MARINE BIODIVERSITY & ECOSYSTEM FUNCTIONING

marbef

Marine Biodiversity & Ecosystem Functioning

Heip, C., Hummel, H., van Avesaath, P., Appeltans, W., Arvanitidis, C., Aspden, R., Austen, M., Boero, F., Bouma, TJ., Boxshall, G., Buchholz, F., Crowe, T., Delaney, A., Deprez, T., Emblow, C., Feral, JP., Gasol, JM., Gooday, A., Harder, J., Ianora, A., Kraberg, A., Mackenzie, B., Ojaveer, H., Paterson, D., Rumohr, H., Schiedek, D., Sokolowski, A., Somerfield, P., Sousa Pinto, I., Vincx, M., Węsławski, JM., Nash, R.

This publication comprises a synopsis of some of the results from the MarBEF project (2004–2008). The success of the project was made possible by the MarBEF partner institutes and associate members. Our acknowledgments to all who contributed research findings and articles for this publication, and to those whose work does not feature in these pages.

Editor – Róisín Nash (Ecoserve)
Assistant Editor – Chris Emblow

Chapter coordinators – Ward Appeltans, Mel Austen, Geoff Boxshall, Fred Buchholz, Tasman Crowe, Carlo Heip, Herman Hummel, Henn Ojaveer, Dave Paterson, Pim van Avesaath, Doris Schiedek

Task team – Christos Arvanitidis, Rebecca Aspden, Nando Boero, Tjeerd J. Bouma, Alyne Delaney, Tim Deprez, Jean-Pierre Feral, Pep Gasol, João Gonçalves, Andy Gooday, Jens Harder, Adrianna Ianora, Brian Mackenzie, Heye Ruhmor, Paul Somerfield, Isabel Sousa Pinto, Magda Vincx, Jan Marcin Weslawski

EC officers – Hartmut Barth, Piia Tuomisto

Design – Cóilín MacLochlainn

Illustrations – © Ferdinando Boero (concept); Alberto Gennari (art); Fabio Tresca (graphics)

This publication to be refered to as:
Heip, C., Hummel, H., van Avesaath, P., Appeltans, W., Arvanitidis, C., Aspden, R., Austen, M., Boero, F., Bouma, TJ., Boxshall, G., Buchholz, F., Crowe, T., Delaney, A., Deprez, T., Emblow, C., Feral, JP., Gasol, JM., Gooday, A., Harder, J., Ianora, A., Kraberg, A., Mackenzie, B., Ojaveer, H., Paterson, D., Rumohr, H., Schiedek, D., Sokolowski, A., Somerfield, P., Sousa Pinto, I., Vincx, M., Węsławski, JM., Nash, R. (2009). Marine Biodiversity and Ecosystem Functioning. Printbase, Dublin, Ireland
ISSN 2009-2539

Marine Biodiversity and Ecosystem Functioning EU Network of Excellence
Sustainable development, global change and ecosystems
GOCE-CT-2003-505446

Table of Contents

Executive Summary

Marine biodiversity is an all-inclusive term to describe the total variation among living organisms in the marine environment, i.e., life in the seas and oceans. Marine systems have a series of characteristics which distinguish them from terrestrial systems, and marine organisms play a crucial role in almost all biogeochemical processes that sustain the biosphere. The organisms also provide a variety of goods and services which are essential to the well-being of mankind.

One of the major consequences of the unsustainable use of the Earth's resources is biodiversity loss. The aim in establishing a European network on marine biodiversity and ecosystem functioning (MarBEF) was to increase our understanding of large-scale, long-term changes in marine biodiversity.

MarBEF, an EU Network of Excellence, started with a new way of thinking, taking a bottom-up approach by bringing together over 700 scientists from around Europe to integrate their research. The skills and expertise of these scientists, who work in a wide variety of disciplines in the marine science sector, was combined to address the scientific challenges of the most topical marine biodiversity questions, and to provide new insights and answers at a scale of research never before attempted. This core strategic research programme consisted of three research themes: (1) examining patterns of species diversity, (2) identifying what structures the species diversity, and (3) the socio-economic consequences of biodiversity change.

The first challenge was to identify a baseline from which trends in marine biodiversity change could be detected at the relevant spatial and temporal scales. The integration of 251 datasets, provided by more than 100 scientists from 94 institutions in 17 countries, provided new insights into ecosystem processes and distribution patterns of life in the oceans. MarBEF captured 5.2 million distribution records of 17,000 species.

MarBEF published 415 scientific articles, 82% of which are 'open access' since MarBEF joined the Open Archives Initiative. These papers include several describing new species. During the project, MarBEF added a total of 137 species new to science to the European Register of Marine Species (ERMS). Using recent advances in molecular technologies, MarBEF found that a single seawater sample may contain up to 10,000 different types of organisms, and MarBEF identified the key microbes that participate in biogeochemical cycling in different areas around Europe. This provided further crucial data for understanding the links between biodiversity and ecosystem functioning.

The project made many specific findings. For example, cold-water marine caves were shown by MarBEF scientists to exhibit strong faunal and ecological parallels with the deep sea and provide a refuge during episodes of warming. A study on deep-sea vents showed that the distribution of the assemblages on the surface of vents was related to the position of the fluid venting and the resulting temperature gradients.

MarBEF scientists applied the most advanced genetic technologies to study marine biodiversity and phylogeographic structures. Their results will be of use in improving the way fisheries are managed.

MarBEF scientists specialising in chemical ecology discovered that bacteria communicate at the molecular level; that some diatoms produce chemicals that induce abortions and birth defects in the copepods that graze on them; and that dinoflagellates produce potent neurotoxins that can be transferred up the marine food chain. All of these discoveries give us a better understanding of the role of secondary metabolites in maintaining marine biodiversity and driving ecosystem functioning.

MarBEF scientists identified distinct, vulnerable marine populations that are now living on the edge of survival as a result of climate change. One of the findings made by the network was that, contrary to expectations, a warming climate could be leading to higher biodiversity in the Arctic and simultaneous food shortages for the top predators there. Concurrently, warming temperatures are contributing to an overall increase in fish species diversity in the North Sea, and initiating changes in phytoplankton assemblages in Mediterranean waters. Shifts in different elements of the deep sea-bed communities at the Porcupine Abyssal Plain are attributed to the North Atlantic Oscillation, a climatic phenomenon.

Research into the evolutionary effects of fishing on fish biodiversity indicated that fish populations may be becoming more vulnerable (and less resilient) to perturbations including fishing, climate change and invasive alien species. Also, increased river inputs, due to climate change, may be altering food webs and thus fisheries. MarBEF scientists showed that alterations in the abundance of key species affect ecosystem functioning more than changes in species diversity, and that only some types of human disturbances have strong effects on the stability of rocky shore assemblages.

MarBEF scientists defined specific ecosystem goods and services provided by marine biodiversity and suggested that they have the capacity to play a fundamental role in the ecosystem approach to environmental management. Marine biological valuations in the form of maps developed by MarBEF could be used as baselines for future spatial planning in the marine environment. MarBEF also developed a demonstration prototype of a decision support system (MarDSS) for identifying and selecting alternative solutions for the protection of marine biodiversity.

MarBEF identified and studied many critical marine biodiversity issues, which are now much clearer than before. It also identified areas where further work is essential and that will require concentrated effort, such as: the impacts of global climate change; synergy of anthropogenic impacts additional to global warming; coastal management; phase shifts and alternate stable states; habitat diversity; ecosystem function; biodiversity diversity; the role of species; biodiversity at a genetic level; microorganism diversity; marine biotechnology.

MarBEF will continue after EC funding has ceased because the MarBEF members are of the opinion that multidisciplinary marine biodiversity research requires long-term commitment and integration at a large scale, and that the integrative bottom-up approach within MarBEF is the proper mechanism to accomplish this. MarBEF has reached the critical mass to promote, unite and represent marine biodiversity research at a global scale, with 95 institutes as members. Therefore, it is beneficial to all if the network is kept alive and active. In preparation for such a lasting infrastructure, MarBEF is cooperating with MARS (the European Network of Marine Research Institutes and Stations) and Marine Genomics Europe to extend the network of institutes involved in marine biodiversity research in Europe and beyond.

Going where no one has gone before

What is it all about?

What is biodiversity?

A definition of biodiversity that is simple and yet comprehensive enough to be fully operational (i.e., responsive to real-life management and regulatory questions) is unlikely to be found. However, intuitively biodiversity equals the diversity of life on Earth.

According to the Convention on Biological Diversity, biodiversity is ‘the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.’

Biodiversity thus encompasses genetic diversity, species richness and habitat heterogeneity (rather than ecosystem variability). These three components are linked, obviously so between genes and species and somewhat less clearly between species and habitats. Because these three aspects are not easily reduced to a simple physical unit that can be studied, biodiversity is a somewhat abstract and even mythical concept.

In practice and also in public perception, and implicit in the day-to-day practice of many scientists, biodiversity often equals species richness, the number of species in a certain area or volume of the biosphere. Species richness and genetic diversity are studied and understood using organisms and their molecular products but increasingly, attributes of whole plant and animal communities and habitats can be measured, e.g., through remote sensing.

Biodiversity present today is the result of over two billion years of evolution, shaped by natural processes and increasingly by humans, whose impact is now leading rapidly to the sixth great extinction crisis in the history of life on Earth.

Marine biodiversity

The three domains of life, bacteria, archaea and eukarya, are present in the marine environment. In addition to which, there are viruses, infectious agents that are unable to grow or reproduce outside a host cell. Almost 230,000 species of marine plants and animals, and a few thousand bacteria and archaea, have been scientifically described. This known biodiversity represents only a fraction of the number of species existing in most groups (possible exceptions are the better known macrophytes and seagrasses of coastal environments and the pelagic macroscopic fauna and flora of the open ocean).

For animals and microbes, the exploration of environments that are difficult to access, such as the deep-sea floor, chemosynthetic environments or marine caves, and the application of new technologies are constantly yielding new species at a higher taxonomic level, and in some cases up to phylum level. The availability of rapid sequencing technologies has shown that variability in the microbial domain, including the small eukaryotes, is extremely high and that tens of thousands of ‘species’ may occur in a single litre of sea water. The estimates of the number of marine species that remain to be described are therefore very uncertain.

Why marine biodiversity is so important

The theoretical foundations as well as the experimental approach required to understand marine biodiversity are very poorly developed in general, particularly so when compared to terrestrial ecology. In fact, the whole literature is so dominated by theory developed for terrestrial ecosystems that until recently one could hardly find mention of a marine biodiversity field. One basic question is whether terrestrial and marine systems are similar

The distinctive features of marine biodiversity

(Heip *et al.*, 1999)

1 Life originated in the sea and is therefore much older than life on land. As a consequence the diversity at higher taxonomic levels is much greater in the sea, where there are fourteen endemic (unique) animal phyla in comparison to only one endemic phylum on land. There is also a remarkable diversity of life-history strategies in marine organisms. The sum total of genetic resources in the sea is therefore expected to be much more diverse than on land.

2 The physical environment of the seas and land is totally different. Marine organisms live in water; terrestrial organisms live in air. Environmental change in the sea has a much lower frequency than on land, both in time and in space.

3 Marine systems are more open than terrestrial ones and dispersal of species may occur over much broader ranges. Although most species in the ocean are benthic and live attached to or buried in a substratum, in coastal seas a very large proportion have larvae that remain floating in the water for a period of days to months. These high dispersal capacities are often associated with very high fecundities and this has important consequences for their genetic structure and their evolution.

4 The main marine primary producers are very small and often mobile (phytoplankton), whereas on land primary producers are large and static (plants). The standing stock of grazers in the sea is higher than that of primary producers; the opposite is true on land. Ocean productivity is on average far lower than land productivity. In the largest part of the ocean, beneath the thin surface layers, no photosynthesis occurs at all.

5 High-level carnivores often play key roles in structuring marine biodiversity, but are exploited heavily, with unquantified but cascading effects on biodiversity and ecosystem functions. This does not occur on land, where the ecosystems are dominated by large herbivores and increasingly by humans, who monopolise about 40% of the total world primary production.

6 A greater variety of species at a higher trophic level is exploited in the seas than on the land: man exploits over 400 species as food resources from the marine environment, whereas on land only tens of species are harvested for commercial use. Exploitation of marine biodiversity is also far less managed than on land and amounts to the strategy that hunter-gatherers abandoned on land over 10,000 years ago, yet exploitation technology is becoming so advanced that many marine species are threatened with extinction. Insufficient consideration has been given to the unexpected and unpredictable long-term effects that such primitive food-gathering practices engender (Duarte *et al.*, 2007).

7 All pollution (of air, land and freshwater) ultimately enters the sea. Marine biodiversity is thus most exposed to and critically influences the fate of pollutants in the world. Yet marine species are probably least resistant to toxicants. The spread of pollutants in marine food chains, and therefore the quality of marine food, is uncontrollable by man.

© F Boero, A Gennari, F Tresca

Many species of coastal plankton are active for a short time and remain in the sediments as resting stages, sometimes for very long periods.

enough to allow theory from one domain to be used for the other. Most probably this is not the case. Marine systems have a series of characteristics which distinguish them from terrestrial systems (see panel, page 3).

There is probably less species diversity and more genetic diversity in the marine environment than on land. If one looks at the arthropods, the insects and chelicerates on land and the crustaceans in the oceans, the difference is striking. A single tree in a tropical forest may harbour over a thousand species of insects, whereas the entire planet harbours only eighty species of euphausiids (krill). This indicates that the mechanisms of speciation are very different in the sea and that competition for resources does not constitute a dominant selective pressure (although you will find more species in fine-grained marine sediments than in the water column).

The upper water column has a very dominant vertical gradient in light availability and nutrient concentration, i.e. a limited range of resources, but supports more species (especially the micro- and picoplankton) than one might expect. This was called the paradox of the plankton by limnologist GE Hutchinson (1959) and was later applied to the marine environment by Margalef (1968).

However, no studies have attempted to define resources in the sea at the same level of detail as is customary in the terrestrial environment. Overall, the smaller number of marine species make it reasonable to assume that the mechanisms of diversity generation and maintenance are different on land and sea.

Goods and services

Marine organisms play a crucial role in almost all biogeochemical processes that sustain the biosphere, and they provide a variety of products (goods) and functions (services) which are essential to mankind's well-being. Goods include marine foods (about 100 million tonnes produced annually) and natural substances, ingredients for biotechnology and pharmaceuticals, and even land (e.g., the carbonate platforms that make up the Bahamas), and these substances are mainly delivered by macroscopic organisms.

The rate and efficiency of the processes that marine organisms mediate, as well as the range of goods and services that they provide, are determined by interactions between organisms, and between organisms and their environment, and therefore by biodiversity. These relationships have not yet been quantified and we are at present unable to predict the consequences of loss of biodiversity resulting from environmental change, in ecological, economic or social terms.

Besides goods, marine ecosystems deliver services that are essential to the proper functioning of the Earth. These services include regulation of climate, the production and mineralisation of organic material, the storage of carbon, the storage and detoxification of pollutants and waste products from land, the buffering of the climate and of climate change, coastal protection (mangroves, dune-beach systems, coral reefs) and regulation of the biogeochemical cycles in general.

Marine organisms play crucial roles in many of the biogeochemical processes that sustain the biosphere. The carbon and nitrogen cycles are dominated by ocean processes and by micro-organisms in the oceans, but the interplay between natural processes and human activities is becoming increasingly important.

Two examples of major processes involving carbon and nitrogen are primary production and nitrogen fixation. A limited number of species account to a large extent for the magnitude of these processes, and the characteristics of such species, as shaped by natural selection, may be important to understanding global change.

Thirty years ago, the major carbon fixers in the oceans had not yet been discovered. Cyanobacteria of the genera *Prochlorococcus* and *Synechococcus,* organisms of around 1µm in size, are now known to be responsible for as much as 30% of all global primary production.

It is not clear what impact human activity may have on the biodiversity of microorganisms in the open sea, or what the consequences might be. One example of an interaction is the limitation of primary production by iron availability in large parts of the world's oceans; this limitation could be modified by direct (fertilization) or indirect (climate change) human action. Another possible impact is increasing CO_2 uptake by seawater, leading to a lowering of pH (greater acidity). This may have important consequences for organisms such as *Emiliania,* which besides being photosynthetic are also important calcifiers.

When this simple picture holds – i.e., that overall the goods in the oceans are provided by macro-organisms and the services by micro-organisms – it is clear that the marine food web should be a central point of attention and research to clarify the consequences of human activity. Only in a multidisciplinary approach can we hope to understand what the interactions between species and biogeochemical cycles really mean in terms of global change. This requires more directed exploration, description and experimentation effort as well as a modelling framework. This framework can only be put together by a new scientific network.

Valuation and use of marine biodiversity

The economic value of harvestable marine biodiversity is very high, and the valuation of goods and services has been the subject of much research and debate. Although it is possible to attribute monetary value to many goods and services and to show that this value can be extremely high, it is also important to recognize that non-use values such as intellectual interest, aesthetic pleasure and a general sense of stewardship towards the non-human life of our planet are important prerequisites for public support of the conservation and sustainable use of the marine environment.

Biodiversity is a key consideration in understanding human exploitation of the living resources of the oceans, whether they be fish, invertebrates, natural products or enjoyment and beauty of the environment; it all depends heavily on which species we are considering. If one species of fish disappears, it cannot just be replaced by another: taste is species-specific and so are human consumer interests. In terms of conservation of natural resources and sustainable exploitation of living marine resources, marine biodiversity is therefore very important.

It is clear that exploitation of marine biodiversity has increased dramatically in intensity over the last century. With the increasing power and range of fishing vessels, more and more large species have seen their populations plummet. Larger and then smaller whale species were the first to go, and while these species are now protected, they are still only recovering. Large predatory fish such as tuna have been decimated in recent years. Tens, perhaps hundreds, of millions of sharks are mutilated and slaughtered each year. Bottom trawling has destroyed benthic habitats worldwide. Deep-sea fish such as the orange roughy have become increasingly targeted as the fisheries descend to water depths greater than 1km. The worldwide decimation of the top trophic levels of the marine food webs have cascading effects down to the level of the phytoplankton.

Fisheries and aquaculture put heavy pressure on a number of species. Both demersal and pelagic fish species have undergone major changes in abundance and population structure, even in the vast areas of the open ocean. Aquaculture puts an additional pressure on fish stocks as the most valued species are often fed on other fish species and as genetic diversity is eroded. The continued effects of pollution and eutrophication are well documented around the world, especially near industrial areas and where agricultural activities are high. The introduction of exotic species, where humans serve as a vector, is accelerating enormously, mainly due to transport in ballast water and the physical removal of biogeographical barriers. This threatens to change biological communities and lower the global marine gene pool, as successful species tend to be the same in different places.

Habitats are also being changed and destroyed by a number of human activities, including dredging (sand and gravel exploitation), deep-sea mining (oil and gas exploitation), bottom trawling, the blasting of reefs and the clearing of mangroves. Perhaps most alarming is the rapid deterioration of coral reefs worldwide, which seems to be due mainly to rising water temperatures and increasing phosphate concentrations. Deep-water corals in Europe are increasingly subject to destruction by fisheries activities and may in the future suffer from ocean acidification.

Marine conservation

Is marine biodiversity being lost?

Loss of marine biodiversity has been documented extensively for larger vertebrate and a few invertebrate species which are directly exploited by man. One of the most spectacular examples is the loss of diversity in pelagic fish due to the long-line fisheries of a number of nations (Myers & Worm, 2003). Marine turtles worldwide, including in Europe, have undergone dramatic declines. Marine birds are the most important victims of accidental oil spills, such as recently from the *Erika* in Brittany in 1999 and the *Prestige* off Spain in 2003. Marine mammals such as monk seal, harbour porpoise and some dolphin species have disappeared from some areas. However, there are examples of spectacular recoveries of marine mammal populations after protection, such as several seal species in Europe and sea lions, sea otters and some whale species elsewhere.

Only a few marine species have gone completely extinct, as far as we know. Still, the threat is there and protection of marine species and conservation of marine areas are on the political agenda and have been for many years. In many EU countries coastal marine reserves exist that protect high diversity areas and may serve as reserves from which other areas can be repopulated. Slowly but surely, marine protected areas in the Natura 2000 framework are being established. Fisheries are regulated by establishing quotas for individual species, based on a virtual population analysis based on abundance and size. Because basic statistics exist for a number of fish populations, the long-term trends of biodiversity of pelagic and

Threats to marine biodiversity

As with climate change, biodiversity loss is one of the major consequences of the unsustainable use of the resources of the Earth. This is as true for the marine environment as it is for the terrestrial one.

It is difficult to judge which biodiversity changes are due to direct human impact, but most evidence suggests that coastal and open ocean marine species are under heavy pressure in most parts of the world from the following five major factors:

- Overexploitation of resources
- Pollution and eutrophication
- Introduction of invasive 'alien' species
- Habitat destruction (e.g., reefs, mangroves, habitat loss as a result of sand and gravel exploitation, etc)
- Global climate change and acidification of the sea.

demersal fish are known for a number of areas. The spectacular decline of large pelagic fish species due to long-line fishing by a number of countries has been mentioned. In general, the average trophic level as well as the average size of exploited fish populations has decreased over the last decades. This is the concept of fishing down the food chain. Since top predators are removed, the structure of the food chain changes as well. Smaller species tend to increase in number, putting more grazing pressure on the zooplankton, which in turn releases the phytoplankton. Such changes may therefore increase primary production and the capacity of the oceans to absorb excess CO_2, but this is very speculative. Nevertheless, the notion that fisheries regulations require an ecosystem approach has gained momentum and is now appearing in many policy documents.

One reason why it is so difficult to clearly establish the reasons for changes in biodiversity is that, besides changes in food webs due to direct human exploitation, there are also long-term changes that are probably due to climatic factors. One of the best known examples is the changing distributions of copepod species in the Atlantic Ocean, as described in the work of Gregory Beaugrand and his colleagues from SAPHOS (Beaugrand *et al.*, 2002). Over the last decades there has been a gradual shift in copepod distributions from south to north. This shift may be having direct consequences for fisheries as there appears to be a positive correlation between the abundance of copepods and that of gadoid fish.

References

Beaugrand G, Reid PC, Ibanez F, Lindley JA, Edwards M (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296** 1692–1694.

Duarte CM, Marba N, Holmer M (2007). Rapid domestication of marine species. *Science* **316** 382–383.

Heip C, Warwick RM, d'Ozouville L (1999). A European Science Plan on Marine Biodiversity. European Science Foundation, Strasbourg.

Hutchinson, GE (1959). Homage to Santa Rosalia or Why are there so many kinds of animals? *Am.Nat.* **93** 145–159.

Margalef R (1968). Perspectives in Ecological Theory. Chicago University Press.

Myers RA, Worm B (2003). Rapid worldwide depletion of predatory fish communities. *Nature* **423** 280–283.

A novel approach

The introduction gave an overview of the reasons and arguments that led to the creation of the MarBEF (Marine Biodiversity and Ecosystem Functioning) Network of Excellence (NoE). MarBEF **(www.marbef.org)** was the first initiative of its kind funded under the EU Sixth Framework Programme.

Networks of excellence were a new way of thinking, designed to strengthen scientific and technological excellence on a particular research topic through the durable integration of the research capacities of the participants. They aimed to overcome the fragmentation of European research by gathering the critical mass of resources and expertise needed to provide European leadership.

For MarBEF, the network represented a huge challenge and a huge opportunity. It brought together over 700 scientists from 95 separate institutes in 24 European countries with the aim of integrating research from a variety of disciplines within marine science and providing training, exchange and outreach opportunities and initiatives that will be of huge importance both to science and society.

Better integration of research helps to support the legal obligations of the EU and its member states and of associated states for the Convention on Biological Diversity, the OSPAR, HELCOM, Barcelona and Bucharest Conventions, as well as EU directives (Bird Directive, Habitat Directive, Water Framework Directive and more recently the Marine Strategy Framework Directive).

MarBEF NoE

The challenges and obstacles

The new instrument and the dimension of the network posed a challenge to the management of MarBEF. MarBEF was the first NoE to be installed and therefore the corresponding managerial and administrative mechanisms had to be adjusted. The increasing number of members in the MarBEF NoE, and the corresponding increase in the managerial burden and amount of paperwork (despite the efforts of the European Commission to streamline the administration of FP projects), together with the finite resources for the management of the consortium, were challenges to manage in a timely and proper fashion.

The success of the network was achieved only through the huge efforts and patience of the management team and the individual MarBEF members who, like all research institutions, were more interested in the science than in the project management and paperwork. It was through the integration made possible by the network – which created so many unique scientific challenges and new insights – that the related managerial burden was sufficiently counterweighted. This involved a high degree of adaptability of the MarBEF members.

Recipe for success: a bottom-up approach

Despite the burden of deadlines for reportage, the many forms that needed to be completed, and uncertainties in budget and planning, the members kept on supporting and focusing on the goals of the network. Although one may think this is normal, we believe that the way MarBEF was organised and managed significantly contributed to its success.

MarBEF had a strong, bottom-up approach involving the members from the start and allowing them to propose and participate in joint integrative research activities, training exercises and workshops that supported the main aims of the NoE. This increased the commitment of the members to the project, and thus the integration.

The science

In Europe, we have world-class marine scientists with outstanding skills and expertise in their disciplines. MarBEF united these eminent marine scientists under one network, thereby bringing this dispersed scientific excellence together to create a virtual European centre of excellence in marine biodiversity and ecosystem functioning.

One of the basic problems that was at the heart of the MarBEF proposal in 2003 was the challenge of understanding large-scale and long-term changes in marine biodiversity in Europe. Although a number of studies on marine biodiversity existed, there was no programme that tried to establish the baseline from which trends in marine biodiversity change could be detected at the relevant spatial and temporal scales. Such a baseline would encompass an inventory of the marine species in Europe (now at about 32,000 plants and animals). One of the first objectives that were formulated within MarBEF was to bring together the numerous data on marine biodiversity species richness that existed in many research institutes but were never compared and synthesized to provide a picture for the entire continent. MarBEF has been extremely successful in this objective.

The MarBEF network of scientists addressed the most topical questions in marine ecology, biogeochemistry, fisheries biology, taxonomy and socio-economics in Europe through a core strategic programme which consisted of three themes.

Theme 1: Patterns of species diversity

Before we can answer the question of why biodiversity varies, we need to know the basic patterns of its distribution in space and time. The most fundamental data on diversity are the numbers of species in different places. It is a fundamental problem for marine biodiversity studies that this is largely unknown. There are some exceptions, such as some animal groups from the zooplankton, a number of plant and animal species from intertidal and shallow subtidal zones, and increasingly the microbial flora and fauna from hydrothermal vents. But we know next to nothing about the distribution and the dynamics of the large majority of species living in the sediments covering millions of square kilometres of the deep-sea floor.

Terrestrial ecologists have used geographic distributions of species extensively and have discovered relationships between these data and latitude, climate, biological productivity, habitat heterogeneity, habitat complexity, disturbance, and the sizes of, and distances between, islands. Several of these relationships have suggested mechanisms that might regulate diversity, but a general and comprehensive theory of diversity accounting for most or all of these relationships does not exist.

Spatial scale is the overriding variable that needs to be considered when discussing the changes in diversity and what has caused these changes. Definition of scales is not straightforward, neither in terrestrial nor in aquatic environments. Scales are often defined from the perception of the human observer and less as a function of the species or communities considered. It is customary to distinguish between local, regional and global spatial scales. Locally, species diversity in any locality is seen as a balance between two opposing forces. On the one hand, local abiotic processes, interactions between species and chance tend to reduce diversity; on the other hand, immigration from outside the locality tends to increase diversity. Each local population is seen as a sample from a larger species pool. Theories on larger, mesoscale patterns take migration and dispersion explicitly into account. The metapopulation concept and connectivity of land(sea)scapes are central to this approach. Global patterns are, for instance, latitudinal gradients. Within most groups of terrestrial organisms the number of species reaches its maximum in tropical latitudes and decreases both northward and southward toward the poles. In many cases the latitudinal gradient in diversity is very steep. Tropical forests, for example, may support ten times as many species of trees as forests with similar biomass in temperate regions (Latham and Ricklefs, 1993).

Since many factors vary in parallel with latitude, the causal mechanisms that explain such patterns are difficult to distinguish and, moreover, nearly all studies are from terrestrial environments. In marine communities, the existence of such patterns over large geographical scales has only rarely been studied (Rex *et al.*, 1993). Whether they are as widespread as in the terrestrial environment is questionable, but even in terrestrial environments the general trend in diversity is sometimes reversed, as it is for shorebirds, parasitoid wasps and freshwater zooplankton, of which more species occur at high and moderate latitudes than in the tropics. These counter-examples may reflect the latitudinal distribution of particular habitat types, the history of the evolution of a taxon, or ecological circumstances peculiar to a particular group.

Theme 2: What structures species diversity?

The second main question that MarBEF addressed was to understand why biodiversity changes and what the consequences of these changes are for ecosystem functioning. Traditionally, species interactions are considered to be important for structuring biological communities, but this has not been investigated in great detail and has not been shown to be true also for the open ocean. Experimental work in the marine environment to test hypotheses is mostly known from intertidal areas that are well accessible for controlled experiments. Also, modelling of marine systems has been part of this effort. Furthermore, the importance of species identities and species interactions for regulating biogeochemical cycles, as supported mainly by microorganisms, needs further study, which has become extremely urgent in view of the rapid changes in climate and biodiversity itself.

The composition of species assemblages changes constantly. Species disappear and appear all the time. But how does that impact the ecosystem? One of the great challenges of contemporary science has been the elucidation of the link between biodiversity and ecosystem functioning. Cycles in the biosphere have been known to operate through biological agents for at least two centuries. But the question of whether the precise identity of these agents matters is still looming large. In the oceans, where most of the cycles are driven by microbes, the question is even more pertinent than on land: we now know that there are endless numbers of 'species' and long tails in the species abundance curves of relatively rare species. Redundancy therefore seems to be almost inevitable; if one species disappears another will appear and take over its functionality. Biodiversity then becomes a buffering capacity factor of an ecosystem.

