when evaluating proposals from research consortia.

8.3.5. Outreach beyond the formal education system is of equal priority. Presenting reports in an clear and accessible style is one method of engaging a wider audience, used for example by the World Ocean Review (2010) to present an overview of the complex state of the world's oceans and the OSPAR Quality Status Report (2010) to report on the state of the North-East Atlantic. Innovative and active approaches beyond reports and publications are needed to join the science community with stakeholders in society beyond policymakers to deliver knowledge transfer. In the Dutch national project 'Building with Nature', natural and social scientists, engineers from universities and building/dredging and consultancy companies have worked together on the development of a new vision on sustainable coastal development ([19]). This multidisciplinary interaction provided an excellent platform for the injection of ecosystem knowledge and sustainability concepts into the everyday practice of coastal engineering. The emphasis was not on the one-way communication from science to society, but on the joint development of innovative concepts shared by scientists and important stakeholders.

8.3.6. Citizen science is an emerging channel which can advance science and empower people interested in science by engaging them actively in data collection and research, particularly in science issues that affect their communities. There is a broad spectrum of citizen science initiatives, from simple observational programmes to coordinated, training-intensive environmental monitoring programmes (e.g. beach litter monitoring organised by local organisations). Citizen science initiatives enable people to learn about science and the ecosystem dynamics of natural communities. Citizen science initiatives can also enable coordinated networks of volunteers to collect data that can inform our understanding of how human activities may be altering ecosystems. Much of citizen science is facilitated through advances in web-based technologies that allow citizens to collect and analyse data through accessible platforms, such as smart phones and personal computers. Examples include the monitoring of jellyfish along the Italian coast ([20]), which is now extended to the whole Mediterranean ([21]), and the EEA's marine litter smartphone application. Several institutes, including marine stations, universities and museums, have developed sustained outreach programmes that include citizen science.

8.3.7. A key priority for developing a strategy for improved ocean literacy in Europe is to build baseline information on what the European public knows and wants to know about the oceans. There is a need to engage in discourse with the public about important ecological processes and move beyond the purely charismatic and anecdotal.

([19]) http://www.ecoshape.nl

([20]) http://meteomeduse.focus.it/

([21]) http://www.perseus-net.eu/en/jellyfish_map/index.html

8.4. RECOMMENDATIONS ON DEVELOPING SCIENCE FOR MARINE SUSTAINABILITY

8.4.1. We recommend that organisational structures for stimulating and funding European marine research programmes should be coordinated to reflect the interconnectedness of the sea, with a slim administrative structure ensuring effective governance of the programmes and effective cooperation between the projects, the European Commission, and national authorities. Shared funding from European Union and national resources should secure:

(a) the possibility to perform research at an international level;

(b) effective selection mechanisms ('one-stop evaluation') of international programmes based on quality;

(c) the sustained viability of national marine research by the Member States.

8.4.2. Human capacities need to be built both in the individual disciplines and their combination and integration to support data interpretation. This requires:

(a) enhanced training of specialists in key disciplines (including modern taxonomy) and steps to ensure their retention as a valued part of the marine science structure;

(b) focused training of graduate scientists capable of transdisciplinary integrative marine science.

8.4.3. We recommend that a European Marine University is established as a virtual institution charged with leading the development of enhanced graduate education, training and research in interdisciplinary integrative marine science. The European Marine University should coordinate a coherent and sustained Europe-wide curriculum and develop more harmonised goals for marine science. In support, we recommend that a specific focus of the Erasmus Mundus cooperation and mobility programme should be an interdisciplinary graduate marine research programme that focuses on the issues specified in this document.

8.4.4. Intensified efforts to develop ocean literacy in Europe are needed, building on and developing the work of EMSEA. This work should have the aim of enhancing public understanding of the importance of the ocean to humankind as the basis for a better appreciation of the environmental costs of economic development. To support this development work, information is needed on the current level of knowledge of the European population of processes in the ocean and the key challenges. Outreach from EU and national research needs to be given more attention during funding decisions. Communication and outreach skills should be a standard part of scientists' skillset. Agenda processes should be promoted whereby scientists develop activities and initiatives together with groups interested in the ocean, such as enterprises, local and regional communities, non-governmental agencies and decision-makers. Citizen science projects provide a further means of generating knowledge and engagement within society.

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Meetings of the Marine Sustainability Working Group

Meeting 1: European Commission, Brussels, Belgium, 11 February 2014

Meeting 2: European Commission — Joint Research Centre, Ispra, Italy, 2 and 3 June 2014

Meeting 3: Academy of Sciences of the Czech Republic, Prague, Czech Republic, 27 and 28 October 2014

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Annex 3: List of abbreviations

ABNJ	area beyond national jusrisdiction
AMAP	Arctic Monitoring and Assessment Programme
API	application programme interfaces
Barcelona Convention	Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean adopted in 1995
CIESM	Mediterranean Science Commission
CoCoNet	EU FP7 project: Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential
CleanSeas	EU FP7 project: Towards a Clean Litter-Free European Marine Environment through Scientific Evidence, Innovative Tools and Good Governance
DCF	EU Fisheries Data Collection Framework
DEVOTES	EU FP7 project: DEVelopment Of innovative Tools for understanding marine biodiversity and assessing good Environmental Status
DOM	dissolved organic matter
EACEA	Education, Audiovisual and Culture Executive Agency
EASAC	European Academies Science Advisory Council
eDNA	environmental DNA, DNA isolated from various natural settings for the purpose of laboratory screening for genes encoding certain functions
EEA	European Environment Agency
EEZ	exclusive economic zone
EIA	environmental impact assessment
EMBRC	European Marine Biological Resource Centre project is funded by the European Union's Seventh Framework Programme
EMODnet	European Marine Observation and Data Network
EMSEA	European Marine Science Educators' Association
Euroceans	EURopean research on OCean Ecosystems under Anthropogenic and Natural forcingS consortium building on former European network of excellence. (now part of EuroMarine network)
FP7	the EU's seventh framework programme for research and technological development
GES	good environmental status as defined under the EU marine strategy framework directive

GIS	geographic information system
Helcom	Baltic Marine Environment Protection Commission — Helsinki Commission Helsinki Commission
ICES	International Council for the Exploration of the Sea
INF	Interdisciplinary Faculty — University of Rostock
INSPIRE	Initiative on infrastructure for spatial information in the European Union centred around Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE Directive)
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre of the European Commission
Lifewatch	E-Science European Infrastructure for Biodiversity and Ecosystem Reseach (European Research Infrastructure Consortium)
MARLISCO	EU FP7 project
MarBEF	Marine Bioidversity and Ecosystem Function
Marine Genomics	EU framework programme support action on marine genomics
MARS Network	The European Network of Marine Research Institutes and Stations
MEA	multilateral environmental agreement
MIDAs	EU FP7 project: Managing Impacts of Deep-seA reSource exploitation
MPA	marine protected area development of innovative tools for understanding marine biodiversity and assessing good environmental status
MSFD	the EU’s marine strategy framework directive
NANOPLAST	EU FP7 project
Natura2000	EU-wide network of nature protection areas established under the 1992 habitats directive and the 1979 bird directive
NEAFC	North East Atlantic Fisheries Commission
NOAA	United States National Oceanic and Atmospheric Administration
OSPAR	OSPAR Commission for the protection of the marine environment of the North-East Atlantic
POM	particulate organic matter
SDG	United Nations sustainable development goal
SEAS	Towards Integrated Marine Research Strategy and Programmes — a project funded by the EU FP7 ERA-NET scheme
UNEP	United Nations Environment Programme
VECTORS	EU FP7 project: Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors

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