Theme 3: Socio-economic consequences

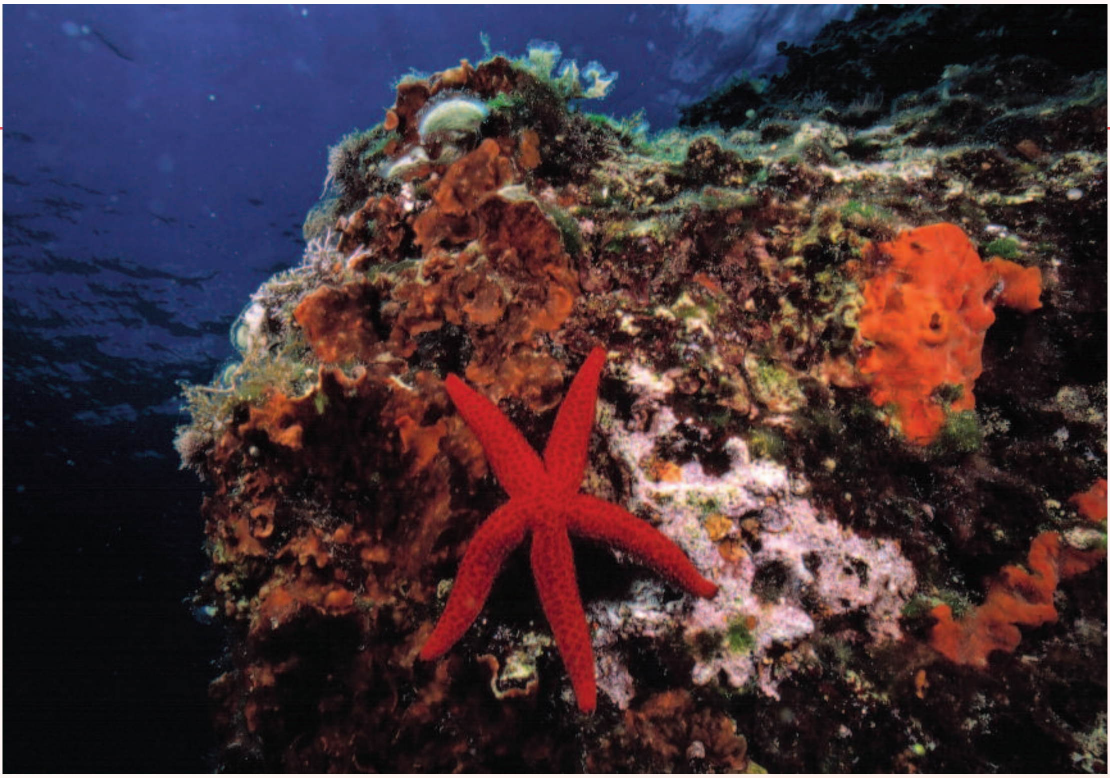
Finally, MarBEF has looked at the socio-economic consequences of biodiversity change. Problems of valuation have been discussed, including valuating the intrinsic biological characteristics of certain communities and areas. This is needed to bring the study of biodiversity into the realm of socio-economic sciences and is considered important for policy-making, e.g., in spatial planning. With the current economic crisis, which catalyses new economic thinking, and an increased awareness of the environmental constraints to economic growth and development, the chances that biodiversity will at last be taken seriously by economists and politicians have increased, but the intellectual framework and even the paradigm shift that is required still needs considerable input and support.

Epilogue

The legacy of MarBEF

When we started the MarBEF network of excellence, biodiversity was hardly known by the general public and not considered an important feature, let alone a problem or an asset of marine ecosystems. All this has changed greatly in terms of what we know about the oceans, in terms of understanding how the oceans work, and in terms of how we handle the problems of the oceans and its inhabitants.

MarBEF has been something unique. It was the first network of excellence, a new instrument in EU Framework Programme 6 to support the development of the European Research Area. This volume, which summarizes the main scientific results from MarBEF, hopefully reflects the feeling of excitement that has stimulated hundreds of the best European marine scientists to devote five years of their attention to helping it thrive. Not for the money – although financial support has been substantial, though it had to be shared by the original 53 partners – but out of enthusiasm and a sense of responsibility and urgency. The planet is changing, and the oceans as well. Over the five years of MarBEF, we have witnessed society becoming aware of the grave consequences of overfishing, of acidification, of physical disturbance and, above all, of the effects of climate change. There is now a community of European scientists who have the experience to work together and the expertise to help adapt human society to the coming changes. This is the most important legacy of MarBEF.



© Robert Hofrichter, ImagDOP

A glimpse at life within our oceans.

With the advent of the European Marine and Maritime Strategy and its requirements for good ecological status of marine waters, the need to understand marine biodiversity changes and their consequences for stability and use of marine ecosystems will only become more urgent. Some of the priorities that we need for the future are further efforts to map biodiversity, including the genetic and habitat components and especially the relationship between them and species richness; data integration and accessibility, and establishing a network for observation and early warning of biodiversity changes that covers most of Europe's coast. After all, more than half of the EU is under water and this fraction is only likely to increase.

The future

MarBEF will continue after EC funding has ceased – because MarBEF members are of the opinion that multidisciplinary marine biodiversity research in Europe essentially needs long-term concentration and integration at large scale, and that the integrative bottom-up approach within MarBEF is the proper mechanism to accomplish this. MarBEF has reached the critical mass to promote, unite and represent marine biodiversity research at a global scale, with 95 institutes as members, all of which are active in marine biodiversity research. Therefore, it is beneficial to all if the network is kept alive and active. In preparation for such a lasting infrastructure, MarBEF is cooperating with MARS (the European Network of Marine Research Institutes and Stations) and Marine Genomics Europe to extend the network of institutes involved in marine biodiversity research in Europe and beyond.

References

Latham RE, Ricklefs RE (1993). Global patterns of tree species richness in moist forests. Energy-diversity theory does not account for variation in species richness. *Oikos* **67**.

Rex MA, Stuart CL, Hessler RR, Allen JA, Sanders HL, Wilson GDF (1993). Global-scale latitudinal patterns of species diversity in the deep-sea benthos. *Nature* **365** 636-639.

Exploring the unexplored

Treasure chest of information

Fishing for data

Scientific data on marine biodiversity is very much fragmented and scattered over many laboratories all over the world, where they are often available only on paper or in old electronic format, stored away and at risk of getting lost. In the past, many research expeditions have gathered biodiversity data which has been funded by government bodies, i.e. taxpayers' money. The results of these surveys produced enormous quantities of data which could potentially be of huge importance to the scientific community at large and yet they sit gathering dust on a shelf – a crime to society!

MarBEF scientists recognised this problem and consequently built a framework and infrastructure to increase the availability and sharing of data which was previously at risk of being lost. Now all this data has been quality controlled and brought together in a single, properly archived system where it will remain available for future generations.

MarBEF's work through the integration of datasets is bringing new insights to ecosystem processes and distribution patterns of life in the oceans.

Key to the management of data was the creation of the **"Declaration of Mutual Understanding for Data-sharing"** (Annex 1). This document provided a solid basis of trust between MarBEF and non-MarBEF data providers, and was instrumental in providing an incentive for collective scientific work. It resulted in the collection of 251 datasets provided by more than 100 scientists from 94 institutions in 17 countries.

Databases

Large-scale marine environment datasets are scarce, so there is a need to integrate and manage local datasets in an alternative way, so that they meet the requirements for data and information on a global scale, and to support decision-making. MarBEF has data records ranging from the deep-sea to the coastal zone and from the Arctic to the Antarctic; it has built the **world's largest databases** on macrobenthos, meiobenthos and pelagic marine species. Three scientific projects within MarBEF alone have created thematic databases and integrated 190 different datasets, containing about 1,000,000 distribution records from European seas.

MarBEF has captured 5.2 million distribution records of 17,000 species in all the European seas and many of the world's oceans.

Large temporal and spatial biological datasets are essential for the study and understanding of long-term distribution and abundance patterns of marine life and how they have changed over time. The analysis of this data allows comparisons to be made between different regions and habitats, to examine broad-scale spatial and temporal patterns in biodiversity and to explore implications from changes. The data needed for this approach could never be

© Karl Van Ginderdeuren

Sorting benthic fauna species during a sampling campaign.

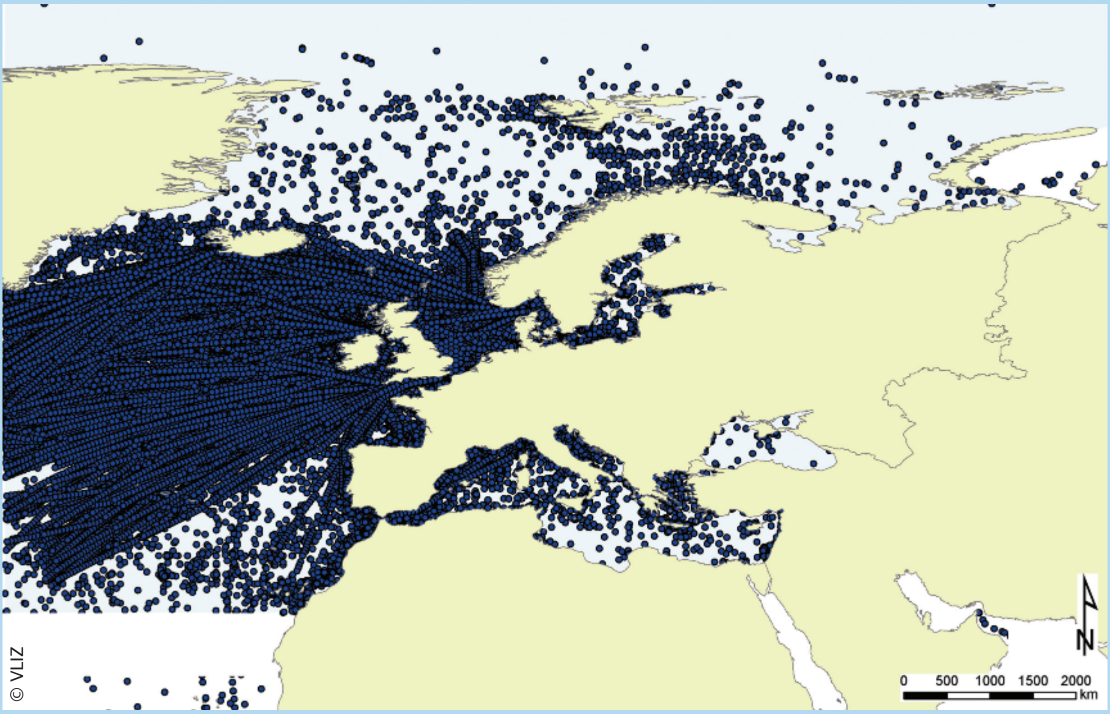


Figure 1. MarBEF data is available through EurOBIS, the largest online queryable public source of European marine biological data. EurOBIS contains 5.2 million species distribution records from 210,832 localities and 32,225 taxa in all the European seas and many of the world's oceans.

sampled by scientists or research groups due to limitations in infrastructure, time and money.

The integrated database of MacroBen (European MacroBenthic fauna) is an important tool for studying and understanding large-scale, long-term distribution and abundance patterns of marine benthic life.

As a consequence of the ever-growing anthropogenic pressures on the sea floor, there is an increased need for sustainable management. Good management decisions need to be based on **sound scientific information** on the ecosystem function and the diversity of the organisms present. Assessing the biodiversity of large areas based on field sampling is a long and expensive process. Therefore, tools predicting and mapping biodiversity are an important tool for managers to underpin their decisions.

Scientists within the MarBEF project **MANUELA** (**M**eiobenthic **A**nd **N**ematode biodiversity: **U**nravelling **E**cological and **L**atitudinal **A**spects) modelled the distribution of roundworms (nematodes) and meiobenthos such as copepods to develop techniques that allow for mapping of biodiversity.

MarBEF is mapping diversity to support ecosystem management and decision-makers.

The MarBEF **LargeNet** (Large-scale and long-term Networking on the observation of Global Change and its impact on Marine Biodiversity) database currently contains over 4,500 taxonomic names and more than 17,000 sampling locations, representing almost 542,000 distribution records.

Analysis of data collected by ArctEco from the All Taxa Biodiversity Inventory site at Hornsund (77°N, Svalbard) in the Arctic shows that the marine benthic biodiversity has increased by 50% (>1,415 marine species) in recent years.

It is anticipated that, following the publication of the LargeNet analyses, more datasets will be attracted into the system. This huge enterprise will be continued in the EMODNET (European Marine Observation and Data Network) project of FP7 that will support the European Marine and Maritime Strategy.

Taxonomic information

Conservation and sustainable use of biological resources are accepted as the way of achieving healthy ecosystems. Biodiversity information, whose basic tool is taxonomy, is the foundation for conservation. Taxonomy has been defined as "the scientific discipline of describing, delimiting and naming organisms, both living and fossil." Taxonomy is of fundamental importance for understanding the ways through which biodiversity may be changing in the context of climate change and the ways that biodiversity may provide goods and services to society.

MarBEF has spent considerable effort on taxonomy through three main activities: the Taxonomic Clearance System and the PROPE-taxon and MANUELA projects. The Taxonomic Clearance System scheme successfully addressed the taxonomic identification bottleneck and streamlined the process of identification of specimens and the description of new species. PROPE-taxon provides European taxonomists with a community-driven e-platform that acts as a web-accessible depository for integrated taxonomic knowledge systems (e.g. databases, taxonomic keys, biogeographic data) based upon existing software and technologies (Scratchpads system developed by the Natural History Museum in London). The MANUELA project employed a second taxonomic information system, NeMys (developed at Ghent University), which contains available taxonomical literature on free-living marine nematodes, in addition to taxonomic keys.

The correct use of names and their relationships is essential for biodiversity management; therefore, the availability of taxonomically-validated, standardised nomenclatures are fundamental for biological infrastructures. The European Register of Marine Species (ERMS), originally funded by the EU MAST research programme, has been updated by MarBEF and is used as the taxonomic reference for checking spelling and harmonising synonymy, thereby improving quality control and standardising species lists. Now an impressive total of 31,455 names of European species are stored within this new database.

Over the last three years the European Register of Marine Species has increased its species numbers by 1,371 species, of which 10% are from species recently described.

LargeNET found that, after matching their species data (1,600 species) with ERMS, 17% of the names could be moved to the status of invalid names. These invalid names were mostly spelling variations, typing errors or synonyms. Without quality control procedures these

© Ward Appeltans

Øjvind Moestrup with tiny microscope. Taxonomy is often about looking at tiny details.

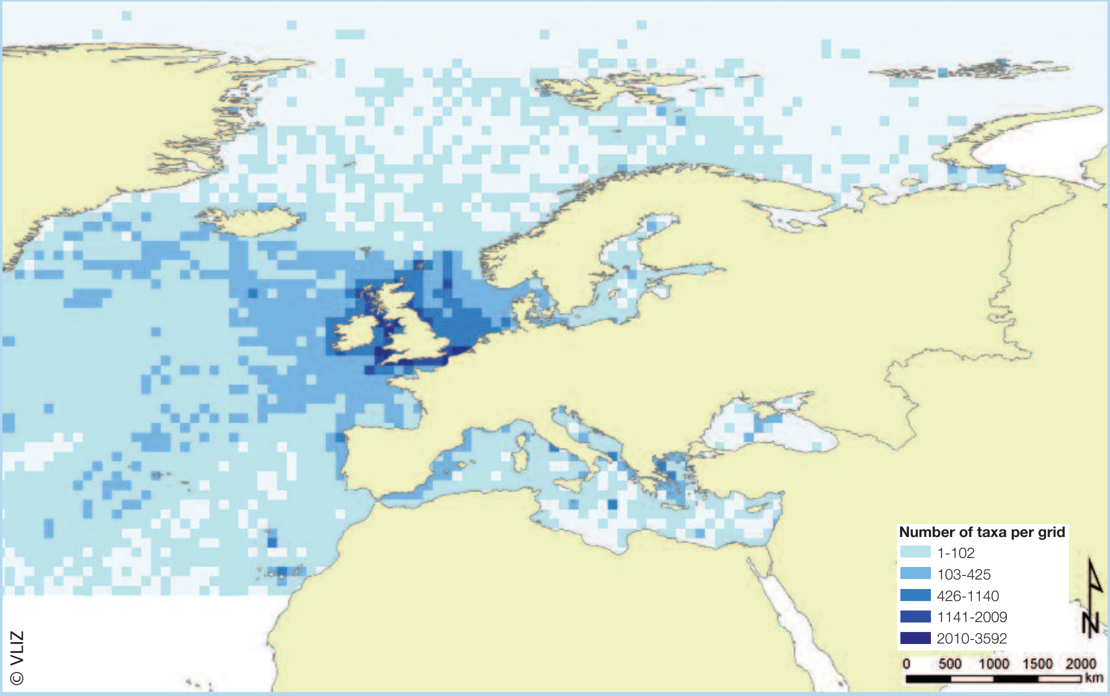


Figure 2. Overview of the species coverage in EurOBIS. On a fine scale (1x1 degree) our knowledge of the diversity of life is still very sketchy (or even non-existent: see grey areas on map).

"erratic names" would have been regarded as extremely rare taxa and could have led to seriously flawed analyses.

ERMS now serves as a basis for the creation of a World Register of Marine Species (WoRMS; www.marinespecies.org). More than 140 world-leading experts on marine species, from 26 countries (50% from EU), are building this world register of marine species. It will be the first expert-validated register of names of all marine species known to science.

Many international biodiversity programmes, among others CoML/OBIS, GBIF, EOL, Species2000, ICZN/ZooBank and IODE of UNESCO/IOC, need a register of valid names and have agreed to use WoRMS for their purposes.

WoRMs currently contains 140,000 valid species or 60% of the estimated number of described marine species in the world.

Geographical information

Geographic Information Systems (GIS) have become indispensable tools in managing and displaying marine biodiversity data. Within MarBEF, we have developed a standardised register of place names, called the European Marine Gazetteer.

The European Marine Gazetteer is the first international, internet-accessible gazetteer for the marine environment.

The ultimate goal is to have a hierarchical standard list that includes all the marine geographical names within Europe and subsequently worldwide. Presently, the Gazetteer includes the names of 983 European locations, seas, islands, sandbanks, ridges, estuaries, bays, sea-mount chains and submarine lava tubes. The Gazetteer is hierarchical and thus recognises that, for example, when a species is reported from a bay in Italy, that bay is part of Italy, the Adriatic Sea, the Mediterranean and Europe. Therefore, users can search for all datasets holding data on a specific area and subsequently find the species occurring in that area, or the people and institutes that are involved in research in that region. Other geographical regions in the Gazetteer include the major oceans and seas, Exclusive Economic Zones (EEZs), Large Marine Ecosystems, FAO Fishing Areas and Longhurst Biogeographical Provinces.

Biogeographical information

MarBEF established the European node of the international Ocean Biogeographic Information System (EurOBIS). EurOBIS is a freely accessible online atlas providing species distribution records from 174 datasets. EurOBIS is the largest data provider to the international OBIS. EurOBIS contains 5.2 million species' distribution records from 210,832 localities and 32,225 taxa in European marine waters (Fig. 1&2).

By combining areas defined in the Gazetteer and the species distribution data in EurOBIS, national or regional species checklists can easily be created.

Meetings and publications

MarBEF has sponsored over 150 meetings, which has resulted in new joint research and strong partnerships between scientists across Europe, which has led to numerous scientific papers already published or in press in international journals.

MarBEF has published 415 papers of which 220 are in peer-reviewed journals.

The MarBEF Open Archive (MOA) contains the digital version of published works that are held within the MarBEF Publication Series (i.e. any class of publication where at least one author is a network member and in which MarBEF is acknowledged). In addition, those papers where MarBEF has bought unrestricted 'Open Access' are automatically part of this archive. MOA can only archive those publications for which the publishers agree on the concept and principles of open digital archives (http://www.marbef.org/moa).

MarBEF has joined the Open Archives Initiative (OAI) and, therefore, 82% (389) of these scientific papers can now be downloaded for free.

Permanent host

The Flanders Marine Institute (VLIZ) and its oceanographic data centre led the data integration activities in MarBEF. All the original MarBEF data files have been described and archived in the Marine Data Archive. Data generated by MarBEF, with EU funding, are available without restrictions. However, following the MarBEF data policy, other datasets that are owned by the participating institutes and/or other agencies will not leave the repository without the consent of the data owners.

The MarBEF data system will continue to be an important knowledge base for future research and storage of marine biodiversity data in Europe.

References

Vanden Berghe, E, *et al.* (2009). Description of an integrated database on benthic invertebrates of European continental shelves: a tool for large-scale analysis across Europe. *Mar. Ecol. Prog. Ser.* **382** 225–238.

Vandepitte, L, *et al.* (2009). The MANUELA database: an integrated database on meiobenthos from European marine waters. *Meiofauna Marina* **17** 35–60.

Vandepitte, L, *et al.* (submitted). Data integration for European marine biodiversity research: creating a database on benthos and plankton to study large-scale patterns and long-term changes. *Hydrobiologia*.

Discoveries

The discovery of new marine organisms continues apace, with an average of about 1,400 new species described each year worldwide. A surprising number of these are from European waters, which one might have assumed were so well studied that they contained no surprises.

In fact, over the last three years a total of 137 species new to science have been added to the European Register of Marine Species.

These novelties range from microbes such as bacteria up to vertebrates, but the majority of newly described species are invertebrates, partly because the formal process of naming new bacteria has lagged far behind the rate of discovery of new microbes.

Species

New microbes

In the ocean, microbes – or organisms from 0.2 to 100µm – are very abundant. It has been calculated that they account for about half of the biomass on planet Earth. In the ocean, *Bacteria* and *Archaea* account for billions of tonnes of carbon (estimates range from 3 to 14 billion) while, in contrast, the entirety of mankind on Earth only accounts for about 0.03 billion tonnes of carbon. In a drop (one millilitre) of seawater, one can find 10 million viruses, one million bacteria and about 1,000 small protozoans and algae (called “protists”). In addition to their high abundance, microbes play a crucial role in most biogeochemical processes occurring in the marine environment:

	Result	Richness	Evenness	Resolution	
***GENETIC FINGERPRINTS* focusing on richness (number of operational units, absolute abundance)**					
DGGE/TGGE	bands	<35 bands	5-100%	>0.5%	
SSCP	bands	<35 bands	5-100%	>0.5%	
T-RFLP	bands	<200 bands	0.1-100%	>0.05%	
ARISA	bands	<500 bands	0.1-100%	>0.05%	
Pryosequencing (454 technology)	100-250bp sequences	>10,000	–		
Clone libraries	sequence	>100	no		usually >200 clones
PFGE bands	<50 bands	5-100%	>0.5%		(genome size)
***GENETIC FINGERPRINTS* focusing on evenness (relative abundance)**					
Quantitative PCR		no	0.01-100%		
FISH / TSA-FISH / CARD-FISH		no	0.1-100%		

Figure 1. A list of molecular methodologies used to measure richness and/or eveness of microbial communities. Also shown is the resolution of the technique. Simplified from a table assembled by the students and professors of the MarBEF training course Genetic Fingerprints in Biodiversity Research.

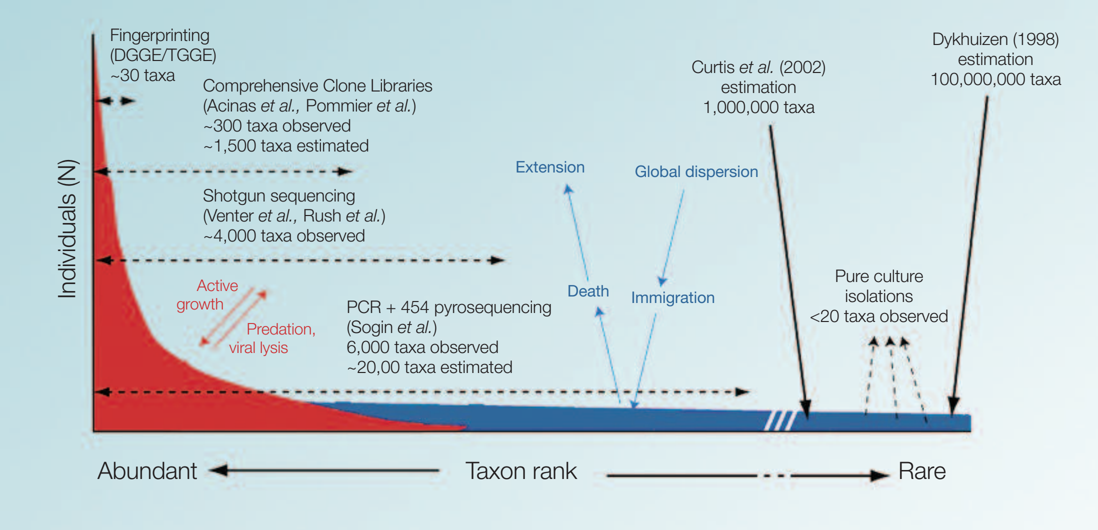


Figure 2. A conceptual model of how microbial diversity in the ocean is expressed, .i.e. a few organisms are relatively abundant and participate in ecosystem functioning while the majority of microbes await more optimal growing conditions, as shown above in the large 'tail of biodiversity.' Adaptation by Thomas Pommier (CNRS) of a figure by Pedrós-Alió (2006).

they account for almost half of global primary production and form a major part of ecosystem respiration and nutrient recycling.

Research in recent years has shown that microbes are not only very abundant and important ecologically but are also highly diverse. This huge diversity is found in organisms that, in most cases, are similar in morphology, but we know they are very diverse in the functions they perform and in the widely different genetic material (DNA) that they contain, which is a coding for a large variety of proteins.

Different types of proteins can be compared to different types of machines in a factory: they allow for great metabolic and physiological flexibility in the microbial world. However, as scientists cannot identify most microbes from their appearance alone, they have to rely on molecular methodologies to describe their diversity. In general, these methodologies rely on the fact that microbes share a common gene that is so important that it has changed relatively little throughout the evolutionary history of life on Earth. Reconstructing the differences in the base sequences of that gene enables organisms to be classified in a "natural" way that reflects their evolutionary history.

There are a variety of techniques employed to obtain microbial diversity data (Fig. 1).
Initial reports of microbial richness in aquatic environments suggested that there were less than 200 different microorganisms in a typical sample. But recent advances in molecular technologies, such as metagenomics [sampling genes directly from the environment], have shown that the diversity is much greater than previously thought.

A single seawater sample may contain up to 10,000 different types of microorganisms.

This is a huge diversity, particularly when compared with the number of formally described species of bacteria, which is fewer than 10,000 (Fig. 2).

To understand plankton distribution and changes, MarPLAN first needed to know how diverse it was. Using new techniques and partnerships that MarPLAN developed have allowed us to answer some fundamental questions, such as: 'Does limited dispersal enable the evolution of local bacterium species?' or conversely, 'Does a bacterium inhabit all European waters?'

Rhodopirellula baltica, an abundant red bacterium that lives attached to marine sediment grains (originally isolated from the Baltic Sea, or more precisely, the Bay of Kiel) was selected to investigate these questions. We obtained 70 strains, which revealed several new species within the genus *Rhodopirellula.* The species *R. baltica* was restricted to the Baltic Sea, the Skagerrak and the Eastern North Sea. A second species was present in Iceland and Scotland, representing the North-Atlantic habitat. Another different species was obtained from the Adriatic Sea, but the majority of the isolates belonged to a species present in the English Channel, on the French Atlantic coast and in the Mediterranean.

The presence of several species of *Rhodopirellula* in European seas showed evolutionary species diversification within the genus.

Molecular techniques allow the detection of the most abundant microbes, or those that actively participate in growth. Therefore, it allows us to attempt to identify the main microbes that participate in biogeochemical cycling in different marine habitats.

MarBEF scientists identify the main microbes participating in biogeochemical cycling, therefore enabling us to link biodiversity (or at least the "identity" component of it) with ecosystem functioning.

The trick is to use methodologies that tell us "who is doing what," and "who is the most relevant" among those that perform a given biogeochemical function and therefore what effect global change will have on that particular species or strain.

Members of the MarBEF project MarMicro have researched the identity of the key microbial organisms in different areas. For example:-

1) Central Baltic Sea

Anoxic and suboxic bottom waters are characteristic features of marginal and enclosed seas and many coastal environments (Black Sea, Baltic Sea, fjords, *etc*) and are increasing in extent worldwide. The oxic-anoxic transition zones are sites of element transformations which impact the overall biogeochemical cycles and are important on an ecosystem scale. Furthermore, these environments can be considered as model systems for ancient oceans which were dominated by anoxia throughout much of the Earth's history. Oxic-anoxic interfaces (chemoclines) are ideal sites to study the link between microbial community structure and biogeochemical transformations (and thus between biodiversity and ecosystem function), because distinct and measurable processes can be related to the activity of key bacterial or archaean species.

Studies of the central Baltic Sea redoxclines (here defined as transition zones several metres thick between suboxic and sulfidic water layers) revealed the exceptional importance of chemoautotrophic prokaryotes, which dominate microbial abundance (20-40 % of total cell numbers) and production. By applying techniques that link structure with function of prokaryotes (e.g., MICRO-CARD-FISH, SIP-RNA), *Epsilonproteobacteria* were identified as the major organisms responsible for chemoautotrophic production. A more detailed study of this group in the central Baltic revealed that *Epsilonproteobacteria* were nearly entirely represented by one phylogenetic cluster belonging to the genus *Sulfurimonas*. This organism can be called a "key player" in this habitat, mediating, for example, chemoautotrophic denitrification. A strain of this cluster demonstrated the exceptional metabolic versatility which includes the capacity to utilise different inorganic redox reactions as well as to make use of different organic substrates. This is likely to be an adaptation for survival in pelagic redoxclines that are characterized by steep

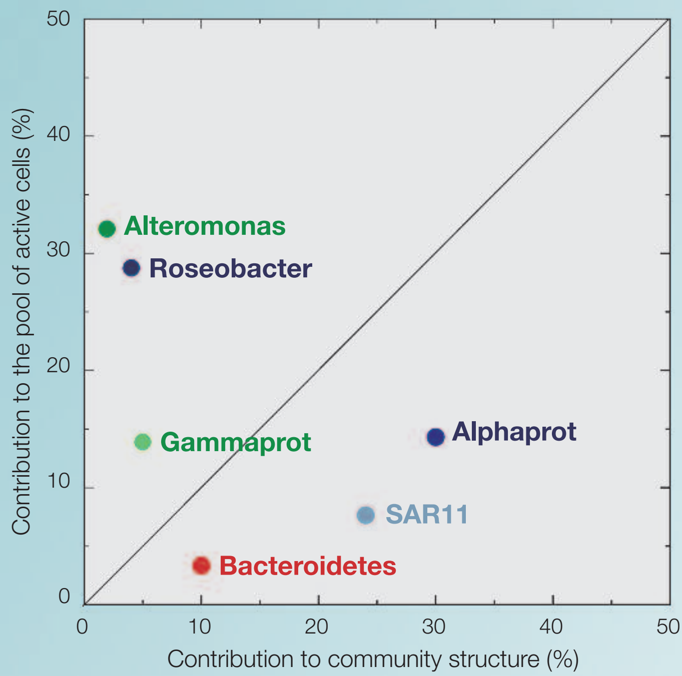


Figure 3. Contribution of different bacterial groups to community structure and to the pool of really active cells. Yearly average. *Alteromonas* is a subgroup of *Gammaproteobacteria,* and SAR11 and *Roseobacter* are subgroups of *Alphaproteobacteria.* Redrawn from Alonso-Sáez *et al.* (2006) and Gasol *et al.* (submitted).

physico-chemical gradients but also by frequent disturbances due to inflow and small-scale mixing events.

The study of redoxcline communities offers many new possibilities to examine and understand the link between diversity and ecosystem functioning in microbial communities.

In future, this will be done in combination with newly-developed tools from metagenomic, transcriptomics and proteomics.

2) Coastal NW Mediterranean Sea

On an annual basis, alphaproteobacteria are the dominant group [29% of total counts and 70% of bacterial clones]. The SAR11 clade is the most abundant during spring and summer, and it uses a variety of organic compounds that we can use as tracers of organic matter. On average, <10% of the SAR11 cells are active in the uptake of aminoacids, glucose or ATP. The *Roseobacter* clade (also from the alphaproteobacteria) is less abundant and can be detected only in winter and spring. In contrast *Roseobacter* cells, which constitute only 5-10% of the community, are much more active in the incorporation of these substrates (Fig. 3).

The phylum *Bacteroidetes* constitutes the second most important group and is equally abundant throughout the year. *Gammaproteobacteria* showed a small peak during summer, but was only very abundant on one particular day. The *Alteromonadas* subgroup of *Gammaproteobacteria* constituted a population of highly active cells that were all actively taking up organic matter. However, they were quickly eliminated from the water by grazers.

This indicates that some groups of bacteria in the NW Mediterranean act as r-strategists [fast-growing opportunists]. They have high rates of growth and they dominate incorporation of substrates when they are present, but they are seldom abundant. These groups would be the *Roseobacter* and the *Alteromonadacea.* Other groups, such as the *Alphaproteobacteriaceae,* SAR11 and the *Bacteroidetes,* follow more the alternative k-strategy, with slow growth and relative dominance.

3) Deep North Atlantic

The bacterial and archaeal community composition of the major deep-water masses of the North Atlantic was followed from 65°N to 5°S, following the flow of North Atlantic Deep Water east of the Mid-Atlantic Ridge. Using a T-RFLP fingerprinting approach, we found that each of the main deep-water masses is characterized by a specific bacterial community. In general, the diversity of bacterial communities was about three times higher than that of the archaeal community throughout the water column (down to a depth of 4,500m).

Studies reveal that neither bacterial nor archaeal diversity decreased with depth, although the total number of prokaryotes decreased from 106 at the surface to 104 ml^{-1} at 4,500m.

A pronounced latitudinal gradient was detected for ammonia-oxidizing *Crenarchaeota.* The only two enrichment cultures of mesophilic marine *Crenarchaeota* currently available, *Cenarchaeum symbiosum* and *Nitrosopumilus maritimus,* use ammonia as an energy source and take up carbon dioxide as a carbon source. Hence, it has been generally assumed that all the Marine Crenarchaeota Group I (MCGI) are nitrifiers. We found that, while MCGI are putatively oxidizing ammonia throughout the water column in the northern latitudes, in the deep waters around the equator only a small fraction of the MCGI utilize ammonia as an energy source. We also found evidence that the MCGI in the deep temperate and (sub)tropical waters are utilizing organic matter as substrate and hence exhibit a heterotrophic life mode. The shift from autotrophic, ammonia-oxidizing northern deep-water MCGI communities to hetero-trophic, deep-water MCGI in equatorial regions is apparently related to the age of the deep-water masses. Deep-water formation in the northern latitudes transfers large amounts of surface-water ammonia into the deep ocean which is then oxidized to nitrate as these deep waters age in the meridional ocean circulation.

MarBEF has identified the dominant bacterioplankton groups in the NW Mediterranean, the Central Baltic and deep North Atlantic Sea in terms of their contribution to bacterial biogeochemical function in the carbon and nitrogen cycles.

Invertebrates

Copepods are small crustaceans, diminutive relatives of the crabs and lobsters, but abundant and diverse in the oceans. There are about 3,000 species of copepods in European waters, and they comprise almost 10% of all species contained in the European Register of Marine Species. Free-living copepods are typically the dominant group of multicellular animals in the plankton, but they are also found on and in marine sediments, where they are usually second in abundance only to the nematodes.

A new genus of benthic harpacticoid copepod has been named *Marbefia* to honour the outstanding contributions of MarBEF to our knowledge of marine biodiversity.

Marbefia is a small, slender copepod, with a female body length of about 0.7mm, and is highly ornamented, with a dense covering of fine hairs (Fig. 4). *Marbefia* is currently known from the Southern North Sea and the Isles of Scilly.

Copepods are also parasites on almost every phylum of marine animals, from sponges to chordates, including whales. For example, sixteen copepod families are parasitic on polychaete worms. These parasites are typically rare and our knowledge of their biology and distribution is extremely limited. Such parasites

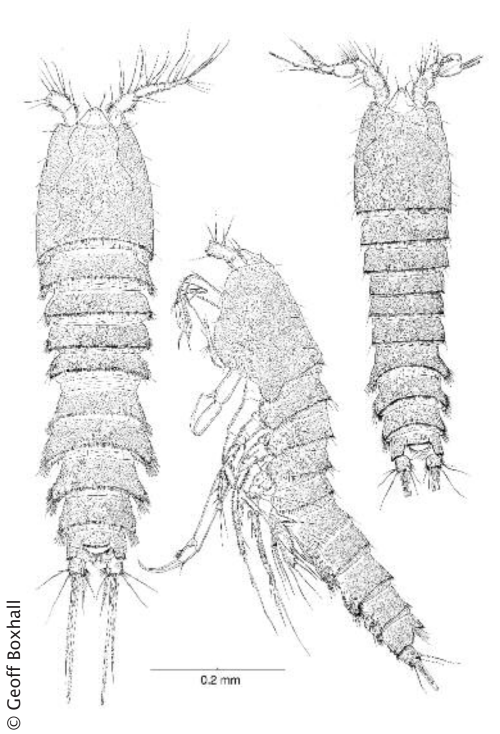


Figure 4. Two females and a male (right) of the new genus *Marbefia.* The male copepod is slightly shorter and has modified antennules which are used to clasp onto the female during mating.

are usually found by researchers studying the hosts, so the sheer volume of sampling and analysis that took place within MarBEF provided an exciting opportunity to collect these very rare animals. The diversity of new forms found was astonishing:

In a large series of samples taken from around the Norwegian Sea and White Sea, a total of 11 species new to science and three new genera of parasitic copepods were identified.

The numerous new host and geographical records have greatly improved our knowledge of the host-specificity of the parasites, their abundance and their distribution in European waters.

As well as numerous new copepods parasitic on worms, MarBEF researchers, with the support of the Taxonomic Clearing System, also discovered new worm species from European seas. Among these, *Osedax mucrofloris* is perhaps one of the most remarkable. It burrows into the decaying bones of whale carcasses – an extremely widely dispersed habitat – and derives nutrients from the abundant sulphur compounds in the carcass.

The roundworms or nematodes (phylum *Nematoda*) are one of the most species-rich phyla of ecdysozoans (animals with cuticles), and one of the most speciose of all animal groups. Nematodes have successfully adapted to nearly every ecological niche, from marine to freshwater and from polar to tropical regions. They are ubiquitous in freshwater, marine and terrestrial environments, where they often outnumber other animals both in individual abundance and in species counts, and are found in locations as extreme as Antarctica and oceanic trenches.

35% (333 species) of nematode species identified in the MarBEF project MANUELA were new records for Europe.

Ecosystem engineers

Conceptual ideas in the role of native and/or invasive ecosystem engineers in explaining biodiversity were developed into two hypotheses by MarBEF scientists, namely: (1) biodiversity effects of epibenthic and endobenthic ecosystem engineers: the epi-endo-engineering exclusion hypothesis, and (2) effects of alien engineers on biodiversity in coastal sediments: the engineering-strength hypothesis (Bouma *et al.,* 2009).

Habitats

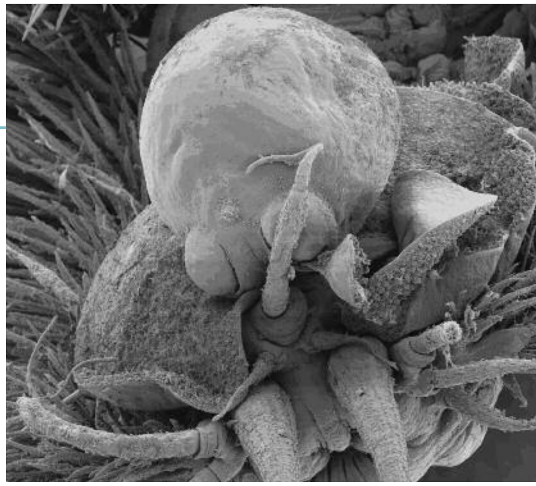
Shallow-water marine caves

Marine caves located in the littoral zone offer a permanently dark, stable, quiescent environment with limited food resources that resembles, at least to some extent, the deep sea. Because they can be visited by SCUBA divers, these caves have tremendous potential as accessible analogues of deep-sea habitats. One important difference is that the water temperature in shallow-water marine caves is usually much higher than near the ocean floor. Parts of the Mediterranean, where the temperature of the deep water (~13°C) is similar to that of the surface waters during the winter in the northernmost part of the basin, provide an important exception to this generalisation. Most of the well-studied caves are located in the NW Mediterranean and have a profile that ascends from the outside in, trapping warm summer waters in the upper parts. However, one particular cave, the 3PP cave near Marseille, has a descending profile that traps cold (~13-15°C) water year round. Similar caves of this type have now been discovered.

The inner parts of the 3PP marine cave studied by DEEPSETS exhibit strong faunal and ecological parallels to the deep sea.

Partly within the DEEPSETS project framework, a detailed study of the 3PP cave fauna was made. The most striking and best-studied examples were the carnivorous sponge *Asbestopluma hypogea* and the hexactinellid sponge *Oopsacas minuta,* both now also found in the bathyal Mediterranean. Similar examples exist for less conspicuous taxa such as bryozoans and brachiopods. It appears that caves, particularly descending cold-water caves, are home to an interesting combination of marine cave fauna, successfully-established true deep-sea species, and an additional consortium of mobile shallow-water taxa using caves as a shelter from predators.

Recent research within the DEEPSETS framework investigated the sediment-dwelling *Foraminifera* and metazoan meiobenthos, mainly harpacticoid copepods, nematodes and annelids. This effort, primarily concentrated on the 3PP cave, was intended to provide background data on cave sediment-dwelling taxa as a basis for a



© Geoff Boxhall

Figure 5. Scanning electron micrograph of a parasitic copepod, *Herpyllobius polynoes,* attached to the head of its host, a polynoid worm. *Herpyllobius* is an extremely modified copepod, having lost limbs and segmentation. It feeds via an embedded rootlet system that penetrates the skin of the host and directly absorbs nutrients.

temporal survey that could be compared with deep-sea time series. Preliminary results showed a strong gradient in meiofaunal composition from the cave's entrance to the darkest parts, with a prevalence of deep-sea components in the inner regions.

Little is known about the temporal stability of marine caves. Seasonality is marked in the littoral zone, and naturally affects the cave entrance. However, seasonal fluctuations also penetrate into the darkest parts of caves, where allochthonous organic matter or indices such as chlorophyll may display considerable intra-annual variations. In addition to the slow advection of material from outside, the circadian movements of some cave residents (fish, mysids) in and out of caves may transport organic matter and thereby transmit a temporal signal. Longer temporal trends are largely unknown, but some marine caves have been affected by current warming trends. A Mediterranean-cave mysid species has been replaced by a congener in the majority of caves of the NW Mediterranean following a series of unusually hot summers.

Cold-water marine caves act as a refuge during episodes of warming such as unusually hot summers.

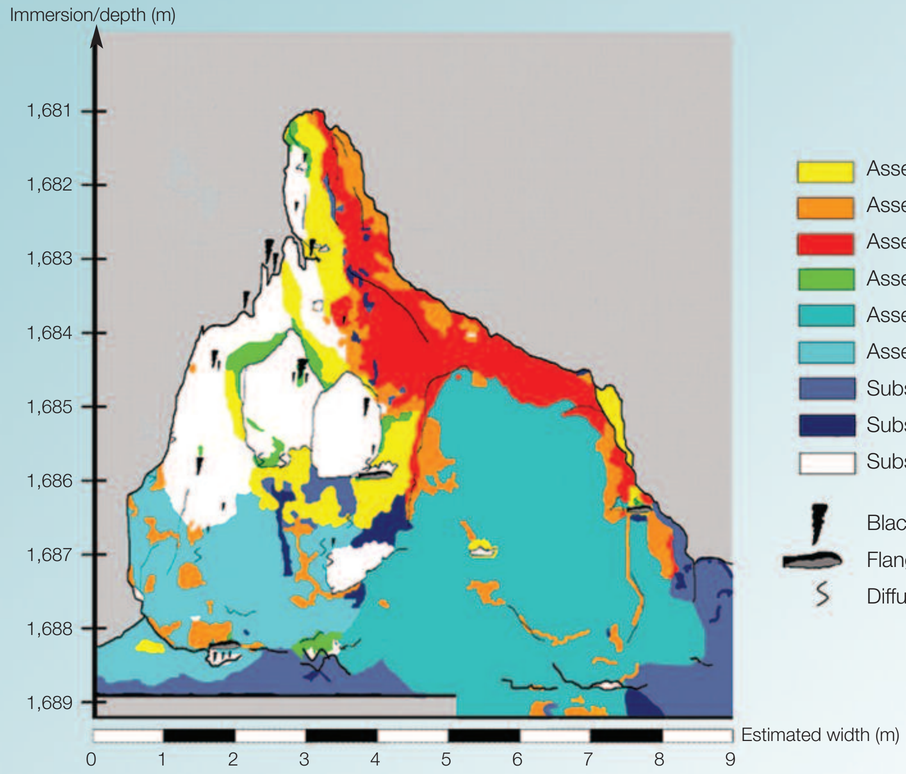


Figure 6. The east side of the Eiffel Tower hydrothermal construct in the Lucky Strike vent field (Mid-Atlantic Ridge). The map shows the distribution of different faunal assemblages and substrates during 2006. The assemblages are characterised by different animals species and the presence or absence of bacterial mats. The main attached animals present are the mussel *Bathymodiolus azoricus* (Assemblages 1, 2a, 2b) and the alvinocarid shrimps *Mirocaris fortunata* and *Chorocaris chacei* (Assemblage 3). Substratum 1b is a bare surface with visible bacterial mats; Substratum 2 is a bare surface with whitish or greyish mineral precipitation and possible bacteria. (Adapted from Cuvelier *et al.,* in press: "Distribution and spatial variation of faunal assemblages on a hydrothermal edifice at Lucky Strike vent field (Mid-Atlantic Ridge) revealed by high-resolution video image analysis." *Deep-Sea Research* **I**.)

There are also indications that some deep-sea taxa (particularly sponges), which are probably living near their thermal limit in the 'cold-water' marine caves, are showing signs of mortality during milder than average winters. Other Mediterranean caves, such as the anchialine caves on Mallorca in the Balearic Islands, are home to new planktonic species of copepods, such as *Stephos vivesi,* which have been described with the support of MarBEF's Taxonomic Clearing System.

Vents

Analyses of high-definition photographs and video records conducted revealed detailed information about the spatial distribution of biotic assemblages on the Eiffel Tower hydrothermal edifice (Fig. 6). This edifice is a part of the Lucky Strike vent field and is situated on the Mid-Atlantic Ridge, south of the Azores. The faunal assemblages comprise bivalves, decapods and other smaller associated fauna ranging from polychaetes and gastropods to bacteria.

The distribution of the assemblages on the surface of the Eiffel Tower hydrothermal edifice is very patchy and is related to the position of fluid venting and resulting temperature gradients.

In contrast to the rapid dynamics observed on edifices from the Pacific, the rate of change in the Atlantic Eiffel Tower communities is clearly lower and remained rather constant between the years during which it was observed (1994, 1998, 2001, 2002, 2005, 2006 and 2008).

Genetics

Ecological information on most marine keystone and foundational species is readily available, while information about their changing geographic distributions through space and in time is seldom available. Temperature is a key structuring feature of biogeographic distribution for most organisms. Therefore, in the context of climate change, many species have already begun to shift their ranges. Using genetic data, it is possible to track both past and present changes, identify past refugia and present-day hotspots of high genetic diversity, and determine particular boundary edges, which may influence dispersal abilities.

Modern approaches to molecular genetics and advances in understanding of fish genetics have improved our knowledge of the structure of fish populations and their adaptation to environmental gradients and local environmental conditions. This knowledge helps us to analyse the environmental basis for spatial structure in fish populations and to examine how the spatial distribution of local populations changes over time (e.g., whether they expand, relocate or shrink), depending on their physiological response to changes in abiotic conditions, and on their genetic capacity for adaptation. New genetic methodologies were applied to several marine species (cod, herring, flounder and sprat) throughout the salinity gradient in the North Sea-Baltic Sea area. These analyses showed that the steepest gradient in genetic variation overlapped spatially with the steepest gradient in salinity – that is, in the western Baltic-Belt Sea area – and that populations in the Baltic were genetically distinguishable from those in the North Sea.

The advances in knowledge of fish genetics and the new genetic technologies can be used to help improve the way fisheries are managed and inspected.

For example, genetic methods can be used to identify and trace the geographical origin of fish sold on markets and, therefore, to identify whether fish sold have been caught from populations which are protected by quotas or other conservation measures. There are now cases in which such technologies have been used in court proceedings, resulting in convictions of fishermen for illegal fishing activities.

The GBIRM (Genetic Biodiversity) project has helped to resolve the phylogeographic structure of a set of species at a level of detail that enables predictions to be made about how global and local perturbations will influence large-scale structure and distribution in the coming decades.

EPIC (Exon Primed Intron Crossing) is filling a gap in the toolbox for studying animal biodiversity. The EPIC project has helped us identify universal genetic markers in the nuclear genome of metazoans. Genetic (molecular) markers provide extremely informative data to study intraspecific biodiversity.

Despite the enormous growth of sequence databases, nuclear markers which are sufficiently polymorphic for population genetics and phylogeography studies, and yet still potentially applicable across various phyla, are crucially needed. Numerous introns (a region of DNA) have invariant positions, even between kingdoms, thus providing a potential source for such markers.

MarBEF has developed a new bioinformatics approach to extract promising loci from genomic sequence databases that are applicable to all living kingdoms, not only animals.

Chemical ecology

Chemical ecology, as an integrative science, has been instrumental in understanding the function of terrestrial ecosystems. Pollination of flowers by bees, homing behaviour of birds and human attractiveness to a partner are some of the many examples of chemically mediated interactions. It is not difficult to imagine the catastrophic consequences of the absence of such crucial relationships. Imagine a similar scenario without chemical interactions in the marine environment. Many key life processes would be compromised, such as food source identification and selection, prey location and capture, mate recognition and location, chemical defence, behaviour, and population synchronisation.

Chemical diversity in the marine realm is an integral part of taxonomic diversity and therefore contributes to overall biodiversity.

Species-specific chemicals can shape community processes such as seasonal succession, niche structure, selective feeding and population dynamics. Similarly, chemical interactions mediate functional diversity, affecting, for example, meroplanktonic larval settlement, signalling within populations, differential production of allelopathic compounds and bloom dynamics.

The MarBEF ROSEMEB (Role of Secondary Metabolites in Ecosystem Biodiversity) project has provided a better understanding of the roles of these chemicals in maintaining marine biodiversity and driving ecosystem functionality.

Microbes

Microbes sense their environment via cell-associated and diffusible molecules such as AHL (N-acylhomoserine lactones) that are constantly produced by many bacteria and diffuse through membranes into the surrounding environment. Beyond a certain cell density of the bacterial population and corresponding concentrations of AHLs, a threshold or quorum is reached, and expression of target genes is initiated, e.g., the proteins for light emission in luminous bacteria or pathogenic factors that cause disease.

Quorum-sensing typically controls processes such as swarming (coordinated movement), virulence (coordinated attack) or conjugation (gene transfer between cells) that require high cell densities for success and that are essential for the survival of the producing organisms (Fig. 7a).

The discovery that bacteria communicate with each other using signal molecules has changed our perceptions of single-cell organisms and interspecies communication and information transfer.

Phytoplankton

Within the plankton community, many prey organisms use chemical defence against their predators, either through toxin production or feeding deterrence. Diatoms are key players at the base of the marine food web and have always been assumed to represent a good food source for herbivores, but some species use chemical defence against being grazed. The discovery that these unicellular algae produced chemicals such as polyunsaturated aldehydes (PUAs) and other oxidised products of fatty acid metabolism (collectively termed oxylipins) that induced abortions, birth defects, poor development and high offspring mortality in their grazers has changed our view of plant-animal interactions in the plankton (Fig. 7c).

ROSEMEB researchers discovered that some diatom species produce chemicals that induce abortions, birth defects, poor development and high offspring mortality on their copepod grazers.

Although the effects of such toxins are less catastrophic than those inducing poisoning and death, they have insidious effects. Such compounds may discourage herbivory by sabotaging future generations of grazers, thereby allowing diatom blooms to persist when grazing pressure would normally have caused them to crash. This defence mechanism is a new model for the marine environment because most of the known negative plant-animal interactions are generally related to poisoning, repellence or feeding deterrence, not to reproductive failure. In fact, the production of PUAs acts mainly as a post-ingestion signal impacting future generations of grazers, with lesser effects on the direct adult grazers. PUAs have also been shown to negatively impact other phytoplankton cells and possibly function as a diffusible bloom-termination signal that triggers active cell-death (Fig. 7b). So, these compounds may have multiple functions within plankton communities, acting as defence molecules against predators and competitors as well as signal molecules driving diatom bloom dynamics and species succession patterns. Other phytoplankton groups such as the dinoflagellates produce potent neurotoxins that can be transferred up the marine food chain and have been responsible for mass fish-kills, both wild and farmed, as well as for the deaths of aquatic birds and mammals, including whales and sea lions.

Dinoflagellates produce potent neurotoxins that can be transferred up the marine food chain.

In humans, consumption of shellfish containing high levels of toxins can induce paralytic, neurotoxic, diarrhetic and amnesic shellfish poisoning. Records of human poisoning by at least two of these syndromes date back hundreds of years, yet the discovery and characterisation of the molecules responsible for this biological activity are quite recent.

Many benthic invertebrates are capable of sequestering compounds from the food they consume and using them as defensive molecules against predators, and the same may also occur in the plankton. Studies on chemical interactions in the plankton are still in their infancy, but there remains great scope for research into the effects of toxins on gamete, embryonic and larval development of herbivorous grazers, and understanding why zooplankton avoid consuming certain metabolites and what happens when they do.

Seaweeds

Seaweeds have been shown to produce a large variety of secondary metabolites with highly variable chemical structures such as terpenoids, acetogenins, amino-acid derivates and polyphenols. Many of these compounds probably have multiple simultaneous functions for the seaweeds and can act as allelopathic, antimicrobial and antifouling or ultraviolet-screening agents, as well as herbivore deterrents.

Most marine herbivores are generalist grazers that consume many different seaweeds, although some herbivore species can be specialised on one or a few algal species. Grazing pressure is highly dependent on the specific seaweed and herbivore involved in the interaction, but is generally considered to be higher in tropical coral reefs than in temperate habitats. Large mobile grazers, such as fish, crabs and sea urchins, can have a more drastic negative effect on seaweed production and fitness than smaller ones. Due to their ability to rapidly consume large amounts of algal tissues, they are thought to select for constitutive defences (i.e., defences that are produced and present continuously within the plants). Smaller grazers use plants both as food and habitat, and they consume individual algae over a more extended period of time. It has been hypothesised that smaller grazers may select for

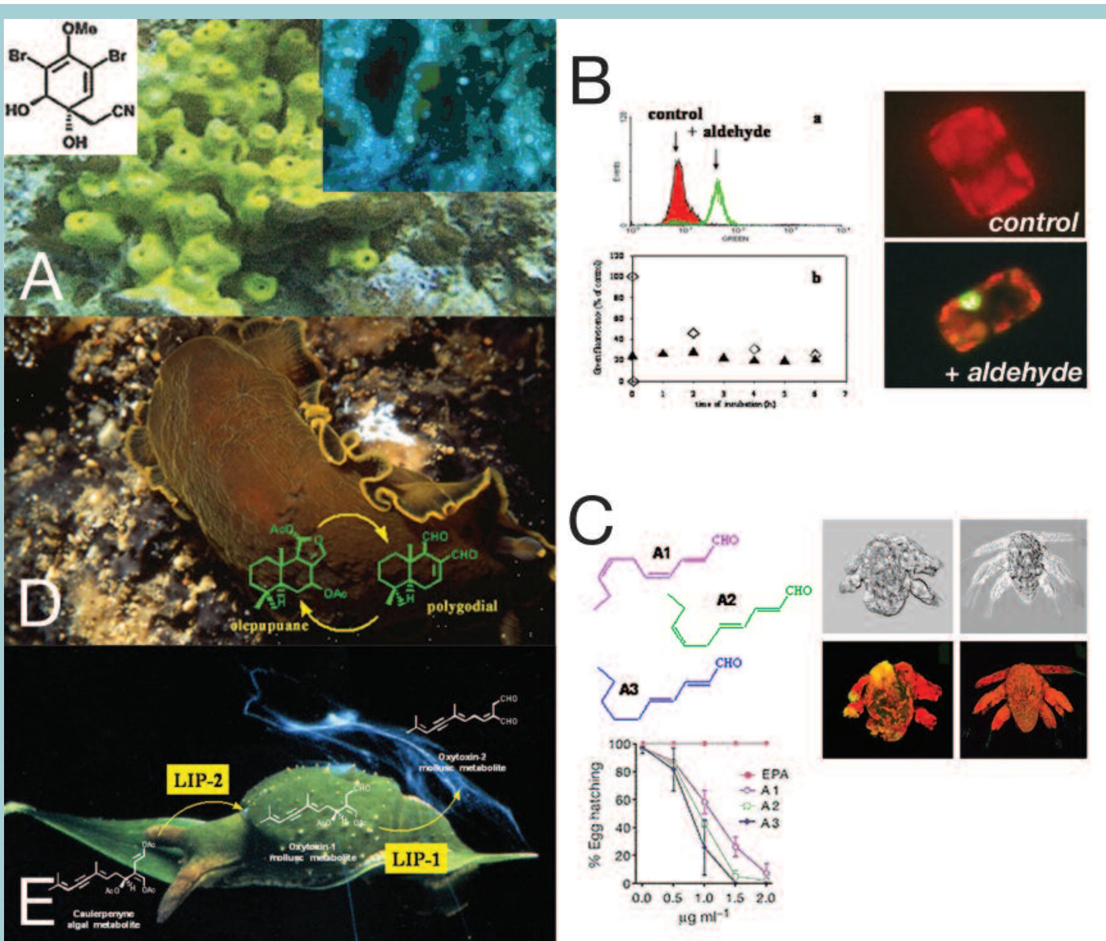


Figure 7: A. The sponge *Aplysina aerophoba* produces the antimicrobial and antitumor compound Aplysinin-1. Staining with DAPI reveals the rich microbial fauna associated with the sponge. **B.** The effect of diatom-derived unsaturated aldehydes on diatoms (a) *Phaedactylum tricornutum* and (b) *Thalassiosira weissflogii.* **C.** The effect of the diatom-derived unsaturated aldehydes 2-trans-4-cis-decatrienal (A1), 2-trans-4-trans-7-cis-decatrienal (A2) and 2-trans-4trans-decadienal (A3) on copepod hatching success (Miralto *et al.,* 1999; Ianora *et al.,* 2004a). **D,E.** Transformation of caulerpenyne in the allomonal oxytoxins by lipolytic enzymes, named Lip-1 (Lipase 1) and Lip-2 (Lipase 2), in *Oxynoe olivacea* (from Cutignano *et al.,* 2004).

inducible rather than constitutive defences (i.e., defences that are produced in response to specific environmental cue).

The hypothesis that sessile or slow-moving organisms, without obvious escape mechanisms and physical protection, are likely to be chemically defended has recently been explored with greater frequency in the marine environment. Of these organisms, opisthobranch molluscs appear to be particularly well endowed with secondary metabolites. In these gastropods, the reduction of the protection offered by the shell is compensated by the development of complex strategies of defence that include use of chemicals. In sea slugs *(Nudibranchia),* the shell is lost, and these species tend to show high specialised behaviour. Opisthobranchs can feed upon sponges, algae, hydroids, bryozoans, tunicates and soft corals. In some cases they are not only capable of accumulating dietary molecules but also transform or even produce chemical mediators *de novo* (Fig. 7d).

***Oxynoe olivacea,* a green sea snail that lives camouflaged upon algae *(Caulerpa),* is able to transform a major algal metabolite, caulerpenyne, to oxytoxins, increasing the toxicity of the algal metabolite 100 times (Fig. 7e).**

Despite its emphasis on the integration of researchers, MarBEF has also served as a catalyst in a remarkable range of new discoveries. New species were found and characterised from across the range of marine life from bacteria to crustaceans, polychaetes and echinoderms. In addition, the application of new tools, which we recognise as one of the fundamental drivers of scientific progress over the last millennium, has generated insight into the astonishing functional diversity of microbial life in the oceans. Molecular tools have allowed MarBEF scientists to probe the functioning of marine microbial communities in novel ways – and their results have reinforced the emerging view that improved understanding of the dynamics of marine life at all scales is the key to developing a predictive model of the Earth Systems.

This understanding will be built by integrating knowledge of which organisms are involved (taxonomy), how they are involved in ecosystem processes (ecology, chemical ecology and functional genomics) and their history of involvement (phylogeny and co-evolutionary history). The discoveries we have made in MarBEF are vital steps in this process.

Food webs

Comprehensive studies on the structure and functioning of food webs in marine ecosystems were carried out by researchers in FOODWEBIO to unravel possible interactions between the organisation of trophic connections and biodiversity. Comparisons focused on macrobenthic communities at twelve coastal and estuarine locations representing a range of ecological systems (the presence of tides, salinity gradients, type of substratum, nearshore and offshore areas), i.e. covering a suite of habitats in Europe: Barents Sea, Baltic Sea, North Sea, Atlantic coast of France and the Mediterranean Sea.

Communities rich in biodiversity do not demonstrate higher stability of the food web or more branched trophic interactions.

References

Alonso-Sáez, L, Gasol, JM (2006). Seasonal variations in the contributions of different bacterial groups to the uptake of low-molecular-weight compounds in Northwestern Mediterranean coastal waters. *Appl. Environ. Microbiol.* **73** 3528-3535.

Beaugrand, G, Reid, PC, Ibanez, F, Lindley, JA, Edwards, M (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296** 1692-1694.

Bouma, TJ, Olenin, S, Reise, K (2009). Ecosystem engineering and biodiversity in coastal sediments: Posing hypothesis. *Helgol. Mar. Res.* **63** 95-106.

Cutignano, A, Notti, V, d'Ippolito, G, Coll, AD, Cimino, G, Fontana, A (2004). Lipase-mediated production of defensive toxins in the marine mollusc *Oxynoe olivacea. Org. Biomol. Chem.* **2** 3167-3171.

Cuvelier *et al.* (in press). Distribution and spatial variation of faunal assemblages on a hydrothermal edifice at Lucky Strike vent field (Mid-Atlantic Ridge) revealed by high-resolution video image analysis. *Deep-Sea Research*.

Ianora, A, Miralto, A, Poulet, SA, Carotenuto, Y, Buttino, I, Romano, G, Casotti, R, Pohnert, G, Wichard, T, Colucci-D'Amato, L, Terrazzano, G, Smetacek, V (2004a). Aldehyde suppression of copepod recruitment in blooms of a ubiquitous planktonic diatom. *Nature* **429** 403-407.

Miralto, A, Barone, G, Romano, G, Poulet, SA, Ianora, A, Russo, GL, Buttino, I, Mazzarella, G, Laabir, M, Cabrini, M, Giacobbe, MG (1999). The insidious effect of diatoms on copepod reproduction. *Nature* **402** 173-176.

Pedrós-Alió, C (2006). Marine microbial diversity: Can it be determined? *Trends in Microbiology* **14**(6) 257-63.

Climate change

Changes from the Arctic to the Mediterranean

Climate change is expected to be one of the major environmental challenges of the 21st century, and its impacts are starting to be seen in the marine environment. MarBEF scientists have measured rising temperatures in European waters and have observed how the warmer temperatures are affecting marine biodiversity. In waters from the Arctic south to the Mediterranean, the project has recorded shifts in species distribution to northern and deeper waters, changes in the seasonal timing (phenology) of life-history events such as migration, reproduction, metamorphosis and settlement, and how interactions among species (e.g., predation and competition) are changing. However, climate change will not only affect the thermal environment of marine ecosystems; rises in temperature will be accompanied by changes in other abiotic conditions of seawater, including acidity (pH), oxygen concentration and, in some areas, even the salt concentration itself (salinity). Moreover, the strength and direction of some ocean currents, on which nearly all marine species depend at some stage in their lives, could change due to climate change. MarBEF has been finding that some of these climate-related changes are already happening and has seen how these changes are affecting, and will continue to affect, marine biodiversity in this century.

The Arctic

Warming in the European Arctic has caused not only sea ice to melt and temperature to increase but also an increasing advance of Atlantic waters to high latitudes by way of the prevailing North Atlantic Current. In MarBEF, the ArctEco project showed how Atlantic water stemming from a biologically diverse marine region (Norwegian Sea, Norwegian and British shelf) is introducing additional species to the relatively species-poor Arctic (Fig. 1). The pelagic herbivores (e.g., krill) from the relatively warm Atlantic water are typically smaller than the cold-water Arctic herbivore species. Naturally, top predators of the Arctic (seabirds, seals, whales) feed efficiently on these relatively large herbivores, often without any intermediate small predators between the herbivores and the top predators. The process of warming is causing a substantial shift in the food web, from large Arctic herbivores to smaller Atlantic species, thus reducing the food resources available to the top predators (Fig. 2). In the warming Arctic, primary production is utilised by smaller, faster-growing species. Additionally, small carnivores are becoming more diversified and numerous, which is dissipating the energy flow considerably. In this way,

Warming effects lead to higher biodiversity in the Arctic and simultaneous food shortages for the top predators.

North Sea and Baltic Sea

Climate models predict a 2–4°C rise in water temperature along with a rise in sea levels in the current century. This will have major implications for species, ecosystems and food webs: spatial distributions, life-histories, phenologies and biotic interactions among species will be altered.

In MarBEF, the MarFISH project examined archaeological evidence from the waters around Denmark (the Kattegat, Skagerrak, the Belt Sea and Bornholm) during a warm period from 7000–3900BC and showed that there were several warm-water fish species then present. These species were: smoothhound *(Mustelus sp.)*, common stingray *(Dasyatis pastinaca)*, anchovy *(Engraulis encrasicolus)*, European sea bass *(Dicentrarchus labrax)*, black sea bream *(Spondyliosoma cantharus)* and swordfish *(Xiphias gladius)*. These species currently have a

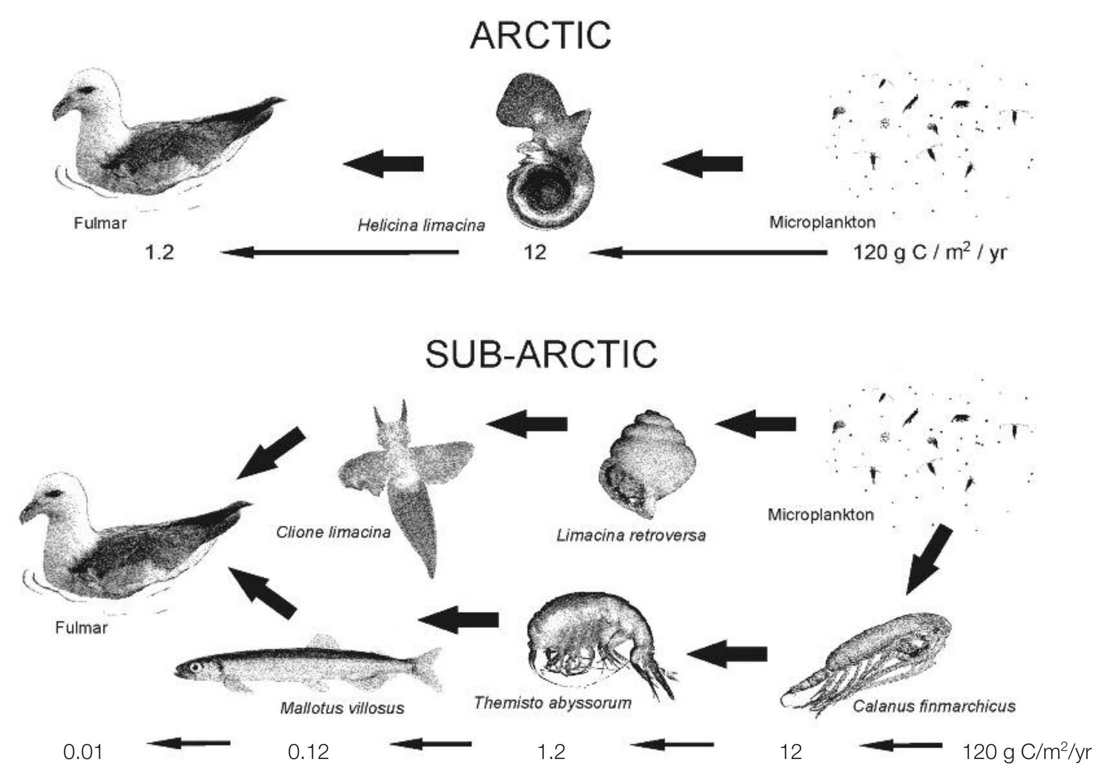


Figure 1. Energy flow scheme showing the typical short-and-efficient food chain of the Arctic (top) compared to the situation in the warmed Sub-Arctic (bottom).

more southerly distribution and their presence near Denmark in the past was presumably due in part to the warmer temperatures at the time. Some of these same species are now being captured regularly by fishermen in the area, in commercially important quantities: catches have been reaching tens and thousands of tons annually during the past decade.

Warming temperatures have been contributing to an overall increase in fish species diversity in the North Sea since the mid-1970s.

This is mainly the case for small-sized southern species while large, northern species have shifted their distributions to northern and deeper waters. These changes have been seen in scientific fisheries surveys which annually monitor the species composition of the North Sea fish community.

Historical evidence shows that climate may cause substantial changes in fish phenology.

During the times of substantially colder climate and severe winters in the 17th century, the herring *Clupea harengus membras* fishery in the NE Baltic Sea (Gulf of Riga) mostly took place during the summer months (June–July). This was probably due to the later migration of herring to the spawning areas close to the coast where the fish were caught. In contrast, nowadays, in much warmer climate conditions, the coastal trapnet herring fishery takes place in spawning grounds a few months earlier than the historical colder times.

Climate change will also have many non-thermal impacts on fish populations. These will include, for example, changes in the strength, direction and location of ocean currents which, for example, will affect the likelihood that fish

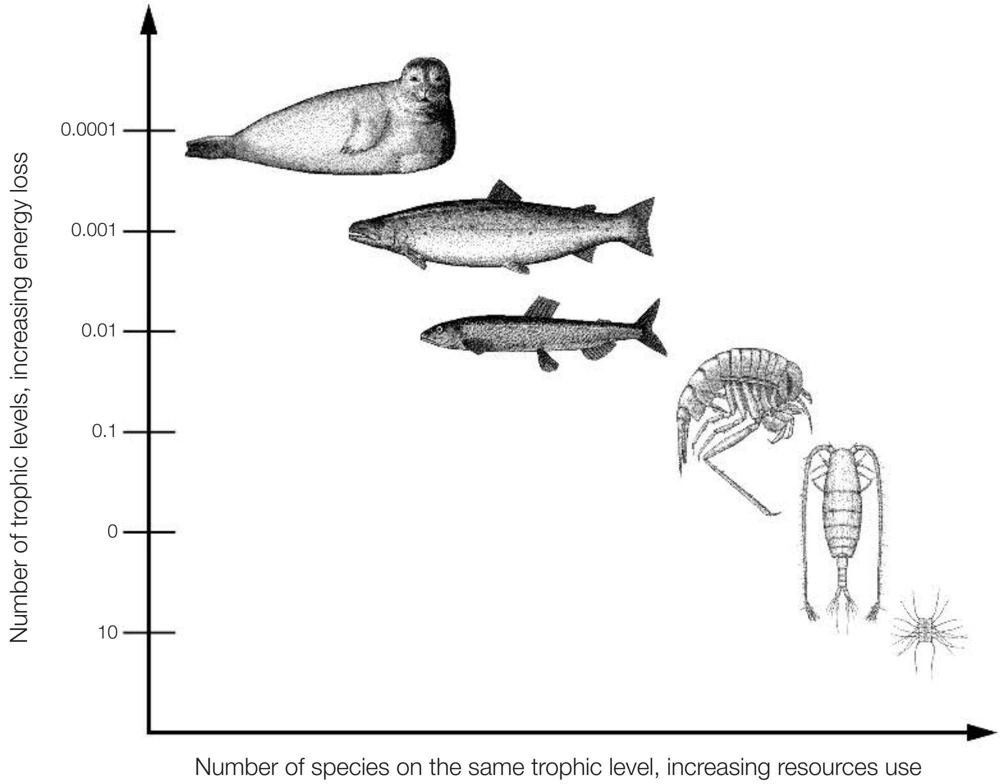


Figure 2. Scheme of the use of resources and energy loss as a consequence of increasing biodiversity.

eggs and larvae can survive and grow. Moreover, as temperatures rise, the ability of the ocean to retain oxygen will decrease. In many coastal areas in Europe (e.g., bays, straits, estuaries) the combination of rising temperature and decreasing oxygen, particularly in areas which already also receive high levels of nutrients (eutrophication), will reduce the size of habitats for, especially, bottom-living fish species such as cod and flatfishes. These species will become less abundant and widespread if coastal areas experience longer and more frequent anoxic periods.

In some areas, climate change could even influence the salinity of the seawater. This could happen because precipitation and the discharge of freshwater from rivers and lakes in, for example, northeastern Europe, could change. For example, in the Baltic Sea, some climate oceanographic models predict that the salinity – which is already so low that some fish species have adapted physiologically to living there, and it prevents many other marine fish species from living there – will fall even further because climate change in this area will increase precipitation. If climate change leads to a fall in Baltic Sea salinity, this will reduce the number of marine fish species, even though one might otherwise predict that the increasing temperature should allow warmwater-adapted species to immigrate. The Baltic Sea example shows that it will be important to consider multiple aspects of climate change, especially in coastal areas, if we are to estimate how marine biodiversity will change in future.

Another impact of climate change will be the rise in sea level due to melting of land-based glaciers and the expansion of seawater as it warms up – as warm water occupies more space than cold water. Both factors will cause flooding of existing coastal lowlands. The newly flooded coastal areas will provide more fish habitat, especially for benthic juveniles stages which are common in coastal areas.

North Atlantic benthos

In the North Atlantic, temporal changes in deep-sea communities at the Porcupine Abyssal Plain (PAP), at 4,850m water depth, have been studied since 1989, most recently within the DEEPSETS project (Fig. 3).

Shifts in different elements of the benthic biota of the deep-sea communities at the Porcupine Abyssal Plain over decadal as well as shorter (seasonal) time-scales have been recorded and attributed to the North Atlantic Oscillation (a climatic phenomenon).

While intra-annual changes reflect seasonal productivity cycles, the decadal-scale changes at the PAP are believed to be linked to the North Atlantic Oscillation, a climatic phenomenon that affects winds, precipitation and storm intensity and frequency. These oscillations lead to changes in upper ocean biology and the export of particulate organic carbon (POC) from the euphotic zone (i.e., the export flux) and to the sea floor, as well as in the quality (biochemistry) of the material that reaches the sea floor. These changes in food quantity and quality (for example, the content of pigments necessary for reproduction) probably underlie the 'boom-bust' cycles observed in the holothurians *Amperima rosea* and *Ellipinion molle.* Vastly increased populations of these small surface-feeding organisms may, in turn, have affected foraminiferal and meiofaunal populations through depletion of food resources and sediment disturbance. A similar relationship between climate, sea-surface processes and deep-sea benthos appears to exist in the NE Pacific Ocean.

The most obvious changes at the PAP were seen among the megafauna (animals visible in sea-bottom photographs and trawls), notably the holothurians *Amperima rosea* and *Ellipinion molle.* These relatively small species both exhibited 'boom-bust' cycles – rapid abundance increases followed by declines – during the period from 1996 to 2005. The rise to dominance of *A. rosea* during 1996 has been termed the 'Amperima event.' Two larger holothurian species, *Psychropotes longicauda* and *Pseudostichopus aemulatus,* exhibited more modest increases while a third, *Oneirophanta mutabilis,* underwent a significant decrease over the entire time-series. Increases in holothurian densities led to a dramatic increase in the extent to which surface sediments, and particularly deposits of phytodetritus (organic detritus derived from surface primary production), were reworked. Probably as a result of these activities, there was little sign of phytodetritus on the seafloor between 1997 and 1999.

Among smaller organisms, densities of foraminifera were significantly higher in 1996-2002 (post-Amperima event) compared to 1989-1994 (pre-Amperima event). The species-level composition of the assemblages changed over this period, reflecting fluctuations in the densities of higher taxa and species. In 1996, following a phytodetritus pulse, the miliolid *Quinquiloculina sp.* migrated to the sediment surface, grew and reproduced before migrating back into deeper layers as the phytodetrital food became exhausted. A substantial increase in the abundance of trochamminaceans, notably one small, undescribed species, may have reflected qualitative change in the phytodetrital food, repackaging of food by megafauna, increased megafaunal disturbance of the surficial sediment, or a combination of these factors. Thus, the PAP time-series suggests that decadal-scale changes have occurred among shallow-infaunal foraminifera at this site, more

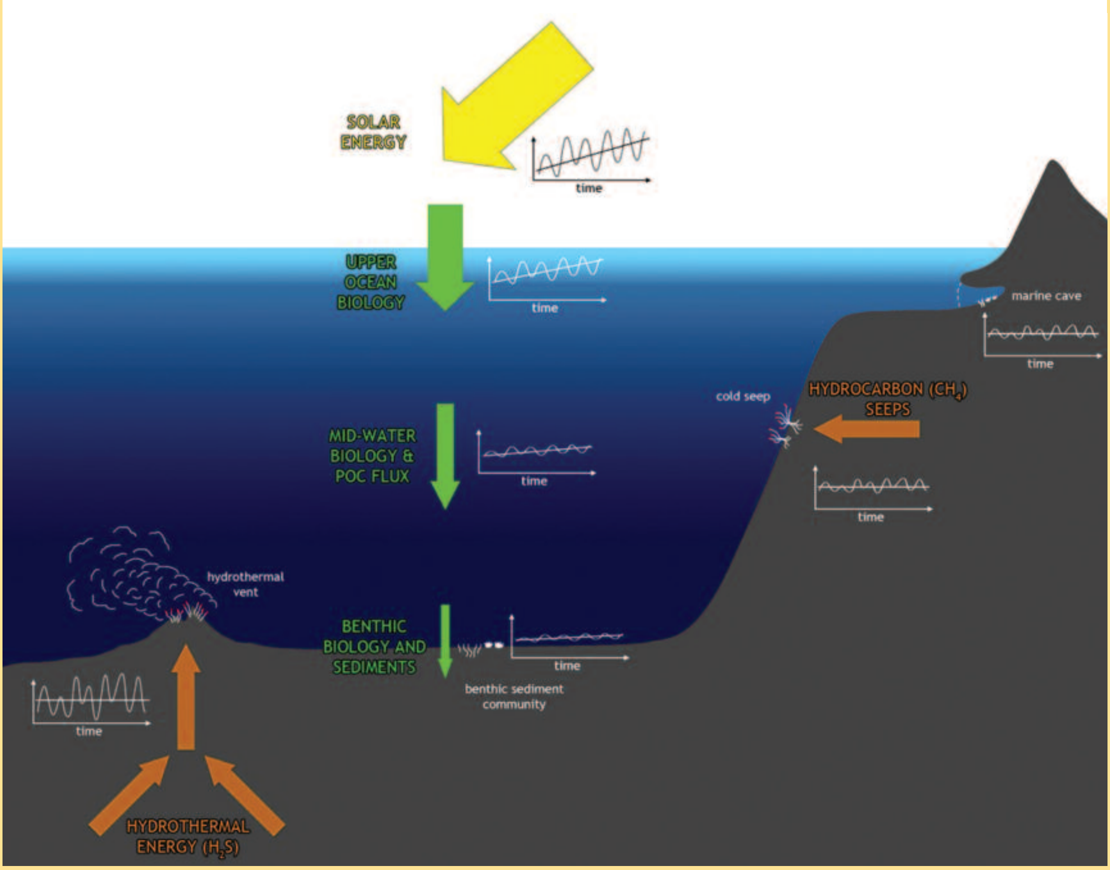


Figure 3. Schematic diagram illustrating forcing factors that influence temporal processes in 'normal' sedimented parts of the deep-sea and in chemosynthetic systems. In the first case, temporal changes are forced ultimately by climatic oscillations. In the second case, they are forced by geological processes that affect fluid flow.

or less coincident with changes in the megafauna, as well as indications of shorter-term events related to seasonally-pulsed phytodetrital inputs.

Densities of metazoan meiofauna increased significantly between 1989 and 1999, driven mainly by the dominant taxon, the nematodes, and to a lesser extent the polychaetes. Ostracods showed a significant decrease while most other taxa, including the second-ranked group, the copepods (harpacticoids and nauplii), did not exhibit significant temporal changes in abundance. MDS ordination of higher taxon composition showed a significant shift from the earlier (pre-Amperima, 1989-1994) to the later (1996-1999, post-Amperima) periods. There were also significant increases over time in the proportion of total meiofauna, nematodes and copepods (but not polychaetes) inhabiting the 0-1cm layer. In addition, seasonal changes in the vertical distribution patterns of total meiofauna and nematodes within the sediment were apparent during the intensively sampled period, 1996-97.

Macrofaunal polychaetes exhibited a more muted response to changes at the Porcupine Abyssal Plain. Although the abundance of the whole assemblage increased significantly before and during the Amperima event, the increase was not on the same scale as that observed in the megafauna, and only certain taxa and trophic groups responded. The same dominant species occurred throughout the study period, with the exception of the *Paraonidae,* where the dominant species declined prior to the Amperima event and was replaced by two other species. Only six of the 12 most abundant species showed a significant response (abundance increase) during the Amperima event. The fact that only some polychaete species responded may be related to efficient foraging by megafaunal deposit feeders that sequestered and repackaged organic matter, leaving less available for smaller organisms. Yet there did not appear to be an impact from physical disturbance caused by megafaunal feeding activities. For example, surface deposit feeders increased during the Amperima event at the same time as disturbance of the surficial sediment by holothurians and ophiuroids was also increasing. The polychaetes indicate that changes in the upper ocean which affect the ocean floor may operate in a complex way and that high taxonomic resolution is needed to establish how the fauna responds.

Temporal changes in the deep sea are not confined to the deep Abyssal Plains; changes have also been recorded in the Arctic and the Mediterranean.

In the Arctic, work by the Alfred-Wegener Institute in Bremerhaven demonstrated a small but important temperature increase between 2000 and 2008 at 2,500m depth in the Fram Strait between Svalbard and Greenland. Within DEEPSETS, a five-year (2000-2004) time-series study of nematodes at this site revealed shifts in nematode abundance and community composition, reflecting changes in food availability.
Although depth-related changes were more prominent than shifts relating to sampling year, interannual variability in nematode community structure was clearly apparent, particularly at the 4,000m station. Parallel observations at several water depths indicated that most of the variation over the time-series was the result of real temporal changes, driven by shifts in food availability as measured by sediment-bound phaeopigment and chlorophyll *a* concentrations. For the larger organisms, a towed camera system revealed a significant decrease in megafauna densities at 2,500m water depth.

The Mediterranean

Global change and microplankton

Plankton is a collective term for all organisms living in the water column that lack their own means of active movement or whose range of movements are more or less negligible in comparison to the movement of the water mass as a whole. Plankton organisms can range in size from a few metres for large jellyfish and salp colonies to less than a micrometre for bacteria. Within the MarPLAN project the biodiversity of eukaryotic marine single-celled plankton organisms was studied in order to answer the question “In what ways can global change affect microplankton?”

To understand plankton distribution and changes therein, we first need to know how diverse it is. Cryptic diversity can be found in easily identifiable morphologically defined species, and while the morpho-species may be considered cosmopolitan, the cryptic diversity therein shows more restricted patterns.

Investigations by MarPLAN uncovered many cases of remarkable species diversity within what was originally perceived as single, widely-distributed species.

For example, MarPLAN discovered that the cosmopolitan species *Fibrocapsa japonica* in fact consists of two cryptic species. The second one was discovered in the Adriatic Sea.

Another research project carried out by CNRS-DIMAR (MarBEF partner) focused on the diatom genus *Skeletonema.* In this genus, several new species were discovered and a biogeographic study showed that some of the newly discovered species had a restricted distribution pattern. For instance, *Skeletonema gretae* is found only along the Atlantic coasts of the US

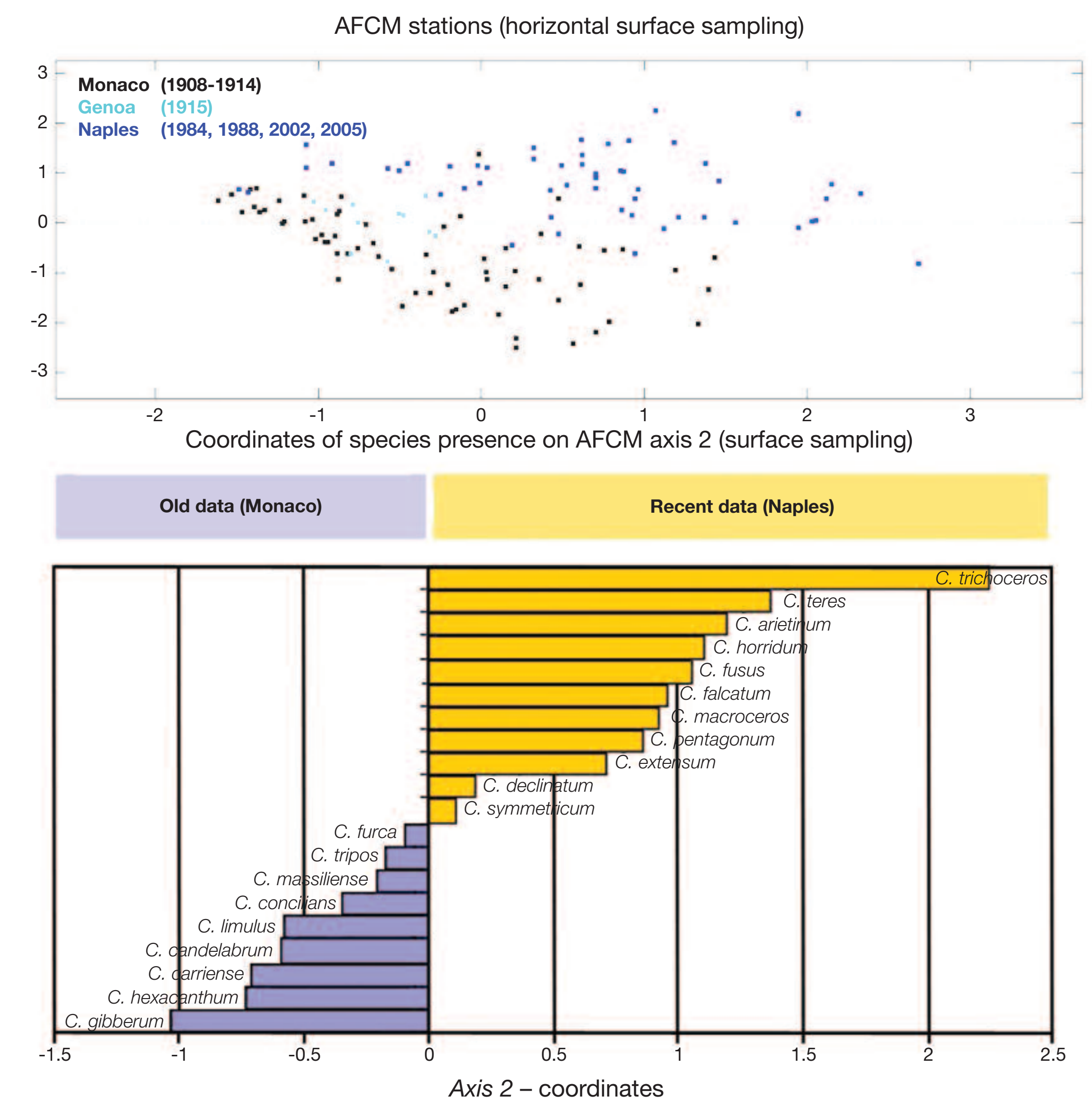


Figure 4. Multiple correspondence analysis results of *Ceratium spp.* in phytoplankton samples from Monaco, Genoa (a century ago) and Naples (at present).

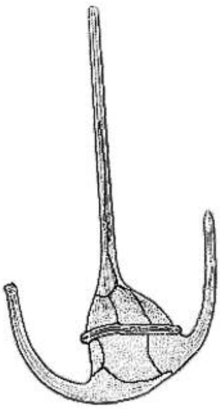
but nowhere else, despite massive efforts to detect it in similar environments along the coasts of Europe, China, Japan, South America and Australia.

In the temperate zones, many phytoplankton species form blooms during restricted periods of the year. Under influence of global warming, some species show a propensity to bloom earlier in some places. In addition, the distribution of these blooms tends to shift polewards. New species may appear in regions, partly through introduction (for example, via ballast water dumping) and partly through polewards range expansion of warm-water species. Several MarPLAN research partners collaborated on assessing these trends in the dinoflagellate genus *Ceratium* (Fig. 4).

Over the last century, several species of the genus *Ceratium* have disappeared from study sites in Villefranche sur Mer and Naples, or have become far less common, while new dinoflagellate species have recently appeared.

The appearance of zooplankton (copepods, planktonic larvae of meiobethos) may be triggered by different factors; increased temperatures may affect the timing of appearance of certain species differently. If grazers such as planktonic larvae find themselves out of phase with their food source they will be short of food and not make it into adulthood. Subsequently, populations of benthic species which rely on them for nutrients may also dwindle. These temporal changes, documented by DEEPSETS, have occurred within our lifetime.

Many phytoplankton species produce toxins or otherwise constitute a nuisance to other species, including humans. Such species (for example, *Fibrocapsa japonica)* are considered harmful and, when appearing in large numbers, form harmful algal blooms (HABs). In the current scenario of global change, coastal regions may suddenly find themselves confronted with increasing numbers of HABs.



Ceratium sp.

Another driver of global change is the increased concentration of CO_2 in the atmosphere, which results in a higher CO_2 concentration in the upper layers of the ocean. This might seem a good thing for phytoplankton. However, there is a less favourable side-effect: with increasing CO_2 in the seawater, the acidity increases (the pH drops).

As the acidity of seawater increases, several phytoplankton species that utilise calcium carbonate as construction material for their cell walls will have difficulty sequestering it from seawater and will thus retain it.

© SZN

Emiliania huxleyi.

The coccolithophorid *Emiliania huxleyi* is one such species: it forms discs of calcium carbonate called coccoliths, which appear to provide protection to the cell.

DEEPSETS research has shown that the eastern Mediterranean is periodically subject to stochastic flux events that deliver large amounts of food to the sea floor, abruptly turning the 'desert' into an 'oasis.' This event-driven character of the eastern Mediterranean was illustrated by the very high phytopigment concentrations in the Ierapetra Basin during 1993. These were linked to significant changes in the hydrography of the Cretan Sea after 1992, involving an increasing outflow of nutrient-rich water masses into the Levantine Basin, resulting in enhanced biological productivity and OM flux to the seabed. In 1993, this enhanced flux caused significant changes in the abundance and composition of the meiobenthic assemblages as well as of the planktonic and macrobenthic communities.

Species detection tools

Reliable tools have been developed for detecting declining species, cryptic populations and non-indigenous species. Despite the growing evidence of range shifts of marine fish species, local extirpations and even extinctions are predicted, but not yet observed, as a consequence of climate change. Small pelagic fish species, in particular, are characterised by large effective population sizes and a high potential for gene flow, and they may respond rapidly to changes in physical oceanographic conditions and have shown large population fluctuations and extirpations over glacial time-scales.

MarBEF presented a range-wide phylo-geographic survey of European sprat *(Sprattus sprattus),* based on a 530-base-pair sequence from the mitochondrial control region, that demonstrates the existence of genetically isolated populations in northern Mediterranean basins. We concluded that these populations – characterised by significantly reduced genetic diversity – remain isolated because of their inability to maintain gene flow under the present physical oceanographic regime. The results demonstrate the effect of glacially-induced changes in physical oceanographic conditions on a cold-adapted small pelagic fish species trapped in a geographically confined area at its southernmost distribution limit.

MarBEF, for the first time, identified distinct and potentially vulnerable populations on the climate-change-induced edge of survival.

The genetic analysis of marine organisms has revealed various examples of cryptic species – populations that we previously thought belonged to the same species because they shared the same morphological diagnostic characters. Genetic comparisons of distant populations demonstrated genetic differences at the same level as we typically find between well separated species. Such studies have generated important new insights into the process of speciation in the marine environment, as, for example, in the case of the Heart Urchin, *Echinocardium cordatum,* which splits into five distinct branches (clades). Such clear-cut genetic distinctions between populations provide strong evidence of reproductive isolation, from which we can infer that speciation has occurred. So now we have a complex of species masquerading under a single name!

This phenomenon suggests that genetic and morphological change may take place at different rates in evolution, and such cryptic species are a product of slow molecular evolution combined with morphological stasis. They provide good models to help us understand the speciation processes which lie at the heart of modern evolutionary theory.

Edges, centres and hotspots

The large, brown fucoid seaweeds are dominant intertidal, foundational species occurring along rocky shores throughout Europe (Fig. 10), whereas in subtidal, soft-sediment habitats, this dominant role is played by seagrasses. Members of the genus *Fucus* and the seagrass, *Zostera marina* were extensively sampled throughout their entire North Atlantic ranges. For most seaweeds and corresponding invertebrates, refugia during the last glacial maximum (ca. 18,000 years Before Present) existed in parts of SW Ireland, Brittany and NW Iberia.

Today, the Brittany peninsula is a hotspot of accumulated diversity for many taxa, whereas NW Iberia is quickly becoming a 'trailing edge' as increased sea surface temperatures push the boundaries northward.

This type of retrospective-prospective analysis aids in understanding changes in biodiversity that will be unavoidable as the natural world responds to climate change. As well as providing detailed information about large-scale connectivity along coasts, such information can help in establishing guidelines for the design of marine protected areas and, in the near future, addressing the genetic potential for adaptation under climate change.

Impacts and disturbance

Human activities

In an era of advancing globalisation, environmental degradation is a major international concern. Human impacts propagate across terrestrial and aquatic environments and throughout the atmosphere because of the inherent connection between these components of the biosphere. A direct consequence of this connectivity is that human impacts can accumulate their effects in space and time, challenging the ability of living organisms to absorb environmental shocks. This is particularly true for marine environments, which are the final recipient of many terrestrial wastes and are simultaneously exposed to human impacts occurring directly in the sea.

Marine ecologists and biologists are engaged in a collaborative effort to understand how escalating trends in human impacts are affecting marine biodiversity and, in turn, how changes in biodiversity affect the functioning of marine systems and their ability to produce the key resources that are necessary for our own well-being. This is not a simple task. Different kinds of environmental degradation affect different species in different ways, and impacts can vary depending on characteristics of the habitat in which the species occur and the locality. Combined effects of numerous sources of impact can propagate throughout ecosystems in extremely complex ways, making it difficult to predict how a given ecosystem will respond to future disturbances and environmental changes.

MARBEF researchers have used a number of different approaches to address some of these challenges, bringing together individuals with a range of different skills and areas of expertise. We have worked with information accumulated over decades of past research as well as collecting new information by undertaking experiments and sampling programmes in a range of marine ecosystems. Below, we summarise some of the key findings and emphasise their implications for management and future research.

Effects of fishing

The consequences for ecosystem structure and functioning

Fishing affects fish populations in many ways – reducing numbers, changing the age and size composition of populations, and changing life history patterns (including evolutionary changes in maturation). Many fish populations have been reduced to low numbers due to long-term impacts of fishing (e.g., cod in Baltic Sea) and some populations may be approaching collapse (e.g., bluefin tuna in NE Atlantic and Mediterranean).

Historical studies have shown that cod in the eastern Baltic Sea were more abundant 400 years ago than in the late 20th century.

This result, highlighted by MarFISH, is surprising, because the Baltic Sea 400 years ago was not very “cod-friendly” and was much less productive than today (i.e., before the increase in nutrients and primary production in the mid-to-late 20th century) and marine mammal predators of cod (seals) were more abundant. Cod were probably more abundant despite the lower productivity because of the overall lower level of exploitation in the 1500s.

Bluefin tuna were abundant in northern European waters such as the North and Norwegian Seas until the late 1960s and into the 1970s, when they disappeared; they have not yet returned. The reasons for their disappearance are not clear. However, since the 1970s, the overall biomass in the entire NE Atlantic and Mediterranean has declined and landings have been too high for too many years to allow recovery of the population. Legitimate fishing quotas are exceeded by illegal landings and catches of undersized fish. As a result, the population is at risk of collapse and has been disappearing from other areas of its range including the Black Sea and parts of the Mediterranean.

Heavy exploitation of fish populations can also have consequences for the other species in the ecosystem.

These consequences include effects on abundances of prey species, and how predators and prey interact (e.g., the structure and functioning of ecosystems). The effects can include "cascading" effects in which abundances of prey species increase in response to decreases in abundances of predators; the increase in the prey species then has a controlling effect on prey in the next lowest trophic level in the food web, and so on.

An early example of this ecological cascade occurred in the Limfjord, Denmark, in the early 1800s, when heavy fishing pressure contributed to the collapse of a local herring population and the subsequent dominance by jellyfish, including *Aurelia aurata.* The ecosystem became so dominated by jellyfish that fishermen were complaining that they could not haul their nets, and the issue was discussed in the Danish parliament. This example seems to have been repeated in other areas around the world where fishing has removed large quantities of zooplanktivorous fish, such as herring, sardines or anchovy, and jellyfish subsequently became abundant.

Evolutionary effects of fishing on fish biodiversity

Fishing is by nature a selective process: some individuals are more likely to avoid capture, survive and reproduce than others due to individual differences in size, morphology or behaviour. Fishing may therefore act selectively on reproductive age- and size-groups. If these differences are heritable, then fishing will have evolutionary effects on the population over time. In addition,

Different populations of the same species may differ in their sensitivity to exploitation; this could lead to a decline of less resilient populations while other populations of the same species are less affected.

Fishing can, therefore, have evolutionary effects on fish populations, and this topic has been receiving increasing attention in the last 10–15 years. One of the most interesting and striking results is that:

Fishing, by increasing the mortality of reproductive age- and size-groups of fish, favours evolution towards earlier maturation.

This pattern has been predicted from theoretical models employed by MarFISH, and has been observed in nature in several wild fish populations. These observations strongly support the hypothesis that fisheries-induced evolution towards earlier maturation at smaller size is commonplace. Remarkably, we see that the pace of fisheries-induced evolution can be very high, leading to detectable changes, even over just a few generations. Present fishing practices typically favour fish on the "fast track" of maturation and development, as opposed to unexploited situations where there is also room for fish in the "slow lane." These findings of evolutionary effects of fishing are controversial and still being debated in the scientific literature. Whatever is the nature of the change – genetic change, plasticity, or community change – phenotypic diversity of fish life-histories is on the decline. As a consequence,

© Ferdinando Boero, Alberto Gennari, Fabio Tresca

Oceans and seas make up the most widespread habitat type on the planet. Industrial fisheries, habitat destruction and pollution are increasingly diminishing fish resources at a global level.

Fish populations may be becoming more vulnerable (and less resilient) to perturbations such as fishing, climate change and invasive alien species.

Effects of an increase in freshwater to coastal regions

Climate models predict increasing variance in rainfall regimes, with increased frequency of droughts parallelled by unusual amounts of rainfall and floods. In anticipation of this, the Mediterranean region is now being subjected to extensive river damming, which can have far-reaching impacts on coastal food webs. For instance, the diets of the five most abundant flatfish species of the Gulf of Lions and their prey depend on river inputs. Two trophic networks occur off the River Rhône, one based on the consumption of carbon of marine origin, the other on carbon of terrestrial origin. The transfers of the latter are most significant between 30 and 50m depth, where river particulate organic matter sedimentation and its uptake by the benthos are highest. The common sole largely profits from the contributions from terrestrial organic matter, via their main prey: deposit-feeding polychaete worms. The increase in abundance of these polychaetes stabilizes the whole life-cycle of the species and consequently the associated fisheries. That means that climate changes inland may affect coastal marine food webs, particularly through variation in river flow.

Increased river inputs to coastal systems may alter food webs and fisheries.

Combined impacts: loss of species and disturbance

Coastal ecosystems are extremely productive and provide a range of economic and social benefits, such as fisheries and coastal protection. They are subjected to a wide range of disturbances and, under forecasted climate change scenarios, including increased storminess, many will experience increased physical stress and organic enrichment. At the same time, a range of local activities are causing the loss of some of the key species in the ecosystems such as large seaweeds, seagrasses and burrowing worms. It is not yet known how these different impacts might

© Ferdinando Boero, Alberto Gennari, Fabio Tresca

Seagrass meadows are a priority habitat under the EC Habitats Directive.

combine to affect ecosystem processes. This information is essential for the implementation of environmental legislation such as the new EU Marine Framework Strategy Directive. Such legislation also requires that specific management strategies are developed for different regions in Europe.

MARBEF workers on the BIOFUSE project used simple experiments to compare effects of loss of biodiversity (specifically, a key species) on a number of marine ecosystems (rocky shores, seagrass beds and sedimentary shores) also subjected to experimental disturbance (physical impacts or organic enrichment) at a number of locations in Europe to answer the question 'Are the effects of biodiversity loss consistent across different habitats and locations?'

The loss of key species affected structure and functioning in many, but not all, ecosystems. The influence of loss of species and disturbance on structure varied among habitats and locations. In only a few cases were there complex combined effects of these two impacts. An influence on functioning was rare, suggesting widespread capacity of ecosystems to compensate for loss of single species, even 'key' species. This is good news with respect to these habitats, but the results showed variation between locations, something which is reflected in the EU Marine Strategy Framework Directive where there is emphasis on regional focus.

There is considerable variation in impacts as a result of biodiversity loss among locations within regions, which requires different management strategies.

Additional field-based experimental research is needed to predict combined effects of loss of 'key' species and disturbance. This research need not be complex, but it does need to be extensive and carefully designed. This information is of direct use to managers to avoid being misled by assuming that impacts of disturbance and species loss are consistent across systems.

Do changes in species abundance have impact?

Many species are being reduced in abundance or driven to local extinction by human activities. Although there are clearly consequences of changing biodiversity for the functioning of ecosystems, the relative importance of different kinds of changes are not clear. MarBEF scientists on the BIOFUSE project used intertidal communities of algae and invertebrates as an experimental system to assess the separate and combined effects of changes in the number and type of key species on the functioning of the selected ecosystem. The results showed that changes in the abundance of species were more important than changes in the variety of species.

The key result was that while effects of changes in diversity vary according to the habitat and location, the effects of changes in species abundance are much more consistent. Current environmental policies focus on conservation of species diversity and habitats, placing less emphasis on preservation of species abundances. MarBEF data shows that:

Alteration of key species abundances affects ecosystem functioning more than changes in species diversity.

This outcome emphasises the importance of preserving not only particular species but also the relative abundances with which species populate our marine coastal environments.

Potential impacts of biodiversity change on ecosystem stability

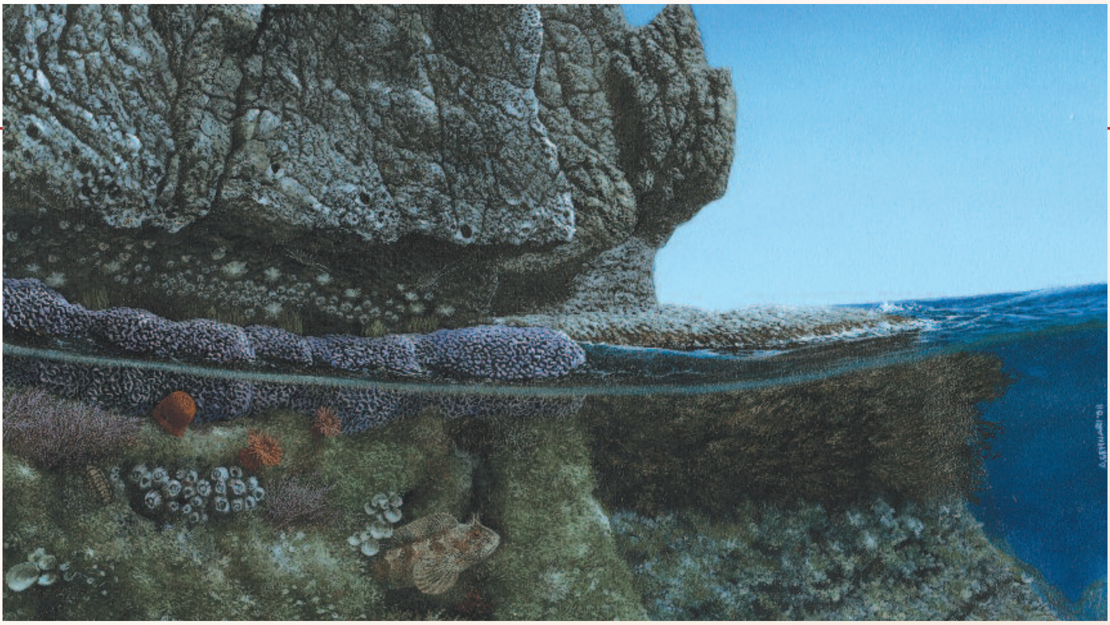
Biodiversity loss is being observed in many ecosystems and raises concerns about the potential effect of this loss on the functioning of ecosystems and their provision of services to society. A key consideration is the extent to which biodiversity can improve the stability of ecosystems through time, both in terms of their structure and functioning. More stable ecosystems are more reliable providers of ecosystem services such as fish catches and stabilisation of coastal habitats.

In this study, the relationship between biodiversity and stability (as temporal variability) of marine benthos was investigated using two approaches: (a) meta-analysis to assess whether consistent patterns could be found in existing datasets, and (b) new sampling at fifty rocky shores throughout Europe.

The overall outcome of the meta-analysis indicated a negative (although weak) relationship between diversity and stability in some aspects of ecosystem structure for each of three habitats (rock pools, emergent rock and sedimentary shores). These relationships were observed at small and large scales, but there was variation in the outcome depending on which habitats and locations were being considered.

In many cases, there was no clear relationship between diversity and stability; research revealed that the relationship varied among regions, depending on habitat, scale and location.

In the sampling programme employed by BIOFUSE scientists, which was focused on emergent rock on rocky shores, there were generally no relationships observed. However, at small scales (areas of less than a metre), we observed a positive relationship between diversity and stability of the suite of species present. The relationships varied among regions, which again helps to support the regional focus of the new EU Marine Strategy Framework Directive. Outcomes from both approaches led to similar results for rocky shores. Therefore, where sufficient datasets exist, meta-analysis of those datasets can provide a cost-effective alternative to collecting new data on diversity:stability relationships.



© Ferdinando Boero, Alberto Gennari, Fabio Tresca

Rocky shores are dynamic and fascinating habitats which are influenced by the tides. They are biologically rich in terms of the number and variety of species they support.

However, more empirical research is required to characterise the link between diversity and stability in many habitats.

Human disturbance and the stability of rocky shore assemblages

The structure and functioning of marine ecosystems is threatened by a range of human activities, including degradation and destruction of habitat, organic and inorganic pollution, enhanced inputs of terrestrial sediments, over-fishing and invasion by alien species. It is not clear, however, how different activities vary in the way in which they influence stability of ecosystem structure. In this study, the BIOFUSE project combined and reanalysed the results of a large number of experimental studies on impacts of disturbances on stability of assemblages of animals and seaweeds on rocky shores.

Only some types of human disturbance have strong effects on the stability of rocky shore assemblages.

Overall, the results of this study indicated that some types of disturbance, such as loss of large seaweeds and nutrient enrichment, did not influence stability. Other sources of disturbance, including removal of organisms caused by mechanical forces or the dominance by exotic species, can reduce, although through different mechanisms, the stability of intertidal assemblages. It is interesting to note that an increase in the severity of mechanical disturbance is predicted in intertidal habitats as a consequence of increased frequency of extreme meteorological events (i.e. sea-storms and hurricanes). Similarly, the introduction of exotic species is increasing rapidly with the intensification of global trading.

Some evidence suggests that management initiatives should focus their attention on responses to climate change and on reducing the impact of invasive species on rocky shore assemblages.

Impacts of disturbance on nematodes

Sediment movement, erosion and deposition are natural processes, and benthic organisms have adapted to such disturbances. Man-made physical disturbances (e.g., beam trawling, dredged material disposal, coastal development) occur at a much larger scale, rate and magnitude which may exceed the adaptive capacity of sediment-inhabiting organisms.

MarBEF researchers on the MANUELA project compiled and analysed an extensive database of experimental and observational studies investigating the effects of physical disturbances in sediments. Some measures of diversity decreased with increasing level of disturbance regardless of the disturbance type. Others, however, were more variable and depended on the nature and origin of the disturbance. Hence, there is no consistent effect of physical disturbances on nematode assemblages. In addition, it was shown that man-induced changes are intrinsically different from those of natural origin. Nematode assemblages were more similar after being subjected to high-intensity disturbances, even if they originated from geographically distinct areas.

Nematode assemblages do not show a similar response to different types of physical disturbance.

However, it is largely unknown whether nematodes respond in a similar way to the same disturbance, independently from the geographical location. In this experiment, MANUELA researchers mimicked the effect of an increased amount and frequency of rainfall on sandy beaches from four different locations in Europe. Experimental beaches were located in Poland (Baltic Sea), Belgium (North Sea), Portugal (NE Atlantic Ocean) and Crete (Mediterranean Sea). Beaches covered a range of tidal regimes (microtidal to macrotidal), salinity brackish to marine) and temperature (north-south gradient) environments. The frequent addition of freshwater to the Baltic beach did not affect salinity in the sand, due to the low natural salinity. All other beaches showed modified salinity profiles. All nematode assemblages changed significantly as a consequence of the experimental treatment but the underlying mechanisms were different.

Nematodes do not show a universal response to disturbances associated with climate change.

This shows that there is no universal response of nematode assemblages to disturbances and that changes occurring at a global scale will have different impacts in different localities. The adaptation of the receiving community to the frequently-changing environment largely determines the effect of the increase in rainfall.

MARBEF has examined impacts of disturbance at a truly European scale – collating, generating and comparing evidence from a wide range of disturbance types, habitats, taxa, places and times. Its researchers have worked to improve methodologies for data collection, archiving and analysis and have completed a substantial body of original research. New evidence has shown that the impacts of key disturbances can vary substantially depending on the environmental context in which they act and are not necessarily predictable based on existing knowledge.

The specific and general findings of the work can be applied directly to the implementation of the existing Water Framework Directive and the new Marine Strategy Framework Directive. Effective decision-support tools must incorporate empirically derived insight into the impacts of key disturbances in specific regions and localities.

The databases generated during MARBEF will provide a lasting legacy and can be built upon and interrogated repeatedly in future with great potential to improve our understanding of variation in impacts of disturbance on marine ecosystems and our approaches to managing marine environments.

Valuation and marine planning

Integrating natural and social science

Initially, MarBEF spent time on integrating activities to discover common ground and common language between the disciplines; developing methodologies for valuation that could be applied in the marine environment and to marine biodiversity issues, and developing the research potential of this heterogeneous group of people. MarBEF recognised that there was barely any existing data on the socio-economic importance of marine biodiversity and, previous to MarBEF, almost no development of methodology to collect such data.

MarBEF developed an ambitious research project (MarDSS) to begin to fill some of the gaps in available data and to test the methodologies it had developed. Such data collection required substantial effort, beyond what was available within MarBEF. MarBEF, therefore, decided to make a substantial contribution to this area by capacity-building and training PhD and MSc students to provide them with appropriate interdisciplinary skills.

Goods and services

Marine biodiversity provides goods and services that yield direct and indirect benefits to people. Understanding these goods and services can indicate the socio-economic importance of marine biodiversity. Within the framework of the Millennium Ecosystem Assessment, MarBEF economists and cultural anthropologists, in collaboration with marine ecologists, have come together and identified and defined specific ecosystem goods and services provided by marine biodiversity.

MarBEF scientists have identified and defined specific ecosystem goods and services provided by marine biodiversity.

Case-studies were used to provide examples of marine ecosystem goods and services and hence an insight into the practical issues associated with their assessment. This validated the definitions of marine goods and services, providing a theoretical framework for their assessment, and identified knowledge gaps and likely difficulties of quantifying the goods and services. The research will enable future assessments of marine ecosystem goods and services.

A 'goods and services' approach has the capacity to play a fundamental role in the ecosystem approach to environmental management

Utilisation of this goods and services approach has the capacity to play a fundamental role in the ecosystem approach, by enabling the pressures and demands of society, the economy and the environment to be integrated into environmental management. Valuation of the goods and services provided by marine biodiversity can be used as a measure of its socio-economic and societal importance.

Development of valuation approaches

A variety of valuation methodologies have been developed to assess the social, economic and biological importance of marine biodiversity:

- biological valuation
- quantification and economic valuation of the different goods and services
- socio-cultural valuation.

Biological valuation

A biological tool that can be used as a decision-support system for marine management has been developed and applied in the Belgium part of the North Sea, the Polish coastal and shelf waters (Baltic Sea) including a detailed study of Gulf of Gdansk, and the Isles of Scilly (Atlantic).

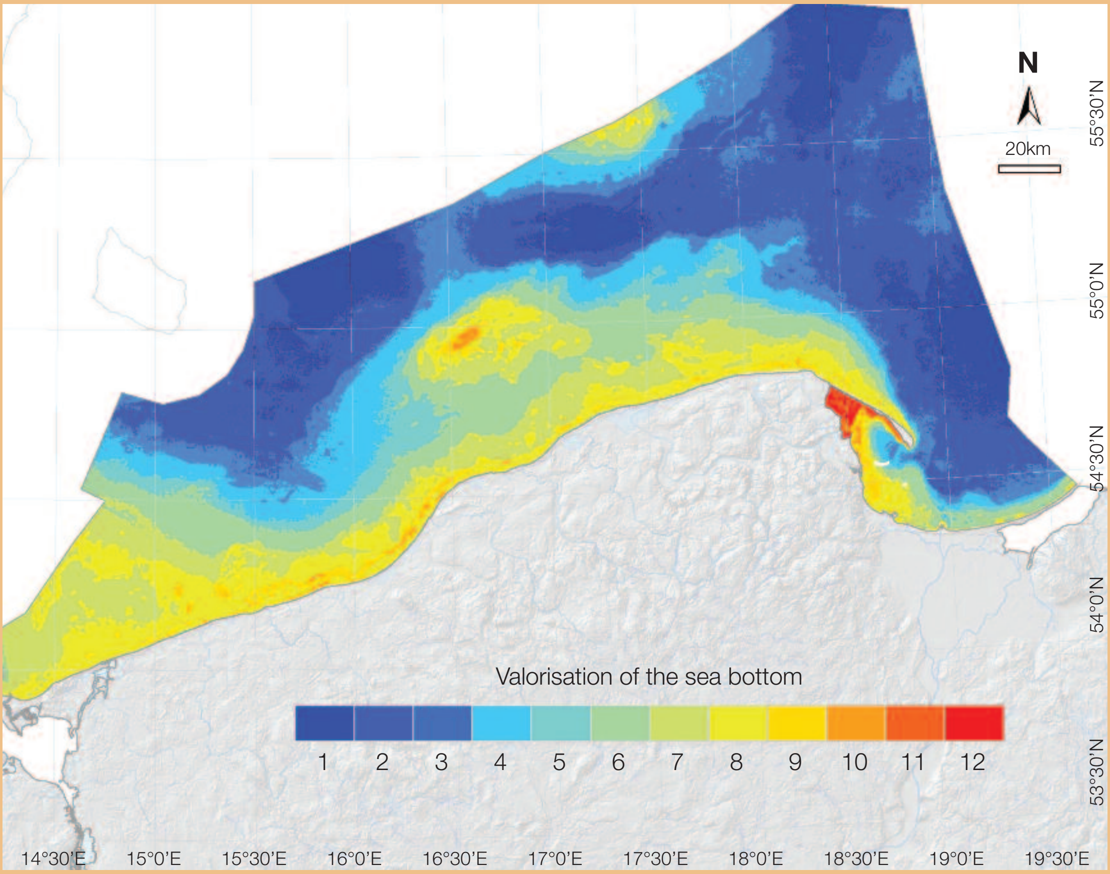


Figure 1. Biological Valuation Maps (BVM) of the Polish economic exclusion zone.

The marine biological valuation methodology is able to integrate all available biological information on an area into one indicator of intrinsic value of marine biodiversity, without reference to anthropogenic use. This methodology should be applicable in every marine environment, independent of the amount and quality of the available biological data or the habitat type.

For each organisational level of marine biodiversity, where data are available, subzones within a study area are scored on a relative scale against two biological valuation criteria: rarity and aggregation or fitness consequences.

Biological valuation maps can be used as baseline maps for future spatial planning in the marine environment.

Marine biological valuation provides a comprehensive concept for assessing the intrinsic value of the subzones within a study area (Fig. 1). It is a tool for calling attention to subzones that have particularly high ecological or biological significance and to facilitate provision of a greater-than-usual degree of risk aversion in spatial planning activities in these subzones.

Generally applicable and transparent guidelines for the practical application of the marine biological concept have been developed. After dividing the study area into subzones and collecting the available biological data, applicable assessment questions are selected, which relate the valuation criteria to the different organisational levels of biodiversity. The biological valuation protocol was developed to be objective and flexible; to allow inclusion of multiple ecosystem components and use of different levels of data availability, and to be applicable to a broad range of marine environments.

Quantification and economic valuation of goods and services

1) Gas and climate regulation

Gas and climate regulation by photosynthetic fixation of carbon dioxide is of particular socio-economic importance because of climate change. Using the Isles of Scilly as a case study to value this service, net annual carbon photosynthetic fixation values were estimated by mapping habitats of keystone species of kelp and seagrass and using literature data to quantify their productivity as well as remote sensing methods to estimate phytoplankton productivity. The economic value of this service was then estimated using 'marginal damage costs avoided.' An adjacent Atlantic Ocean comparison site was used to indicate the relative importance of island biodiversity to this marine service.

The Isles of Scilly marine environment was shown to be almost twice as productive as the Atlantic Ocean region.

The Isles of Scilly marine environment was approximately twice as productive as the Atlantic Ocean region, fixing 136,495 tC y^{-1} with a mean net present value of €59,109,529, while that of the Atlantic Ocean region was calculated to be €28,641,727.

2) Disturbance prevention

The role of coastal wetlands as buffer zones to wave action and storm surges has been quantified and valued using two sets of methods: a) a contingent valuation method (CVM) using coastal householders' willingness to pay to conserve salt marshes and mudflats, and b) a preventative cost method focusing on the savings made in sea defence construction. As well as obtaining an economic value for the sea-defence role of wetlands, the CVM survey also provided indications of coastal householders' preferences on sea-defence provision.

Coastal householders are willing to pay for conservation.

3) Bequest and existence

The value that people place on the existence of European marine biodiversity was assessed across four European sites, using the contingent valuation methodology (CVM). The monetary value of marine biodiversity was indirectly assessed by asking respondents their willingness to pay (WTP) to avoid reductions in abundance (10% and 25% of current levels) of various marine taxa including mammals, birds, fish, invertebrates and algae. A total of 1,732 face-to-face interviews were carried out in the Azores, Isles of Scilly, Flamborough Head and Gulf of Gdansk.

Initial findings suggest that there is a greater willingness to pay for all marine taxa compared with any individual marine taxon group.

Only very small differences were observed in the willingness to pay for different taxa. Mammals and fish were valued more highly than birds, invertebrates or algae. These results show that the general public do value marine biodiversity but, surprisingly, suggest that:

Charismatic animals do not have a disproportionately strong influence on human preferences for biodiversity conservation.

There are demographic differences in the value placed on marine biodiversity, and our research is exploring this further.

Millennium Ecosystem Assessment categories	Good/Service	Monetary value
Production	Food provision	£513 million
	Raw materials	£81.5 million
Regulation	Gas and climate regulation	£420 million - £8.47 billion
	Disturbance prevention	£17-32 billion
	Bioremediation of waste	No £ data
Cultural	Cultural heritage and identity	No £ data
	Cognitive values	£317 million (2002)
	Leisure and recreation	£11-77 billion (2002)
	Non use values	£0.5-1.1 billion
	Option use value	No £ data
Supporting	Nutrient cycling	£800-2,320 billion
	Resilience and resistance	No £ data
	Biologically mediated habitat	No £ data

Figure 2. Economic valuation of goods and services provided by UK marine biodiversity.

4) UK goods and services

A goods and services approach was used to determine the economic value of marine biodiversity in the UK and to provide supporting evidence for a need for new UK marine legislation (The Marine Bill). Only currently available data were used; no primary studies were undertaken. The goods and services resulting from marine biodiversity in UK waters were detailed, including the habitats and species which provide them, and the likely impact of a decrease in biodiversity. Each service was valued (Fig 2), where possible, in monetary terms using a variety of valuation techniques, including replacement costs, damage avoidance, contingent valuation and benefit transfer. The problems with monetary valuation were recognised. For example, nutrient cycling was valued through replacement, yet this service cannot in reality be replaced, so the very large value was unrealistic.

The aim of this valuation process was not to determine a single value for UK marine biodiversity, but to detail current knowledge, focus future research and clarify the role of valuation in conservation of marine biodiversity.

The strength of the UK goods and services valuation data lies in its capacity to raise awareness of the importance of marine biodiversity.

This valuation data, however, should only be used alongside the qualitative information and with a clear understanding of the associated limitations. Descriptive text for each of the goods and services is as important as the monetary data, and clarifies the linkages between biodiversity and the provision of these functions in UK coastal and shelf waters.

A decline in UK marine biodiversity could result in a varying and, at present, unpredictable change in the provision of goods and services.

This could result in severe impacts on society and the economy, including reduced resilience and resistance to change, declining marine environmental health and water quality, reduced fisheries potential, loss of recreational opportunities, decreased employment and reduced carbon uptake. Effective management of marine biodiversity is critical to ensure the

© Ferdinando Boero, Alberto Gennari, Fabio Tresca

All of these marine plants and animals contribute to the production of the food we have on our tables.

continued supply of goods and services. The results suggest that:

The goods and services approach is a viable and comprehensive methodology to value biodiversity.

This approach can facilitate biodiversity management through raising awareness of the importance of marine biodiversity, and also by enabling the optimal allocation of limited management resources.

Socio-cultural valuation

Socio-cultural valuation seeks to elicit stakeholder 'emic' (insider) perspectives and values of biodiversity. The goals of such studies are to discover what aspects of marine biodiversity are important to people, to whom it's important, and how much and why. An approach was developed which would elicit what aspects of biodiversity actually mattered locally. Such preferences can be crucial for developing effective strategies for the conservation of biodiversity through their inclusion in the decision-making process.

MarBEF researchers undertook the socio-cultural valuation of marine biodiversity in the Isles of Scilly in the UK, and it is currently being applied in the Azores, the Guadiana Estuary and the Ria Formosa in Portugal. Four main perspectives were delineated in the Isles of Scilly case study:

The Management Perspective, where the implementation and enforcement of regulations related to fisheries and protected area management are considered important, given that species are diminishing.

The Contingent Value Perspective, whereby value is seen through contingency – for example, an environmental disaster such as an oil spill; the biodiversity valued overall is intrinsic.

The Future Policy Perspective, whereby management policies are important and even more management is felt to be needed, despite the fact they do not view species as diminishing now.

The Goods and Services Perspective: a holistic viewpoint whereby the goods and services, as discussed in Beaumont *et al.* (2007) (cultural heritage, fisheries, etc), and the production values of biodiversity are emphasised.

The socio-cultural perspectives show some agreement among stakeholders of differing backgrounds, and could provide vital information for reaching consensus and acceptance of management measures.

For example, there was consensus among stakeholders of groups which would sometimes be considered adversaries (e.g., fishers and environmentalists) and a group that has been traditionally considered “anti-management,” namely fishers, is actually in favour of stronger management measures.

In a remote, coastal location such as the Isles of Scilly, there is a tension between the needs of employment and livelihood and the protection of the environment. The concourse shows us that this is not a black-and-white issue. Overall, stakeholders value a traditional way of life and do not want it to change; one way to reach this goal is to regulate the environment and protect marine biodiversity properly.

The methodology that was applied is more commonly used for reaching consensus, and is therefore most useful in situations where there are conflicts and disagreement. It was useful in Scilly to see how people of differing stakeholder interests agreed on a number of levels. However, since there was no major conflict at the time of the socio-cultural valuation study, these results cannot be applied to solve any issues at this moment in time.

Indicators: legislation

In policy and regulatory frameworks indicators are used to identify, measure, summarise and communicate relevant information on environmental activities and their consequences.

Indicators can play an important role in legislation where some form of measurable standard or output is required to meet a regulatory objective. UK domestic law tends to utilise indicators indirectly. Rather than specifically mandate particular indicators, their development and use is left to managerial discretion within certain general limits. EC law tends to be more explicit in its use of indicators, as in the case of the Water Framework Directive, which requires specific indicators to be used to ensure a harmonised approach to environmental protection across Europe. International law seldom refers to indicators, although they may be used within management frameworks established by treaties, such as the Law of the Sea Convention or OSPAR.

Indicators can be used to provide information for decision-makers, for example in environmental impact assessments and public inquiries. Here, indicators enable a more informed debate as to the environmental implications of a proposed or challenged development. This frequently occurs in decision-making under planning laws. Indicators may also be used prescriptively. Thus, public authorities, for example, may be required to maintain environmental standards, carry out monitoring and engage in monitoring. The specificity of the information required in these activities depends upon the terms of the regulatory instrument that mandates the use of scientific data.

To investigate how well environmental indicators actually work within the regulatory framework, the utilisation of sustainable development indicators in the UK was investigated using the marine aggregate and dredging industry as a case study.

Management in this area is complex, and the study examined policy and legislative tools at all levels of government – local, national and international. In the recent past, aggregate extraction was undertaken under non-statutory 'Government View' procedures, whereby if the activity was deemed to be environmentally acceptable, this was accepted and applicants were offered a licence. Under this procedure, applicants had been required to provide an environmental statement, which was followed by an environmental impact assessment, including any risk of coastal erosion that might arise from off-shore dredging. Information from these assessments, along with other indicators, has helped to improve the scientific basis for predicting the effects of these extractive activities and the recovery of the ecosystems once activities cease. Public consultation was also required throughout the process, but it was considered highly inefficient, burdensome and even informal in parts.

Good communication between the various government agencies and disciplines is highlighted as being important to better achieve sustainable-development objectives.

In 2007, the Environmental Impact Assessment and Natural Habitats Regulations consolidated the EU directives relating to dredging for land-based activities. The 2007 regulations have placed the use of environmental statements on a formal, statutory footing, improving upon the previous Government View process. Although the 2007 regulations use indicators, they are not overly prescriptive. They establish a flexible system for managing marine-extraction projects and they facilitate an integrated approach to sustainable-development goals. The regulations allow for some discretion in selecting indicators that are appropriate to the activity and consistent with the regulatory framework.

A more detailed study on the operational use of indicators is being carried out under a UK Department of the Environment, Food and Rural Affairs (Defra) project, ME4118, in collaboration with MarBEF. Research shows that indicators should be measured according to the following criteria:

(1) **policy relevance** – they correspond to a management framework with operational objectives;

(2) **legal relevance** – they may be influenced by legal obligations, which are mandatory;

(3) **communication** – there should be an effective line of communication of indicators to both policy-makers and stakeholders, which may involve expert interpretation;

(4) **responsiveness** – indicators should be designed to meet management needs;

(5) **scientific rigour** – they should be accurate and of good quality;

(6) **quality-control review** – they should be subjected to independent and objective quality control;

(7) **process standards** – indicators should be designed according to a process that ensures the indicator can withstand critical scrutiny.

Marine decision support systems

Decision- and policy-making in the marine environment is challenging, as it is a complex system consisting of ecological, economic and socio-cultural factors. Furthermore, the information and data available on these factors is far from complete. As a result of the imperfect information and the complexity of the system, the decision-maker has to consider not only complex and partially unknown environmental data and effects, but the economic, social and ecological consequences of the decision as well. A possible tool to help in decision-making is a computer-based decision support system (DSS) that can:

- assist individuals or groups of individuals in their decision process;
- support rather than replace judgements of individuals;
- improve the effectiveness rather than the efficiency of a decision process.

MarBEF has developed a demonstration prototype of a decision support system (MarDSS) for identifying and selecting alternative solutions for the protection of marine biodiversity.

The DSS currently has a regional focus, but it is being developed so that it can be adapted to operate at all levels of EU decision-making. The final system will illustrate the relationships between marine biodiversity and human marine activities. The spatial aspects of these relationships will be shown in maps so that it is possible to assess the effects of alternative policy scenarios, including the use of weights and choices for different components of the marine ecosystem, marine economic activities and social impacts.

The demonstration version focuses on marine ecosystem issues that relate to human activities in the Dutch North Sea. These issues are analysed in an integrated assessment taking the social, ecological and socio-economic forces into consideration and using the Driving Forces-Pressures-States-Impacts-Responses framework (DPSIR framework) as a starting point. As most problems in the marine environment have a spatial dimension, the decision support models that have been developed are all spatially explicit. Social, economic and ecological information and methodologies collected and developed in MarBEF are being used as baseline data for some of these models, and are visualised on maps, or are provided as background information.

In the models section of the DSS, the decision-maker can choose to model the placement of marine reserves for fisheries or the placement of wind turbines.

The latter model allows the user to designate restrictions such as levels of bird and fish populations that must still be maintained and amount of energy that should be generated. The results are shown in maps and tables. The interactive maps of the European seas enable the user to zoom in and look at the available data for these seas, access some local countries data, oceanographic data, time-series data, models and background information (where available). Biological valuation maps for some of the MarBEF case studies are also included. These maps can serve as a basis for the wind farm model to designate which areas should be afforded protection.

The socio-economic valuation will be used to put a value on the losses of certain activities, whereas the socio-cultural valuation can inform decision-makers about the aspects of marine biodiversity and the marine environment that people find important.

The background section presents a DPSIR analysis of the problems in the European seas, with possible policy instruments to combat some of these problems. The system can easily be filled with more data as it becomes available.

The rise and fall of biodiversity

An ecological dilemma?

Observed increase in species richness (diversity) and shifts in distribution alter the structure of marine ecosystems and their functioning considerably.

The most fundamental meaning of biodiversity is probably the concept of species richness, i.e., the number of species occurring at a given site, or within a region or an ecosystem. Higher diversity has often been seen as an advantage for an ecosystem to better cope with environmental fluctuations (insurance hypothesis). A large species pool might increase the resilience of an ecosystem to changes in environmental conditions or to anthropogenic impacts.

The value of biodiversity as an indication of environment health and for the functioning of ecosystems has been recognised not only by scientists but also by decision-makers and the general public.

The maintenance of high diversity is often seen as something positive to aim for; and to "halt the loss of biodiversity" has become a major political aim. It is now clear that marine ecosystems are at risk, especially those receiving the most sustained and unrelenting pressure from human activities, such as estuaries, intertidal shores and coastal waters. The composition of species within marine communities can change in three main ways:

- species may be lost (extinctions);
- species may be added (invasions or speciation);
- species' relative abundances can change (rare species become abundant, abundant species become rare).

Although the number of rare species comprise the majority of the taxa in a biologically diverse region, they do not play a quantitatively important role in the structuring of the community. However, when species are removed or added to a community, and thus the biodiversity changes, the energy flow, predator-prey interactions or food web-related processes may change dramatically. As a consequence, the productivity of the seas is directly affected.

Structurally complex habitats are becoming rarer across European marine environments.

Habitat heterogeneity is another important factor when describing biodiversity. Presently, a gradual transition from very complex to simpler habitats has been observed. MarBEF explored the numerous ways in which habitat loss can affect marine species diversity, and thus community structure, and some examples are presented in this booklet. The loss of habitat structure is generally thought to lead to lower abundance (biomass) of key species and often to a decline in species richness.

However, experiments in different coastal areas of Europe, performed within MarBEF, have shown that the removal of key species does not always affect the stability of the ecosystem and that effects depend on where, when and what species are removed. For example, an invading species may replace a resident species which plays an ecologically important role for ecosystem structure and functioning. The ecosystem may continue to function and provide similar services, but not necessarily in the same way as before.

MarBEF also showed that, despite increasing pressure from overfishing, habitat destruction and pollution, species richness appears to be on the increase in many coastal and marine European waters. This is due to the establishment of non-indigenous species, especially of warm-water affinity, and to a general northward movement of species due to climate change. The observed increase might also be due to the addition of newly recorded species to already existing species lists which haven't been amended for a long time, or be related to more intensive research and the discovery and description of rare species.

The general lack of boundaries in the marine environment compared to the terrestrial environment is an important factor which facilitates the distribution of species across ecosystems, provided the environmental conditions are suitable.

Anthropogenic activities such as shipping and aquaculture further enhance the spread of species, even across geographic or ecological boundaries. Such shifts in species or changes in regional biodiversity will have consequences on the structure and functioning of ecosystems. However, this raises two questions: Can we expect the same response from all European marine ecosystems? And can we predict how this will affect ecosystem functioning? Below, some examples are provided based on MarBEF activities, to offer some answers to these questions.

The Arctic

With increasing temperatures, the species-poor Arctic is receiving new species. The number of species on the same trophic level is likely to increase, which will benefit small pelagic organisms but will have negative consequences for large, top predators.

For certain habitats in the Arctic, species diversity is considered low compared to European marine ecosystems at lower latitudes. However, during the brief summers with their long day-lengths, the abundance of species is relatively high due to the large numbers of fast-growing food organisms. This seasonal availability of enormous quantities of food attracts animals higher up the food chain, such as whales, and provides sufficient energy for other top predators (e.g., seals, polar bears) to survive the long winter.

With increasing temperatures, there will be an increase in species from southern latitudes. The larger native predators will have to share the available food with these (in a diversified use of resources). Smaller pelagic fish and other species will benefit from a modified food web with a wider distribution of biomass at intermediate trophic levels, so that greater species diversity can be expected. Changes in abundance and distribution of native species will change, with significant impacts on the community structure and thus a modification of ecosystem functioning.

The response of top predators to habitat loss (loss of sea ice) and to changes in food sources will differ depending on whether they are ice-obligate (i.e., polar bear, ringed seals), ice-associated (i.e., certain seals, white whale, narwhal, bowhead whale and walrus) or seasonal migrants (i.e., fin and minke whales).

Polar bears are particularly at risk since their habitat (the ice) is reducing and possibilities for a northward shift in distribution are limited. The loss of polar bears and other top predators in particular will not only affect the functioning of the Arctic ecosystem but also indigent human populations and their traditional way of life (e.g., hunting).

Rising numbers in the low-species Arctic have consequences for top predators.

The Arctic example shows that ecosystems can respond to global warming with greater diversity which, at the same time, leads to a decrease in charismatic species due to more competition or limited adaptation to the new conditions. This could have serious societal consequences in terms of tourism and/or aesthetic aspects (naturalness of the ecosystem that people are used to). From an ecological point of view, changes are likely to occur, but they will not necessarily result in a decrease in functions or in productivity.

The Mediterranean Sea

The Mediterranean Sea is relatively species-rich, with densely interconnected niches. Shifts in species distributions and the introduction of newcomers may cause the disappearance of distinct, sub-regional systems and the establishment of a more homogeneous, tropical ecosystem.

The Mediterranean Sea has a relatively high species diversity, largely due to its long evolutionary history and the "post-Pliocene diversity pump" which, in prehistoric times, brought many Atlantic species into the Mediterranean. The present-day high species richness is due to spatial coexistence of warm-water species (thriving in the summer) and cold-water species (thriving in the winter). This seasonal change in species activity is a buffer against the effects of environmental variation, because a varied set of species is more likely to adjust to environmental change.

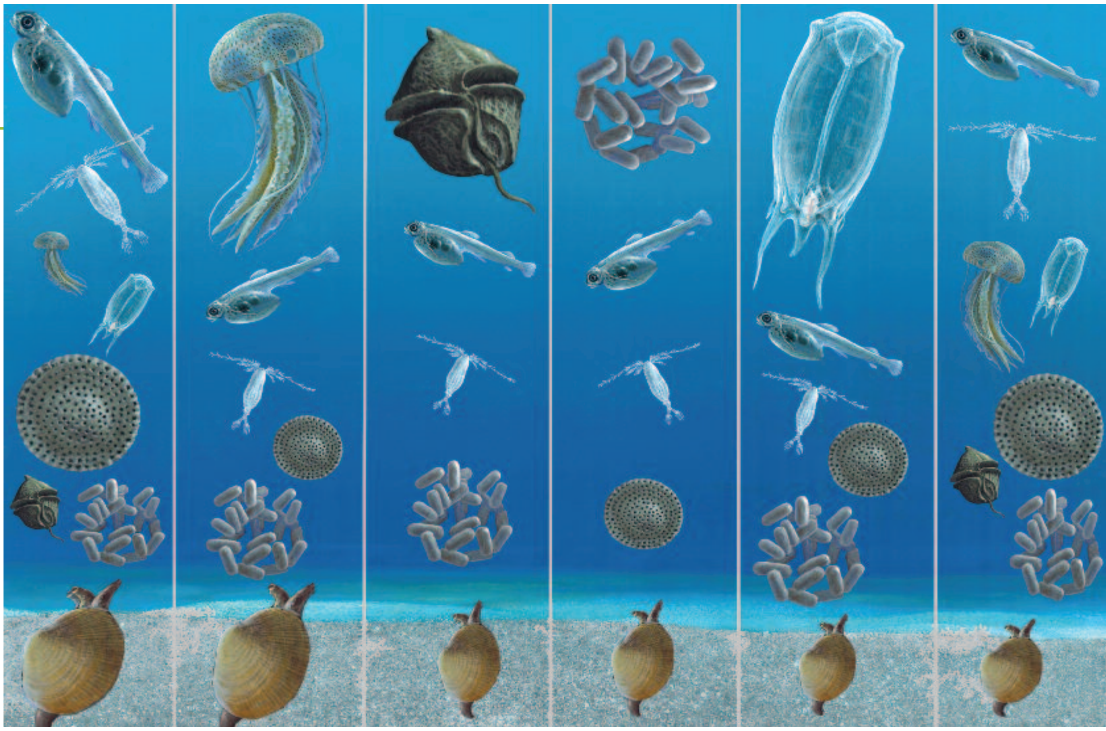
Since the 1980s, the Mediterranean marine biota has experienced rapid, dramatic changes, illustrated by alteration of food webs, mass mortalities, and population explosions such as jellyfish outbreaks. These changes are caused by intense anthropogenic activities, but also by climate change. The case of the Adriatic Sea is a good example (see illustration, opposite page).

The advance of warm-water species represented the first evidence of a linkage between climate change and distribution patterns in the Mediterranean Sea. This phenomenon is particularly evident in fish, where over 30 native (warm-water) species have already spread into northern areas. Almost all of the 100 fish species newly recorded in the Mediterranean are of warm-water affinity. At the same time, the physical properties of the basin have changed and temperatures have increased.

A consequence of new species entering and species' distributions shifting in the Mediterranean could be fewer distinct, sub-regional ecosystems.

Endemic native species with cold-water affinity, common in the northern part of the Mediterranean, will probably decline and eventually be lost. A decline in their occurrence has been reported already. It is also possible that some of these species might become adapted to the new conditions, after periods of stress. The seaweed *Fucus virsoides,* an endemic flagship species of the Northern Adriatic (the coldest portion of the Mediterranean Sea), appeared to suffer severe stress in former years, whereas it is now particularly abundant, for example in Venice. In general, the recent warming has facilitated the establishment and distribution of tropical, exotic species that have been introduced either via the Suez Canal or by maritime transport. This process is fast advancing, and more than 500 non-indigenous species have already been recorded in the Mediterranean. Some undoubtedly raise some concern, such as the jellyfish *Rhopilema nomadica* – which even shut down a nuclear power plant by clogging its cooling system – whereas others are becoming a resource for fisheries. Entire replicas of tropical communities from the Red Sea have already been recorded from a few Mediterranean locations.

If the Mediterranean continues to warm at the same rate, all its sub-regional, biological peculiarities may rapidly disappear, to be replaced by a more homogeneous, tropical-like ecosystem.



This figure reconstructs the history of ecosystem functioning within the Adriatic Sea in the last 30 years. Initially, a microbial pathway sustained the crustacean-fish pathway, leading to a very productive fisheries, leading to the last scenario (present), linked to global warming, where we see a mixture of the previous scenarios and where the yield in fisheries is not as high as previously.

The Baltic Sea

The relatively species-poor Baltic Sea is receiving new species annually (species biodiversity is increasing) with no significant effects on ecosystem functioning, as the newcomers are not competing with resident species because of low niche overlap.

Over 100 new species established themselves in the Baltic Sea during the 20th century. This is a significant addition to the biodiversity of this species-poor, brackish sea, which supports no more than approximately 900 species altogether. Since the Baltic is young in evolutionary terms (<3,000 years old), its colonisation is probably not complete, and newcomers are easily filling available space and ecosystem functions. For example, the roundhead goby *(Neogobius melanostomus)* from the Black and Caspian Seas is now playing the previously-vacant role of small, coastal predator on bivalves. At present, there are no documented examples of any negative ecological impact of these new species on the Baltic ecosystem. A number of new gammarid amphipods frequenting the southern Baltic coast are well mixed with resident species and all show irregular ups and downs in abundance. However, small-scale problems for humans have been recorded, such as local problems with pipelines clogged with the zebra mussel *Dreisena,* or fishing nets covered by the copepod *Cercopagis.*

The Baltic Sea provides newcomers with opportunities for success.

A number of former invaders are now playing an important role in the benthic system. The bivalve *Mya arenaria,* which arrived from North America during the medieval period, is now one of the key species and sediment bioturbators, and it is also a source of food for fish and birds. The sessile barnacle, *Balanus improvisus*, a 19th-century invader, is now one of the few species that builds stable biogenic structures (it is a bioconstructor and habitat builder) in this system. So far, the only documented extinction from the Baltic Sea is the sturgeon, *Acipenser sturio,* a species that is now also believed to be a medieval invader from North America.

Shifts and changes have occurred before. In the early 20th century, the dominant top predators in the Baltic were marine mammals (gray, ringed and common seals and harbour porpoise). The seal populations declined by about 95% during the last century as a result, initially, of hunting (1900–1940) and later of toxic pollutants (1965–1975).

Climate change-related increases in temperature will provide the opportunity for more new species to settle in the Baltic Sea.

However, all of the new species will have to cope with the Baltic's salinity gradient, which forms the key environmental factor structuring this ecosystem, and it will probably continue to remain a key factor in the future.

The North Sea

In the North Sea, new species and communities compete for space and resources with the residents.

In the North Sea, the introduced seaweed (*Sargassum muticum)* and the Pacific oyster (*Crassostrea gigas)* are significantly expanding their range. In both cases, the new species form extensive new habitats hosting a unique epiflora and epifauna, at first sight enhancing local biodiversity. If, and how, such increases in biodiversity affect existing communities and their structure is as yet unclear, but local competition is already changing the natural habitats considerably.

The North Sea suffers from competition. Local competition is particularly drastic in respect of the fast-growing oyster beds and the ensuing suppression of natural mussel banks. The seaweed *Sargassum,* in turn, floats in extensive strands at the surface and impacts intertidal rocky-shore communities simply by shading and by competing for nutrients. In the open sea, many small flagellates replace the indigenous diatoms. On the next trophic level, gelatinous plankton replaces copepods, resulting in changes in the pelagic food web and thus its productivity. Such changes or transition phases have occurred quite abruptly, and have been identified as regime shifts.

Conclusions: what have we learnt?

The examples discussed represent just a selection of the recorded changes in European seas and illustrate how our marine ecosystems are changing in response to multiple stressors, from local habitat destruction or pollution, to global warming. The perceived increases in species numbers, besides resulting in greater diversity, are also causing severe modifications in ecosystem structure and functioning. The insurance hypothesis is validated by the observed trends: ecosystems can support stresses by changing their species composition, thus developing new and different ways of functioning. The possible impacts differ among the European seas.

The long-term impacts of changes in species richness and species distribution, e.g., due to climate change, for the stability of marine ecosystems and the composition of food webs, are not known. Their study will require adequate observation systems and new experimental approaches.

In their strong climatic contrast, the Arctic Sea and Mediterranean Sea are probably good indicators and could be used as model systems to understand and assess effects of ongoing climate change and consequences for biodiversity, ecosystem functioning and productivity.

Future issues

What lies ahead

The European Network of Excellence on Marine Biodiversity and Ecosystem Functioning (MarBEF) has, over the past five years of its existence, moulded a scientific community that has never been so conceptually and operationally united and productive. However, it is important to recognise that marine science is still developing and we do not inherently understand the ocean in the same way as we understand the terrestrial environment. For us, the oceans are foreign habitats which we may enter but not yet inhabit. We recognise the terrestrial "landscape" as our home but have no similar terms of familiarity for the oceans. Our understanding of the oceans comes from abstractions derived from the collection and interpretation of data and largely-remote observations.

MarBEF scientists have focused on and identified many critical marine biodiversity issues, which are now much clearer than before, but MARBEF has also revealed areas of weakness that require concentrated effort. These are as follows:

Impacts of global climate change

Although there is now strong evidence for changes in the global climate, the medium-term and long-term effects on the marine environment are still open to debate. Marine systems, from polar ice to coral reefs, represent charismatic systems which are highly vulnerable to temperature, sea-level and storm frequency changes. Evidence of migrational response to climate from the examination of marine population distributions are accumulating and act as an early warning of the nature of community alteration in the face of global change scenarios. Studies of modifications to ecosystem variation and functionality resulting from climate change must remain of the highest priority over the coming ten years. Some of these studies require long-term databases that are now recognised as being highly valuable and important to maintain.

Global questions require comprehensive datasets

Many current topics in marine biodiversity research are taking place on very large spatial scales and over long-term periods. These topics include baseline assessments in the marine realm, for assessing impacts of climate change on marine biodiversity, and studying the mechanisms by which alien species are introduced. Therefore, MarBEF recognised that its scientists would require analyses on an all-encompassing scale and it funded the LargeNET project.

LargeNET collected and integrated a large amount of data, comprising pelagic, rocky-shore and soft-bottom benthos data from across Europe. This data established a baseline for current biodiversity analyses and future investigations within a changing world. This scale of data collection is essential to provide the necessary understanding for anticipating the consequences of environmental variations on biodiversity, such as the changing distribution patterns of macroalagal species. For example, the database has been employed to assess the current biodiversity status and future changes in marine communities through the evaluation of techniques for the measurement of species richness.

Synergy of anthropogenic impacts additional to global warming

The oceans have been used as a means of transport, resource acquisition and disposal for centuries. While attitudes to the exploitation of the seas are changing, there is still a requirement to understand and manage the transport pathways and the effects of pollutants arising from ocean exploitation. These pathways include run-off of contaminants from the land, direct input through energy (thermal pollution), liquid and solid waste from vessels and accidental addition of xenobiotic material. Research has often focused on single stressor approaches, but multi-stressor systems and modelling are still required. This area of work has particular implications given the overlap between stresses resulting from environmental change, and such linkages should be promoted.

Marine exploitation carries with it a number of responsibilities toward environmental management. Biodiversity impacts include those caused by introduced invasive species and consequent biodiversity and functionality effects.

In addition, fisheries practice (e.g., benthic trawling) has the capacity to cause major localised and regional impact of the shelf ocean systems. In terms of non-fisheries impacts, study of the diverse impacts (noise, habitat disturbance, resource removal) caused by commercial companies (gravel extraction, dredging, oil industry) must continue to be a central issue in protecting oceanic systems. Research to characterise ecosystem- and region-specific impacts of multiple stressors is essential to underpin the effective implementation of the new Marine Strategy Framework Directive.

Coastal management

Most European Union borders are on the sea and, as Europe is a coastal continent, coastal management can only be performed if based on sound knowledge and international cooperation. The passage from knowledge generation to knowledge-based management should not stop our quest for new knowledge, the two being reciprocally stimulating. The speed at which new knowledge can be translated into management practice needs to be improved. The calls for future research development must be aimed at filling gaps in our knowledge – gaps that must be identified by the scientific community, the developers of policy and the stakeholders.

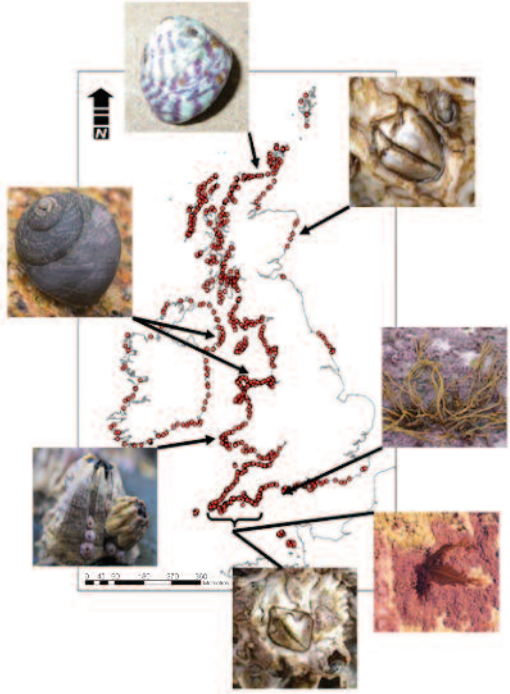


Figure 1. Changes in the range of some common rocky shore species in Britain and Ireland — a response to climate change? (Mieszkowska *et al.,* 2006).

Phase shifts: alternate stable states

Theoretically, a single ecosystem may exist in a number of possible states, or 'alternate stable states.' These alternatives are often considered to represent "good" or "poor" conditions – for example, the switch from a diverse pelagic food web (good) to a low-diversity system dominated by jellyfish (poor). The various alternate stable states for each system must be recognised, triggers causing shifts between them must be characterised, and impacts of shifts assessed.

Habitat diversity

Habitat diversity is of paramount importance in sustaining biodiversity. This is recognised by the EC Habitats Directive, but marine habitats are poorly represented by this directive. European marine habitats must be classified under a consistent rationale and then mapped, as has already been done for terrestrial habitats.

© Ferdinando Boero, Alberto Gennari, Fabio Tresca

A carpet of corals paves the floor of a Mediterranean cave. In spite of the dim light coming from the hole in the background, no algae can survive here. Marine caves are a priority habitat under the EC Habitats Directive.

Ecosystem function

Although the link between biodiversity and ecosystem functioning is now well established, its nature varies in different environmental contexts. Widely replicated experiments are necessary to develop a more effective framework to predict changes in ecosystem functioning in response to changing biodiversity and environmental conditions. The application of the Ecosystem Approach calls for proper understanding of "ecosystem functioning" for the management of fisheries, coastal zones, shelf seas, deep seas and Marine Protected Areas. More integration across habitats, as promoted by MARBEF, is needed. Many marine stations specialise in the study of coastal marine biodiversity and ecosystem functioning, and oceanographic vessels are needed to study offshore marine biodiversity and ecosystem functioning. Different habitats, addressed by different technology, are often treated as mutually exclusive but, instead, should be integrated into more general models.

Biodiversity diversity

The number of species must be linked to habitat diversity. Regional and world monographs on each group should be prepared, based on sound taxonomic revisions, to cope with the fast-changing species diversity of European seas. We are not ready to quantify and evaluate the impact of global change on our marine biota (with some exceptions, e.g., the Atlas of Exotic Species published by CIESM) until we have accumulated sufficient baseline data. The number of species found in a given habitat throughout Europe is changing rapidly. Cold-water species are under stress, whereas warm-water species are thriving and expanding their distributions, with the arrival of many non-indigenous species (NIS) of tropical affinity. The impact of these changes on ecosystem functioning should be assessed, even though it is not clear if the dramatic changes we are going through are due to global warming or to other human activities.

The role of species

Despite our relatively advanced knowledge in some areas, the role or capabilities of many species are still unknown: this is a serious gap in our understanding of marine systems. Indeed, the majority of species are probably unknown, and this is another gap. The life-cycles of most of the species we can identify are still unknown. Fundamental research on the natural history of marine systems and their inhabitants must continue.

Biodiversity at the genetic level

Today, ecological information is available for most keystone species of marine environments, but we lack information on the genetic variability of even the most important species. There is still a requirement to resolve the genetic-structure species at the level of detail necessary to make predictions of how global and local perturbations will influence the structuring and the phylogeography of species and their populations. This knowledge is of tremendous importance for interpreting the different reactions of neighbouring individuals or colonies, living in the same environment, to perturbation – e.g., differential mass-mortality events along the Mediterranean coasts of Italy and France. We do not know whether this observed variation was caused by phenotypic plasticity or genomic differences.

In addition, most benthic organisms disperse by means of the larval phase, the adult phase being sessile or of low motility. The only way to assess the dispersal efficiency as well as the existence of auto-recruitment is through the evaluation of genetic flux. Analysis of the factors influencing the genetic structure of populations of marine taxa will explain the establishment and the evolution of patterns of biodiversity at different scales (population and species structuring), from local to European level. This will make it possible to draw sensitivity maps and to help design the boundaries of Marine Protected Areas.

Microorganism diversity

Too little is currently known about the diversity of bacteria, archae, viruses and small protists in European waters. This is mainly because the technologies used to estimated the number of species provide widely different values and have trouble detecting, quantifying and identifying rare organisms. Also, studies have been performed in very localised sites, so the study areas must be expanded using new, high-throughput technology.

Viruses are the most abundant and genetically diverse organisms in the marine environment. Although estimates of the extent of the impact of viruses on populations of important marine organisms (such as plankton organisms, for example) are still quite approximate, it is clear that they cause a significant amount of mortality. This has a significant impact on the global biological carbon pump. In addition to this role in global geochemical cycles, marine viruses also include pathogens of higher organisms, including viruses with poorly understood impacts on aquaculture.

The enormous variety of marine viruses may also represent a source of potential human diseases. Some marine caliciviruses, for example, are thought to cause disease in humans, but little is known about the potential of marine viruses to infect terrestrial organisms. An important priority for future research will be to obtain a more complete picture of the genetic diversity inherent in populations of marine viruses. These studies should be coupled with functional analyses that will enable a better understanding of their impact on ecosystems and, indirectly, on geochemical cycles.

Marine biotechnology

Sustainable exploitation of the marine environment, and bio-prospecting

A major challenge in the field of marine biotechnology is to develop an efficient procedure and structure for the discovery of novel biomolecules in the marine environment. The high level of biodiversity of marine organisms makes them a prime target for bio-prospecting: a wide range of novel biomolecules are produced by these organisms, ranging from bioactive molecules and enzymes of interest for medicine to biopolymers with diverse industrial applications. Microbes are particularly under-sampled and have great potential, since a recent survey of proteins in the ocean has found thousands of new families with unknown functions. Some of the elements necessary to efficiently exploit this resource on a European level already exist, including marine stations with extensive biological expertise and sample-collection facilities and companies with the facility to develop novel biomolecules for industrial applications.

An effort is required to couple these elements via the promotion of bioprospective analysis of marine samples and the creation of intermediate structures, such as biomolecule collections and screening facilities, to bridge the gap between the biologists and their potential industrial partners.

Secondary metabolites, chemical biodiversity and biodiversity

Biochemical studies on marine organisms are very important, not only for the discovery of new drugs and biological tools, but also for better comprehension of ecosystems and, hence, better management of biodiversity. However, during the last twenty years, the study of the chemistry of natural products from biodiversity became dominated by the search for active molecules directed towards drug production. This bias has sometimes side-tracked the scientific investigation of chemical effects and reduced the potential for this approach to solve crucial questions in areas such as:- examination of the interactions between species; chemical indications of environmental variation; understanding biodiversity at the molecular scale, and comprehending the molecular reactivity and its impact on biological functions.

The challenge for the next ten years will be to explore the significance of the variation in rates of metabolite production in model organisms, including microbes, in terms of interaction with the environment and of response to environmental changes (climatic, pollution, exceptional phenomena). To achieve this goal, it will be necessary to study the role of the bioactive molecules within communities, their roles in inter/intra-specific competition for space and resources, and their role in defence against predators and pathogens. This will promote parallel studies in taxonomy, phylogeny, phylogeography and chemistry and clarify the link between biodiversity and chemodiversity.

Model development

In many areas of research, modelling is proving very effective, particularly with respect to slowly developing and predictable systems. However, in a period of rapid change such as we are experiencing, irregularities are extremely important. Ecosystems are non-linear and inherently unpredictable, and we must develop models that cope with episodic and irregular events and identify trends and depict scenarios. It should be emphasised, however, that empirical data and mechanistic understanding derived from experiments are essential to underpin models, particularly where regionally-focused models are required.

Reaching the next generation

Outreach

Knowledge of marine biodiversity

Stakeholders of the coastal zone range from the very young to the very old and, as a result, constitute very different audiences. Knowledge levels of marine biodiversity vary enormously, even within a single audience. Although more than 50% of the European population lives within the coastal zone, some people rarely visit the seashore. Surveys of university undergraduate students and coastal tourists by MarBEF projects (BIOFUSE and ArctEco, respectively) showed a wide variation in how biodiversity loss and conservation in Europe were perceived and also in how willing those surveyed would be to pay to preserve biodiversity. These target groups were also used to obtain an understanding of the level of awareness of environmental issues within the community and this, in turn, helped to refine MarBEF's communication strategies.

Awareness and perception of marine biodiversity and the surrounding issues vary enormously across communities.

Awareness and understanding of marine biodiversity issues should not be confined to the scientific community. Promoting and developing interest, awareness and 'ownership' of marine biodiversity should also be focused on the non-scientist. Marine biodiversity issues are appreciated by a much wider audience than the scientific community, though unfortunately the information conveyed through the media is frequently limited to pollution incidents (e.g., the *Prestige* disaster) or to specific habitats (e.g., coral reefs), although more recently the debate on climate change and its potential impacts has focused the public's attention on broader international issues.

In order to try and bridge this information gap MarBEF developed an outreach strategy to provide a structured approach to disseminating information aimed at all ages, from the very young to the very old, and all levels of knowledge.

Scientists

MarBEF scientists produced over 200 high quality peer-reviewed science papers during the MarBEF project and continue to produce papers beyond its lifetime. Scientific research results were disseminated through presentations and posters at scientific conferences and meetings worldwide. Individual research projects each had their own website, giving both the researchers involved and the scientific community at large greater accessibility.

A biannual newsletter was produced by the outreach team and this acted as a dissemination tool, not just to those in the MarBEF network but also to the wider marine community in Europe. The newsletter was distributed to a broad audience of marine scientists, science communicators, environmental managers and policymakers. As the readership was so wide, articles were written in an interesting manner that grabbed the attention and the understanding of the non-specialist reader.

Over 8,000 copies of the MarBEF newsletter were distributed worldwide and in excess of 9,300 were downloaded from the website.

Promoting both the network of excellence and marine biodiversity and ecosystem function to the European non-scientist was addressed in numerous ways, including dedicated outreach web pages on the MarBEF website.

The general public

With the rapid advances in communications technology, people now venture to the internet rather than libraries to get their questions answered. Therefore, MarBEF ensured that there

Monitoring the rocky shores in Portugal during a Spring School in which thirty-five high school students and researchers from five countries participated.

was easy access to information on marine biodiversity on the outreach website including a 'what's new?' section which was regularly updated with compelling stories and novel, stimulating material on marine biodiversity for the general public from a variety of sources. Frequently asked questions on marine biodiversity were answered and information on the opportunities to become actively involved or to find out more about marine biodiversity were given. Relying on people to find out for themselves was not enough: MarBEF also went out to meet the public by participating in a number of roadshows. These included a Bioblitz in Poland [explain], the British Science Association festival in Dublin and the UK, and the World Conference in Valencia, which had a week of public outreach on marine biodiversity.

Students

A number of desk studies were carried out to identify what information was already available in terms of marine biodiversity education. Two review papers on European school languages and science policies and existing marine biodiversity websites in Europe resulted and are available on the outreach pages. Unfortunately, the reviews highlighted the lack of educational material on marine biodiversity being taught in schools throughout Europe and secondly the lack of resources for teachers on the topic.

A fun approach to dissemination of resources was undertaken, particularly when targeting the very young ages. Resources included drawing competitions, games, puzzles and activities. Educational organisations and students were the primary target of the activity sheets, which also had a fun element. The activity sheets contained sustainable material covering the basic concepts in marine biodiversity. Here, the information was tailored to specific age categories, made easily accessible in pdf format and, for the younger age categories (<12yrs), provided in five European languages (Polish, Norwegian, Spanish, Finnish and English).

MarBEF identified a lack of educational material on marine biodiversity and produced freely downloadable resources in the form of activity sheets.

MarBEF produced an online paper, using the curriculum in Ireland as a case study, to illustrate how marine biodiversity topics could, potentially, be introduced quite simply to a curriculum. It is clear that the education curriculum is only the starting point or platform which teachers use to educate their students. However, from this platform teachers must engage their students by setting suitable learning challenges while taking into consideration the diverse learning needs and any potential barriers to learning by the students.

MarBEF illustrated how marine biodiversity can be introduced into the school curriculum.

A Marine Biodiversity Wiki (online encyclopedia) was developed under the banner of MarBEF and is linked in depth with the Coastal Wiki information pages in order to avoid duplication of articles. There are currently over 100 articles on a variety of topics directly related to marine biodiversity on the Wiki. This can be searched by the public but only registered MarBEF members can edit the articles, ensuring that they are of a high scientific quality.

A Wiki was launched by MarBEF to encourage scientists to communicate directly with the public by sharing information on their research.

Europe has an existing network of high quality research institutions operating in all the European regional seas. Many institutions have an outreach and education programme operating in isolation and linked to current research of the organization. MarBEF provided the opportunity to bring the educational activities together to share ideas and best practice, provide a common European monitoring resource and enthuse the younger generation in the marine science of European seas while providing opportunities for cultural exchanges. This European network started with a pilot project, MoBIDiC (European Education Marine Monitoring Network) or, in other words, "the school goes to the beach" (see also, www.marbef.org/mobidic).

MoBIDiC is engaging students across Europe in marine biodiversity research and monitoring, using established research institutions.

MoBIDiC is now operating regularly in Portugal with ten schools and three volunteer groups with a biannual monitoring exercise and several other projects. Periodic monitoring exercises are performed by young students and their teachers under the supervision of researchers. Data obtained is stored in a database open to the public. This allows students to compare data from different places and different years. The first "spring school" was held in Porto in 2009. This workshop was attended by 35 high school students and researchers from five countries. Different field and laboratory protocols were used and compared and there was a lively discussion on what should and could be achieved in a European network of students for marine biodiversity. The results from this workshop were used to continue to build this network beyond MarBEF and to continue to encourage the exchange of young students. Other existing monitoring projects with schools and volunteers connected with MarBEF institutions are also integrating to increase the European network.

© Isabel Sousa de Pinta

Identifying flora and fauna as part of a monitoring programme established by MoBIDiC (the European Education Marine Monitoring Network).

Training and education

A key product of MarBEF is the new generation of professional marine ecosystem scientists trained and now carrying out research in Europe. MarBEF's research programme identified a set of high priority research topics which required support at the postgraduate level (postdoctoral fellowships and doctoral studentships). The work of all doctoral students was supervised by an international panel, and each student carried out research at a minimum of two different MarBEF institutions based in different countries.

Postdocs and PhD students collaborated with MarBEF scientists to help resolve the many questions surrounding marine biodiversity and ecosystem functioning.

MarBEF also assessed the demand for highly specialized training courses, and during the lifetime of MarBEF thirty specialised training courses were organised by MarBEF members (Fig x?). Integration of this local knowledge and expertise within Europe on several marine biodiversity topics and cutting-edge technologies was provided in order to help to prepare a new generation of professional marine scientists for Europe. These training courses covered topics ranging from species diversity (e.g., phytoplankton) to genetics (e.g., genetic fingerprinting).

Short-term sabbaticals

MarBEF recognised that direct personal training, debate and discussion is vital for the progress of science as well as for the communication of research results to the user communities. In order to support this, MarBEF established a system of short-term sabbaticals, i.e., research visits. This allowed technicians, students, postdocs and scientists to travel from one

Students being introduced to new techniques during the Erasmus Mundus Master of Science in Marine Biodiversity and Conservation course.

MarBEF institute to a second MarBEF institute for a period of two weeks to three months. Short-term sabbaticals were a MarBEF initiative to support integration in Europe.

The MarBEF spirit in education

During the lifetime of MarBEF the idea arose of establishing a specialised Master's programme, the Erasmus Mundus Master of Science in Marine Biodiversity and Conservation (see also, www.embc.marbef.org). The course involves six European universities (Ghent University (Belgium), which coordinates the whole programme; University of Bremen (Germany); University of the Algarve (Portugal); University Pierre et Marie Curie - Paris 006 (France); University of Oviedo (Spain), and University of Klaipèda (Lithuania)). In addition to these six universities which already have close relations with MarBEF, it was decided to also include the other MarBEF institutes, where possible, in the programme. In this way, research and education can go hand in hand. MarBEF institutes can, for example, offer thesis subjects, offer summer schools and take part in specialised courses. European Union funding has also facilitated the participation of students from outside the Europe Union.

The programme has been divided into a series of thematic modules, each containing a number of specialised courses:

- Understanding the structure and function of marine biodiversity;
- Toolbox for investigating marine biodiversity;
- Conservation and restoration of marine biodiversity.

Students must all take courses from these modules and develop a study curriculum which best fits their interests. A key feature of the Master's programme is that the students are obliged to be mobile throughout the course of the Masters, i.e., all students have to move between universities during their two-year Master's programme. After a first year in either Ghent, Bremen or Faro, they move to Paris, Oviedo or Klaipeda. In between, they have to take some extra summer school courses, and for their last semester (dedicated to thesis work), they can move again to one of the six universities or to a MarBEF institute. In this way, students learn how networking in a European context really works, and they are able to gather experiences in different European countries.

MarBEF joined forces on one of its roadshows with MarLIN, HERMES and the European Census of Marine life at the BA Festival of Science in York in the UK.

EMBC, an initiative born out of MarBEF, is helping to build the marine research capacity of the future.

MarBEF believes that by combining the research strengths present throughout Europe and beyond, and by embedding education in research, the result will be the key to providing young people with the best possible chance to become excellent researchers of the future. In this way EMBC is helping to develop the foundations of the next generation of networks of excellence.

World Conference in Valencia

MarBEF organized the first World Conference on Marine Biodiversity where all of MarBEF scientists presented their latest research results in a five-day meeting that clearly demonstrated the enormous progress in the field of marine biodiversity and ecosystem functioning over the last few years and the contribution that MarBEF has made in this field.

Nearly 600 scientists from 42 countries were present at the world conference organized by MarBEF in 2008 at the impressive venue of the City of Arts and Sciences in Valencia, Spain.

Besides giving 200 oral presentations and nearly as many posters, the participants discussed and agreed upon a Valencia Declaration for the Protection of Marine Biodiversity (see Appendices).

Scientists at the conference reviewed the current extent of understanding of marine biodiversity and its role in marine ecosystem functioning. They assessed the current and future threats and the potential mitigation strategies for conservation and regulation of marine resource and defined the future research priorities.

Some of the research highlights of the Conference

A rapid, climate change-induced northern migration of invasive marine species was one of many research results announced during the opening day of presentations. Investigators reported that invasive species of seaweed were spreading at a rate of 50km per decade, a distance far greater than that covered by invasive terrestrial plants, and that this difference may be due to the rapid dispersion of seaweed propagules (e.g., seeds) in the ocean.

Rapid advances have been made in deep-sea research capability, thanks to technical developments such as customised submarines, remotely operated vehicles (ROV) and autonomous vehicles (AUV). These have enabled study of hydrothermal vents or submarine volcanoes first discovered in 1977. Researchers have described more than 500 hydrothermic vent species, most of them endemic, as well as 200 cold-water seep species and 400 morphological species of chemosynthethic ecosystems which form on the carcasses of whales. For instance, on the mud volcanoes in the Cadiz gulf, thirteen new species of polychaetes (marine worms) are described including a new genus, *Bobmarkeya (k or l?),* which owing to its characteristic appearance was named after Bob Marley. These submarine volcanoes sustain high densities of fauna which, with specific adaptations, live independently of solar energy.

During the conference, the results of collaboration between more than 160 expert taxonomists on the identification and description of marine species was presented. Their goal: to complete a database before 2010 which describes all known marine life – a world registry of marine species, or WoRMS.

Researchers reported on how they are examining the genetic composition of new species of bacteria in order to identify potential genes that may be useful to the pharmaceutical industry, medicine, the production of biofuels, bioremediation, etc. There are an estimated 100 to 1,000 million species of bacteria, with only 6,000 of them having been described. Thanks to the availability of new, cheaper techniques, researchers have now begun to explore the largely undiscovered world of microbial diversity. What's more, a greater understanding of this diversity of bacteria, hidden until now, will help us to improve our understanding of the evolution of life.

A price-tag on the benefits derived from the protection of coastal ecosystems was

The MarBEF World Conference venue, the City of Arts and Sciences in Valencia, Spain.

presented. It was calculated that effective protection of 20–30% of coastal ecosystems costs between 5 and 19 billion dollars per year, but can generate benefits in terms of improving the associated fish stocks, exceeding the costs. As the actual expenses to maintain the currently unsustainable fishing industry are between 15 and 30 billion dollars per year, it was estimated that the creation of the network of Marine Protected Areas would be a more efficient way to boost the fishing industry than the direct financial assistance it now receive.

Some other exciting discoveries highlighted at the meeting were the Antarctic ancestral origins of many species of octopi; hundreds of new species found on the Mid-Atlantic Ridge at depths of 2,500 metres; the world's deepest known active hot vent near the Mid-Atlantic Ridge at 4,100 metres; a "Brittle Star City" off the coast of New Zealand with tens of millions of brittle stars living in close proximity, and a comb jelly living more than 7,000 metres depth near the Ryukyu Trench near Japan.

Other developments highlighted discoveries in previously unexplored regions of oceans, new forms of life and completely unexpected finds such as a diverse group of "giant, filamentous multi-cellular bacteria" in the eastern South Pacific.

Inspired by the sea

On the occasion of the World Conference of Marine Biodiversity, the City of Arts and Science and CSIC organized an outreach event, "The Living Sea: Marine Biodiversity Week," an imitative that encompassed a broad array of activities, parallel to the conference, to inform the general public, from children to adults, of the benefits of marine biodiversity to society and human well-being. These activities included a wide range of activities from a cycle of IMAX movies featuring marine life to music events and performances, exhibitions and colloquia on the role of marine life as a source of well-being and artistic, scientific and gastronomic inspiration.

To conclude, the World Conference on Marine Biodiversity was an enormous success and a fitting way to culminate the MarBEF project and present its findings on a world stage.

The economic force of SMEs

SMEs in marine biodiversity research

There are an estimated 23 million SMEs in Europe, employing 75 million people. For the European Union to retain and further enhance its competitiveness, the development of SMEs is essential. Encouraging innovation by enhancing investment in research activities to acquire new knowledge for growth in Europe's knowledge based economy is the key to this development.

Small and medium sized enterprises (SMEs) form the backbone of the European Union economy, contributing 65% of GDP.

Marine biodiversity research is a sector, as a whole, which has a wide diversity of SME involvement. During the MARBENA project, a precursor to the MarBEF network, a position paper was produced to examine the possible role of SMEs and large industries in marine biodiversity research (Emblow *et al.,* 2005). This paper concluded that a series of actions were needed to increase the involvement of SMEs in research networks. The MarBEF network aimed to explore these further, and established some long-term aims:

- to increase awareness of biodiversity issues within SMEs and end-users, and to identify where biodiversity research could benefit their activities
- to increase involvement of SMEs in biodiversity research in general
- to increase funding of SMEs working with biodiversity research and biodiversity applications
- to explore how SMEs can act as a mechanism for the exploitation of new and existing technologies and observing systems, in the exchange between basic research institutes and the industry.

MarBEF addressed these points through a number of targeted actions led by the two main SME partners directly involved in MarBEF, namely Ecological Consultancy Services Limited from Ireland and Akvaplan-niva from Norway. Both companies have first-hand knowledge of how SMEs operate within the marine biodiversity research sector and what the needs of SMEs and end-users of marine diversity information are.

MarBEF identified that SMEs in the marine biodiversity sector can be divided into three main categories:

- Producers, exploiters and marketers of biodiversity: mariculture, fisheries, tourism, bioprospecting, etc
- Manufacturers and developers of equipment: commercial equipment and gear for the above groups, research equipment, etc
- Research and consultancy companies: providing a service to industry and governments

SMEs within each of these categories have a need for marine biodiversity research in order to ensure their competitiveness and sustainability. Marine biodiversity research carried out for SMEs includes a diversity of research topics including: physiological studies (growth, reproduction, metabolism, feed conversion, etc); life-history studies, habitat preference and distribution of target organisms; environmental drivers influencing target organisms; studies of impacts of gear on biodiversity; biological indicators (anthropogenic impacts, climate change); ecotoxicology; biodiversity mapping and monitoring, and general applied biodiversity research.

The SME group of research and consultancy companies provide a key strategic link between research and industry. However, progress in

An Akvaplan-niva research scientist takes benthic samples near an oilrig to determine the health of the seabed.

science and technology is so rapid and involves so many fields that in general consultants find it difficult to keep abreast of developments. In fact, scientists themselves are only able to keep themselves updated in highly specialized niche areas of knowledge. Similar to consultants, scientists are, if the truth be told, not unlike the general public when something outside of their field is being discussed.

Direct involvement in a network of excellence such as MarBEF allows consultants to stay up to date and involved with the latest research and in turn to apply this knowledge to a practical setting.

Knowledge gained within a research project is, in turn, applied in areas such as environmental impact assessments (EIAs), which have become an increasingly important tool – not only to assess the environmental effects of a proposal but to aid the design with the objective of eliminating or minimising any associated environmental problems. However, the clear message appears to be that the aims and objectives of all SMEs are primarily commercial, and any activities that SMEs become involved in need to, in the long or short term, generate income. While MarBEF has been successful in attracting further SMEs as associated partners during its lifetime, the future challenge remains: how to retain and increase the number of SMEs within the European Marine Biodiversity and Ecosystem Functioning Virtual Institute (EMBEF).

MarBEF held a workshop to identify ways to improve SME participation in EU marine biodiversity research programmes and to identify obstacles and see how best these could be overcome, taking into account the specific needs of SMEs and the nature of marine biodiversity research. The workshop included representatives from the EU SME research unit, environmental consultancies, the oil and gas industry and biotourism. The outcome was a white paper outlining the opportunities for SMEs in EU marine biodiversity research. The paper summarised that, despite the encouragement from the EU in providing specific funding opportunities for SMEs, practical barriers are still particularly prevalent with a high financial risk in some cases, not to mention the administrative complexity of applying and participating.

Participation of knowledge-based SMEs in the marine biodiversity research sector is still under-represented; this is most likely due to the complexity of the field along with the challenge and unclear benefits of converting the results of participation in such projects into a marketable commodity.

References

Emblow, CS, Stel, J, Cochrane, S, Dahle, S, van Avesaath, P, Hummel, H, Heip, C, Weslawski, JM, Hendriks, I, Buchholz, F, Magni, P, Mustapha, KB, Appeltans, W, Flander-Putrle, V (2005). The market of 'supply and demand' of marine biodiversity information, and the possible role of SMEs and large industries in European marine biodiversity research. MARBENA position paper.

Building global partnerships

Joint ventures & durable integration

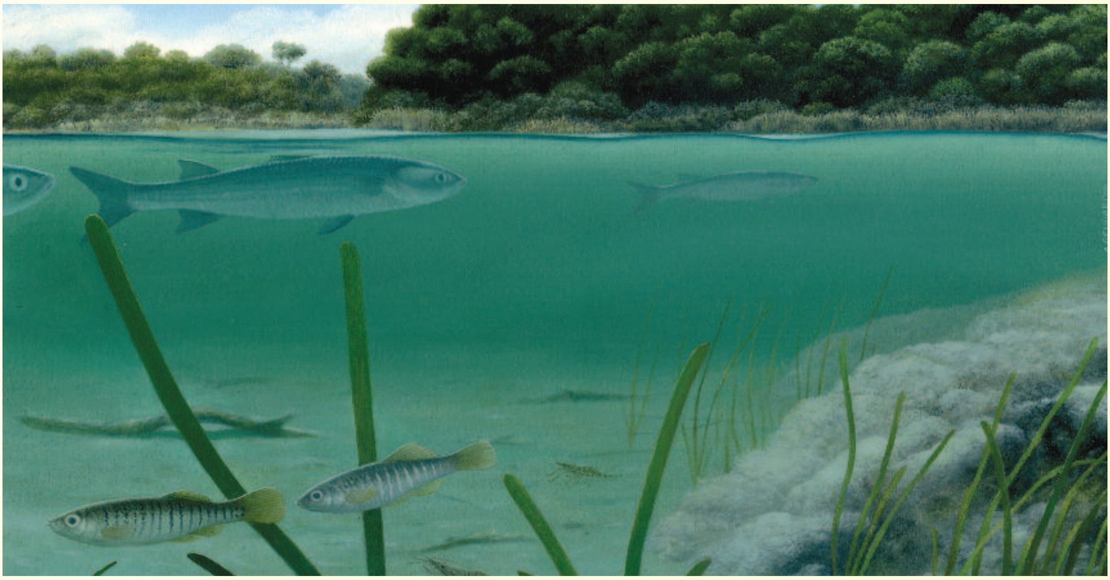
Europe has a rich history of marine biodiversity research, a history of many research institutes independently developing and accumulating expertise and knowledge at local or regional level. However, in recent years a consensus has grown that integration and co-ordination at European scale is urgently required to implement long-term and large-scale marine biodiversity research and to plan more effective use of the European research infrastructure. Many research questions cannot be addressed at local scales: they require cooperation and the establishment of a committed network of scientists and institutes.

Better integration of research is also required to support the legal obligations of the EU and its member states, and also of associated states which are signatories to the Convention for Biological Diversity and the OSPAR and Barcelona Conventions. The legal obligations include several EU directives: the Birds Directive, Habitats Directive, Water Framework Directive and the forthcoming Marine Strategy Framework Directive.

Such integration could also provide improved links and resources to the large and growing number of industries dependent on the sustainable use and exploitation of marine biodiversity. These include existing tourism, fisheries and aquaculture industries, all of which are developing, but also new industries which are exploring and commercialising marine genetic and chemical products.

Integration of research

MarBEF adopted a phased approach to addressing its identified research priorities. Three research themes were identified, namely: Global Patterns of Marine Biodiversity Across Ecosystems; Marine Biodiversity and Ecosystem Functioning; and the Socio-economic Importance of Marine Biodiversity.
Each of these themes began with the Core Strategic Programme (CSP), the major



© Ferdinando Boero, Alberto Gennari, Fabio Tresca

Transitional waters are among the most productive environments on the planet and therefore are of particular interest for ecosystem functioning.

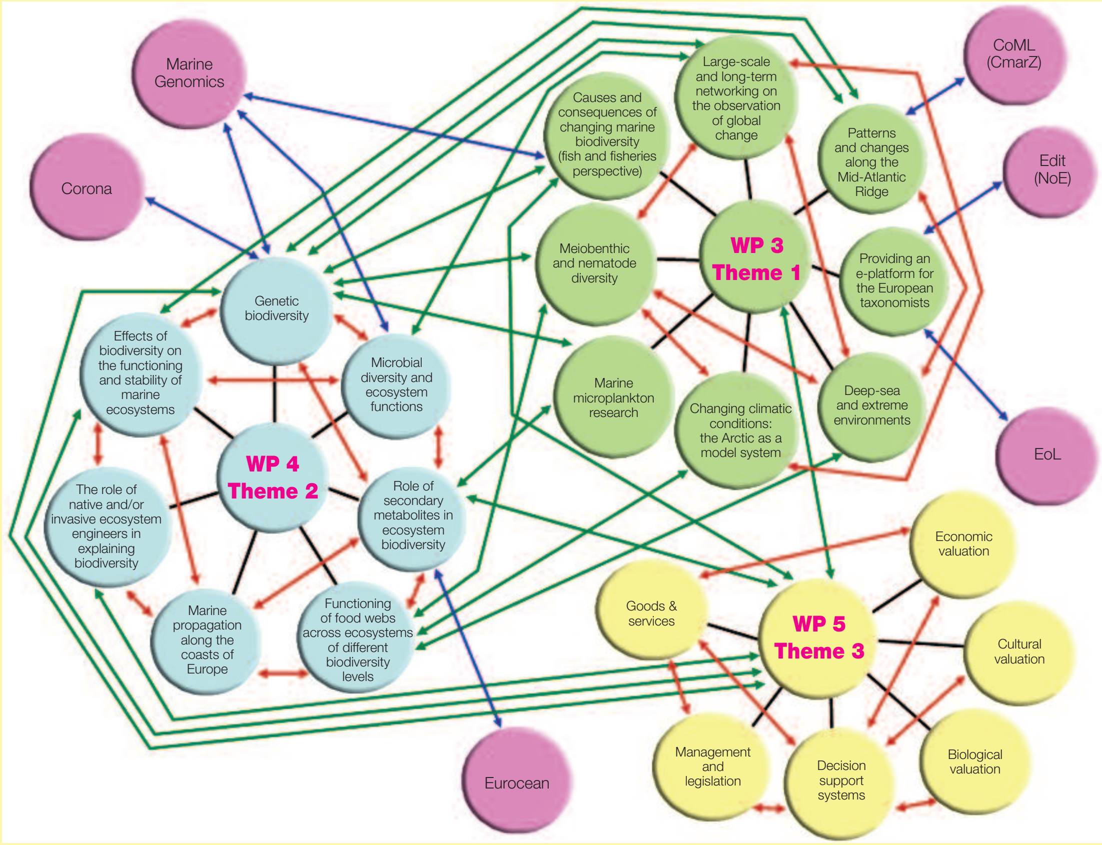


Figure 1. A schematic diagram indicating the pathways of cooperation and integration between the scientific research sections of MarBEF that developed during the project. This process is highly dynamic and new linkages are constantly being formed. Red lines (red line) signify integration between research groups (RMPs) but within scientific themes. Green lines (green line) signify integration between scientific themes. Blue lines (blue line) signify integration with organisations other than MarBEF.

integration activity for joint research, i.e., Spatial and Temporal Patterns in European Marine Biodiversity; Comparative Analysis of Marine Biodiversity and Ecosystem Functionality; and Valuation of Marine Biodiversity and Marine Ecosystem Management. The CSP engaged a large proportion of the MarBEF members and guaranteed that MarBEF focused on and devoted major resources to meeting the priority objectives and deliverables.

In the second year, this top-down approach was combined with a bottom-up approach where key areas for responsive action were identified and Responsive Mode Projects established, including some outstanding smaller-scale projects. The areas of research were particularly relevant to MarBEF's objectives and, combined with the Core Strategic Programme (CSP), provided a more comprehensive research result for each of the three programme themes.

In the third year, both the CSP and RMP programmes identified many different issues of importance to marine biodiversity and obtained concrete results. It became clear that all should be further combined and integrated to better increase our understanding of marine biodiversity, and so it was agreed to combine the findings.

Synergy: two plus two makes five!

The MarBEF programme began with 56 partner institutes, but by the time of its completion five years later the number had increased to 95 institutes. With this large community of scientists it was only to be expected that the products of MarBEF would be extensive – but has this association produced value beyond the simple amalgamation of these groups? Synergy occurs where the addition of two or more values results in products greater than the sum of their parts – *where two plus two really can equal five!* In research terms, this often happens when scientists experienced in a particular discipline interact with colleagues with different experience to approach a problem in a new way. This multi-disciplinary approach provides many new and often unpredicted results which would not be possible without this new combination of skills. One of the greatest achievements of MarBEF has been to provide a platform on which these new synergies can take place (Fig. 2).

Many of the highlights described in this publication are the results of new cooperative effort, and they demonstrate the success of MarBEF in expanding our knowledge of marine biodiversity issues. One example is the collaboration between biodiversity experimentalists and molecular scientists: this is now providing information on the biodiversity of assemblages and systems which was, until recently, beyond our experience. Scientists working on specialist habitats such as seagrass beds, deep-sea sediments and the water column can ask molecular biologists about the diversity of the bacterial assemblages or even search for important functional attributes of the communities, such as nitrogen fixing capability or stress proteins. Metabolic pathways can then be linked with system dynamics, resilience and even the response to external stressors such as climate change.

Thus, the synergistic relationships within MarBEF's large, integrative scientific programmes have provided added value for the community at large.

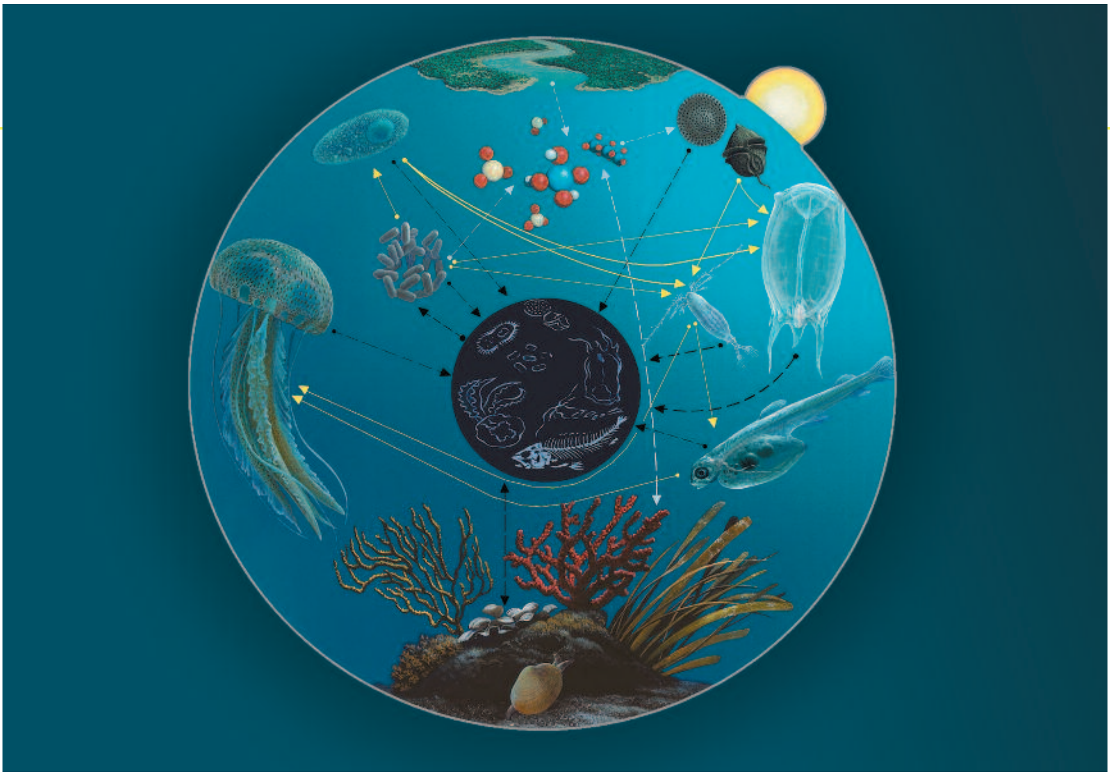
Working together

Communication and sharing of data and ideas between research institutes on such a large scale poses many logistical difficulties. Of great importance to MarBEF has been the strong ethos of cooperation and sharing, built on an early formal agreement between all participants. This agreement deals with data sharing and provenances, the real currency of science. Thus, a clear basis for integration between scientists has been promoted from the start.

There are many examples across MarBEF, but one perhaps stands out. The integration of social, economic and natural science research under MarBEF Theme 3 (The Socio-economic Importance of Marine Biodiversity) was critical to the wider impact of the project. Experts were encouraged to work in an interdisciplinary manner and the majority had never met or worked with each other before.

The first eighteen months of their time was spent initiating activities to discover common ground and common language – which is not a trivial matter between the disciplines – and developing the research potential of this heterogeneous group of people. The amalgamation of this varied experience was used to develop new methodologies that could be applied in the marine environment and to marine biodiversity issues. Since then, progress has been impressive and Theme 3 (see also, page xx) has provided one of the strongest examples of synergism within the MarBEF project.

Further initiatives within MarBEF, such as workshops, training programmes, conference presentations and research projects, have also been designed to contribute to developing cooperative effort. Examples of different types of collaborative output have included:



© Ferdinando Boero, Alberto Gennari, Fabio Tresca

Marine ecosystems are regulated by a fundamental pathway (the microbial pathway), which recycles the organic matter deriving from the death and excrement of all living beings to produce new living matter.

- **New books,** including a new text commissioned by Oxford University Press, entitled *Marine Biodiversity Futures and Ecosystem Functioning Frameworks, Methodologies and Integration.*

- **New research,** including a proposal to study *Novel Marine Bioactive Compounds for European Industries*.

- **Policy and position papers,** such as the Aberdeen and Valencia Declarations, and a joint-theme synthesis on *The Application of the Ecosystem Approach Across Habitats.*

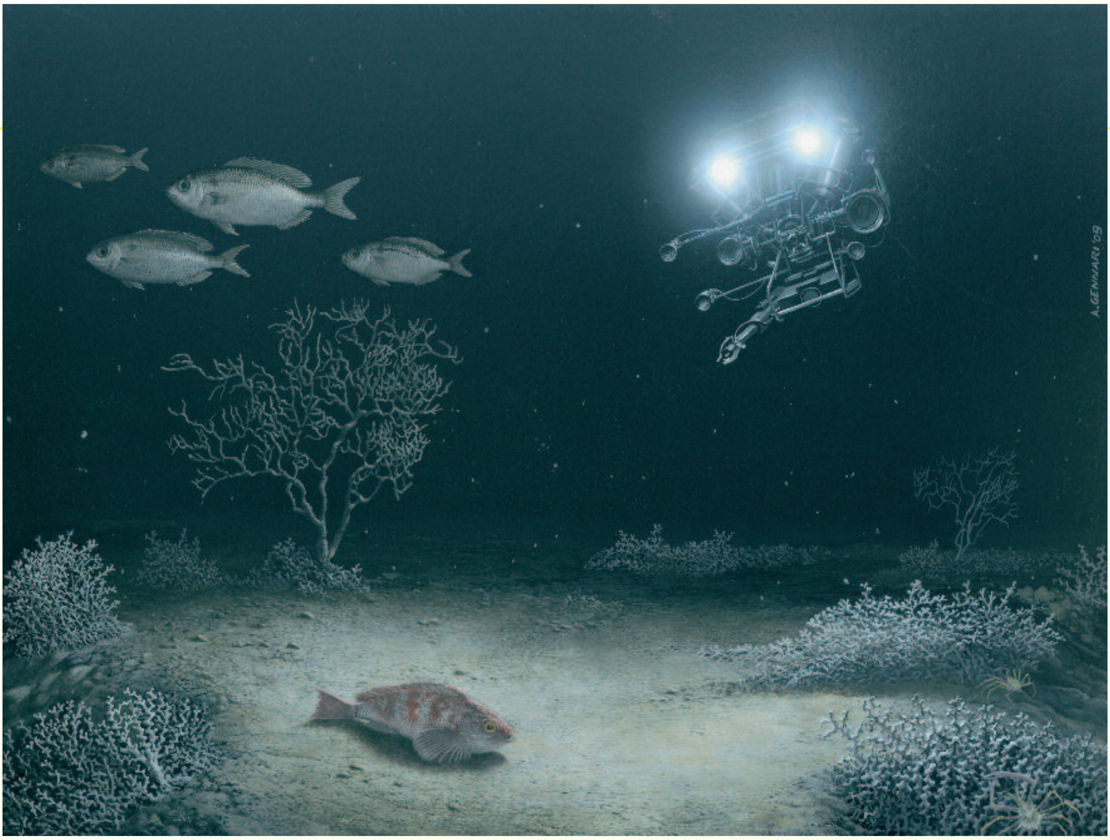
Cooperation at even higher levels, between MarBEF and other European networks of excellence, has resulted in successful lobbying of the European Parliament to contribute towards developing the EU science programme and policy.

The products

In addition to standard scientific output, MarBEF has promoted dissemination of research results, and as the network has grown, the amount and complexity of data has increased dramatically. This has been handled by a dedicated team of specialists serving the entire MarBEF community. In addition to their internal work, these specialists have provided an open gateway to MarBEF resources and data through web-based information. MarBEF has fully embraced the potential of the internet to provide integration, dissemination and education systems.

Future integration: beyond Framework Programme 7

The MarBEF community formulated a list of priority issues for EU Framework Programme 7 (FP7) which has been submitted to the European Commission and to the Marine Board of the European Strategy Forum (ESF). MarBEF has excellent and regular contact with its sister



White coral communities consist of seleractiniam corals that thrive in the ocean's bathyal depths (~200-4,000m). In the Atlantic Ocean, white corals are known to form complex, three-dimensional structures on the seabed that attract vast amounts of other organisms, accumulate suspended detritus, and influence the local hydrodynamic flow field.

networks Euroceans, Marine Genomics Europe (MGE) and Alternet, and has participated in their meetings. Together with Euroceans, MGE and the ERA-net Marinera, the discussion on the creation of a virtual European Institute in Marine Sciences (MarBEF+) has started in four working groups, and a first overview will be made available as a Position Paper.

In view of the 7th Framework Programme of the EU, the MarBEF community has composed a range of potential pre-proposals linked to the RMP programmes. In this frame, together with five other NoEs, MarBEF has elaborated a proposal for the European Strategy Forum on Research Infrastructures (ESFRI) to create a network of observatories and collections called LifeWatch. For the foundation of LifeWatch, a proposal will be submitted to the first call from FP7.

MarBEF members have also contributed to the discussion on the Green Paper on the future Maritime Strategy of the EC.

Appendices

Appendix I

Declaration of Mutual Understanding for Data Sharing within MarBEF Theme 1

This text declares the principles upon which the rules for sharing data within MarBEF Theme 1 are based. The text has been developed during a number of meetings in the context of the MarBEF Network of Excellence and with the assistance of Partners outside the MarBEF community. It provides a solid basis of trust among MarBEF and non-MarBEF Partners for data-sharing.

The first attempt to perform 'try out' methods on existing large-scale data was the Oslo Meeting (15-18/03/2005). The meeting held in Oslo was a small workshop with invited specialists to quality-control the database and to try out initial analyses to check the performance and usability of the database. The database from the Oslo workshop consists of a large set of quantitative data on benthic macrofauna which ranges from the Arctic to the eastern Mediterranean, with all sample sites geo-referenced in a GIS system.

In October (24-28), an open workshop will be held in Crete to discuss spatial patterns. We are planning to have half of the workshop devoted to analyses of the new database, and half to presentations and discussions of spatial patterns of diversity. Analyses of data will be carried out at two levels: a) over large biogeographical areas across Europe, species inventories and schemes of phylogenetic relatedness, and b) information on environmental and biological variables, will be analysed in order to derive relationships between species diversity patterns and associated environmental variables.

Results of research into patterns of marine biodiversity in space, deriving from the Oslo-Crete workshops, will be presented in a series of publications in peer-reviewed journals.

Article 1: General definitions and abbreviations

The following terms are defined as follows and apply to the whole document:

1.1 **Declaration of Mutual Understanding (DMU):** The present document, through which the general rules for sharing data among MarBEF and non-MarBEF Partners in the course of Theme 1 are set out.

1.2 **Data Providers (DPs):** Individuals, Institutions or Academic Establishments, which are willing to provide Data Sets for the needs of the Marine Biodiversity and Ecosystem Functioning (MarBEF) Network of Excellence (NoE), and share the mutual benefits that may accrue from these Data Sets.

1.3 **Dataset(s) (DS(s)):** Any sequence of data, which can be used for biodiversity studies.

1.4 **DB (DB):** The single electronic system including all the existing information within the DSs.

1.5 **Core Strategic Program (CSP):** Common activities carried out in the course of the MarBEF life, for each Work Package, as described in the Description of Work (DOW) part of the Project.

1.6 **Responsive Mode Proposals (RMPs):** Activities in the course of specifically targeted Projects, which allow MarBEF to achieve the deliverables and the scientific excellence, as described in the DOW.

1.7 **Theme Leaders (TLs):** The Leaders of the respective Themes, as described in the MarBEF DOW and the minutes of the Scientific Steering Committee (SSC).

1.8 **Data Task Force (DTF):** The Committee of persons charged with the collection of DSs from MarBEF and non-MarBEF Partners (individuals, institutions or academic establishments) for the achievement of the deliverables of Theme 1 and the communication and implementation of the DMU to all interested parties *(see also Annex 1)*.

1.9 **Quality Control; Quality Assurance (QC; QA) activities:** All activities aiming at amending the DSs provided by the DPs in order to improve and safeguard their scientific quality and reliability. This will include comparing the DSs against standard lists for taxonomy, geography and methodology.

Article 2: Data collection and storage

2.1 Collection and storage of DSs will be carried out through the MarBEF Data Management Work Package. CSP or RMPs should not collect DSs for Theme 1, independently.

2.2 Potential DPs will be contacted and informed about the data collection only by the DTF members. Information on the hypotheses already set by MarBEF Partners *(see Annex 2)* and on the various working groups is also provided by the DTF. DPs are encouraged to join and assist the working groups both in data analyses and interpretation, and to propose potential original hypotheses to be tested.

2.3 DPs are requested to deliver DSs, which will assist MarBEF in making assessments of Patterns of Marine Biodiversity across Europe, as described in Theme 1. Potential DPs will be clearly informed as to the requirements of the DSs. To what extent DSs can assist MarBEF objectives is an interactive procedure between the DPs and the DTF.

2.4 Any proposed DS is evaluated and accepted, accordingly, by the DTF members as valid for the Theme 1 analyses. Decision on the acceptance of a DS is irrevocable and implies its incorporation in the subsequent analyses and the co-authorship in all written scientific documents to be produced each time that this DS is used.

2.5 DSs are stored in the MarBEF DB but remain as a property of DPs unless they decide to have their DSs freely accessible on the web. However, meta-data (e.g., information on the location of the stations and sampling details, details of the DP, etc) will be freely accessible on the MarBEF web site.

Article 3: Rules

3.1 DPs are obliged to sign electronically the DMU on MarBEF web site, once their DSs are delivered and accepted, as valid for the purposes of Theme 1. This automatically implies acceptance of the full text of the current DMU and their willingness to act in the context of the DMU, both scientifically and ethically. Co-authorship in all scientific documents in which the MarBEF NoE has made use of these DSs is an irrevocable result, once the DPs have signed the DMU.

3.2 The MarBEF Data Manager undertakes the task of performing QA-QC procedures, to collate the DSs into a single DB and to publish the meta-data on the MarBEF web site. He also delivers the DB back to all DPs at least two months before the workshop in Crete.

3.3 All DPs have the right to perform analyses on the DB, by joining the working groups. Any of the DPs willing to test additional and original hypotheses may be allowed to do so under the condition that s/he informs the DTF.

3.4 No DP has the right to focus his/her analyses on a specific geographic area, as the corresponding DSs may constitute scientific material for on-going Theses, Dissertations and scientific publications, unless this area is exclusively addressed by his/her own DS. However, any kind of mutual collaboration may be allowed after the workshop in Crete, provided that the involved DPs agree to this procedure.

3.5 All DPs are invited to the Workshop in Crete, along with the Theme Leaders and the members of DTF.

3.6 During the Crete Workshop all results from the analyses, as performed by the working groups, will be communicated to all DPs and discussed. Additionally, any potential new hypothesis and corresponding analysis will be communicated and discussed.

3.7 Details on the scientific peer-reviewed publications will be discussed during the Crete Workshop.

3.8 Any violations of the Articles of the DMU detected will be assessed by the DTF and submitted to the MarBEF SSC. The SSC is obliged to discuss these issues on a case-by-case basis and act according to the MarBEF Consortium Agreement and to the relevant EU legislation.

Annex 1: Data Task Force

A Data Task Force (DTF) has been established during the 2nd MarBEF General Assembly meeting in Porto (21-23/03/2005). The DTF has the responsibility for communicating this DMU to the MarBEF and non-MarBEF potential DPs and for communicating the scientific and ethical aspects resulting from the relevant activities. DTF is compulsorily working closely with the MarBEF Theme 1 Leaders (John S. Gray, Friedrich Buchholz).

The DTF consists of the following members of the MarBEF NoE:

1. Dr. Christos Arvanitidis, HCMR, Greece
2. Dr. Anne-Lise Fleddum, UiO, Norway
3. Dr. Ward Appeltans, VLIZ, Belgium
4. Prof. Herman Hummel, NIOO, The Netherlands
5. Dr. Paul J. Somerfield, PML, UK
6. Dr. Doris Schiedek, IOW, Germany
7. Dr. Jean Marcin Weslavsky, IOPAS, Poland
8. Dr. Salve Dahle, Akvaplan-niva, Norway
9. Dr. Antoine Gremare, CNRS-LOB, France
10. Prof. Ferdinando Boero, UNILE, Italy

MarBEF Theme 1 Leaders:

Prof. John S. Gray, UiO, Norway
Dr. Friedrich Buchholz, AWI, Gremany

Annex 2: Working groups and hypotheses to be tested at a pan-European scale

A number of preliminary working groups on specific hypotheses have been established during the Oslo meeting. Other MarBEF partners are most welcome to join these groups. These hypotheses are strictly coupled with the objectives and the deliverables of Theme 1 of MarBEF.

Modelling/Analyses of Patterns Group: John Gray, Peter Herman, Karl Ugland, Anders Bjørgeseter

Taxonomic Distinctness Group: Paul J. Somerfield, Christos D. Arvanitidis

Functional Diversity Group: Annelise Fleddum, Dave Rafaelli, Frode Olsgard, Kari Ellingsen

Appropriate questions and/or hypotheses to test:

1. Relationship between numbers of species and system functioning. How do functional characteristics vary in different areas? What are the number of species within different functional groups, and how do they vary over European waters?

2. Are there differences between offshore and coastal benthic assemblages in structure and functional processes?

3. What are the relationships between functional traits and productivity?

4. How do major water masses (e.g., Arctic, Mediterranean, etc) influence benthic diversity?

5. Are there spatial and temporal correlations in assemblage structure?

6. How are local and regional species pools defined in a European marine context?

7. How do species abundance patterns vary across geographical areas? Species:area relationships in European soft-sediment assemblages in relation to scale/extent and in relation to traits (e.g., larval modes)?

8. What are the range-size estimates for marine species across Europe (we do not have many for European marine soft-sediment species)?

9. Is the biodiversity of the Arctic really lower than that at lower latitudes?

10. Are there differences in structure between marine and terrestrial/freshwater systems? (This will need collaboration with terrestrial ecologists.)

Appendix II

The Valencia Declaration

A Plea for the Protection of Marine Biodiversity

Recognising the fundamental importance of marine biodiversity to human well-being,

Concerned that the convergence of global environmental pressures pose critical threats to the sustainability of marine biodiversity in the oceans,

Acknowledging efforts by many agencies to give increased attention to marine biodiversity, but aware that the current pace of efforts to protect marine biodiversity is insufficient,

We, the community of scientists engaged in research relevant to marine biodiversity and ecosystem functioning and ocean management, gathered in the City of Arts and Sciences of Valencia, Spain, at the World Congress of Marine Biodiversity, November 2008, agree, on the basis of the overwhelming scientific evidence presented, that:

- Marine biodiversity and ecosystems are essential to the functioning of our biosphere and, hence, to human well-being
- The pace and scale of anthropogenic changes occurring in the oceans, and the impact of these changes on marine biodiversity and ecosystems, are cause for grave concern
- When effectively designed, managed and enforced, marine protected areas can deliver many ecological and socio-economic benefits as well as building the resilience of marine ecosystems in the face of increasing global pressures
- Emerging human activities, such as geo-engineering of the oceans to mitigate climate change, may deliver negative impacts to marine ecosystems
- Research efforts to explore marine biodiversity and assess its status are insufficient, lagging well behind similar effort on terrestrial biodiversity
- To be effective, networks of marine protected areas must be ecologically coherent and should be embedded in integrated ocean management frameworks that address the range of human activities and impacts, both within and beyond the protected areas
- Deep-sea ecosystems differ significantly from coastal ones, such that the dynamics of most deep-sea fish stocks are so fragile and slow to recover that they should be approached with an exceptionally high degree of precaution

We urge that:

- Integrated ocean management be put in place covering human activities impacting on marine biodiversity and ecosystems both within and beyond national jurisdiction

- Ecologically coherent networks of marine protected areas be developed at an urgent and accelerated pace based on existing scientific data and understanding

- Participative management structures be developed, where they do not exist, engaging those involved in the exploitation of marine living resources with the goal of sustainable use of marine biodiversity

- Research efforts to explore and better understand marine biodiversity be enhanced and promoted to provide the knowledge base necessary to underpin an adaptive management process

- Mechanisms be established to enhance cooperation between scientists, governments and relevant organizations to identify and protect ecologically and biologically significant areas based on the scientific criteria adopted by the Parties to the Convention on Biological Diversity for the open ocean and deep seas

- Deep-sea fisheries be authorised only where evidence has been gathered to conclusively demonstrate that a stock can be sustainably exploited in full compliance with FAO Technical Guidelines for deep-sea fishing in the high seas

- The United Nations General Assembly builds on the Law of the Sea and the Convention of Biological Diversity to achieve an international governance regime for the effective stewardship of marine areas beyond national jurisdiction and the fair and equitable use of living resources for the benefit of human kind

Background

Oceanic and coastal marine ecosystems provide a wide range of goods and services that are fundamental to continued human well-being. All ecosystem services ultimately derive from ecosystem functions – that is, the processes, products or outcomes arising from the interactions of organisms with their environment and their activities in the ecosystem. These services are provided on both the global scale – including the production of oxygen, nutrient cycles, carbon capture through photo-synthesis, and carbon sequestration via the biological pump – as well as on the regional scale, including the stabilization of coastlines, bioremediation of waste, and a variety of aesthetic and cultural uses.

In the marine realm, a lower-bound estimate of the total economic value of these ecosystem services indicates that it exceeds by at least two orders of magnitude the value of the more familiar direct extraction of goods, such as fish and other marine species. Marine biodiversity underpins the functioning of marine ecosystems and their provision of services – without biodiversity there would be no ecosystem services. Maintaining biological diversity is crucial to maintaining ecosystem resilience and thus to the continued provision of ecosystem services.

Anthropogenic impacts on the oceans are well documented. As summarised by the Secretary General of the United Nations: “The facts are clear. The world’s seas and oceans are becoming increasingly tainted by untreated waste water, airborne pollution, industrial effluent and silt from inadequately managed watersheds. Nitrogen overload from fertilizers is creating a growing number of oxygen-starved “dead zones” in coastal waters across the globe. Moreover, despite the growing reach and intensity of commercial fishing operations, total global fish catch is declining.”

These pressures and their synergistic effects cause serious threats to the functioning and viability of marine ecosystems. Moreover, they reduce their ability to adapt to new threats, such as invasive alien species, climate change and ocean acidification. Rising sea temperatures and ocean acidification are robustly predicted consequences of increasing greenhouse gases concentrations in the atmosphere and will impact on the structure and functioning of ecosystems. Climate change is emerging as a force able to deliver the coup de grâce to the ocean’s biodiversity.

However, despite wide concern over the health of marine systems and of global fisheries, less than one per cent of the oceans are currently afforded protection. Marine protected areas (MPAs) are recognised as a powerful tool to sustain the viability of marine biodiversity. Existing studies indicate that networks of well-managed MPAs can make ecosystems more resilient to external threats such as eutrophication or climate change, can protect valuable habitats, and can support species that use these habitats for feeding or breeding.

Indeed, government leaders at the World Summit on Sustainable Development (Johannesburg, 2002), the Convention on Biological Diversity (CBD) and the United Nations have committed to the establishment of MPAs consistent with international law and based on scientific information, including representative networks by 2012. In May, 2008, Parties to the CBD adopted scientific criteria for the identification of ecologically and biologically significant areas in the open ocean and deep sea beyond national jurisdiction and guidance for the development of representative MPA networks. However, despite encouraging progress such as the Northwestern Hawaiian Islands National Monument and the Phoenix Islands Protected Area, Kiribati, progress must be accelerated or the 2012 target will not be met until 2060, half a century late.

Appendix III

MarBEF research projects, data and outreach
(Further information can be found at the websites listed below)

ArctEco Biodiversity and ecosystem function under changing climatic conditions: the Arctic as a model system.
www.marbef.org/projects/arcteco/index.php

BBDO **B**ringing **B**iogeographical **D**ata **O**nline
www.marbef.org/projects/bbdo/index.php

BIOFUSE Effects of **Bio**diversity on the **Fu**nctioning and **S**tability of marine **E**cosystems: European scale comparisons
www.marbef.org/projects/biofuse/index.php

Data www.marbef.org/data/

DEEPSETS **Deep-sea** & Extreme Environments: Patterns of **S**pecies and **E**cosystem **T**ime **S**eries
www.marbef.org/projects/deepsets/index.php

Development of decision support systems
(No website)

FOODWEBIO Functioning of **Food We**bs across ecosystems of different **Bio**diversity level
www.marbef.org/projects/foodwebio/index.php

GBIRM **G**enetic **B**iodiversity
www.marbef.org/projects/gbirm/index.php

LargeNet **Large**-scale and long-term **Net**working on the observation of Global Change and its impact on Marine Biodiversity
www.marbef.org/projects/largenet/index.php

MARECO Integration of different methods to study patterns and changes in pelagic biodiversity in the open ocean along the **M**id-**A**tlantic **R**idge
(No website)

MarFish Causes and consequences of changing **mar**ine biodiversity: a **fish** and fisheries perspective
www.marbef.org/projects/marfish/index.php

MANUELA **M**eiobenthic **A**nd **N**ematode biodiversity: **U**nravelling **E**cological and **L**atitudinal **A**spects
www.marbef.org/projects/manuela/index.php

MarPace **Mar**ine **P**ropagation **A**long the **C**oasts of **E**urope
www.marbef.org/projects/settlement/index.php

MARPLAN European integration of **mar**ine micro**plan**kton research
www.marbef.org/projects/marplan/index.php

Microbial diversity and ecosystem functions: concepts, open questions and recommendations for integration of microbes into general ecological frameworks
(No website)

CoastWatch Pilot MarBEF **Coast Watch** network of students and amateurs in Europe
www.estgm.ipb.pt/~projig/mobidic/index.php

Outreach
www.marbef.org/outreach/

PROPE-taxon Web Accessible Taxonomic Expertise in MarBEF: **PRO**viding an e-**P**latform for the **E**uropean Taxonomists
www.medobis.org/prope/index.php

ROSEMEB **Ro**le of **Se**condary **Me**tabolites in Ecosystem **B**iodiversity
www.marbef.org/projects/rosemeb/index.php

The role of native and/or invasive ecosystem engineers in explaining biodiversity
(No website)

MarBEF participants

1. NIOO-CEME, Yerseke, The Netherlands
2. NHM, London, UK
3. PML, Plymouth, UK
4. UIB, Palma de Mallorca, Spain
5a. USTAN-GML, St Andrews, UK
5b. USTAN-SMRU, St Andrews, UK
6. SZN, Naples, Italy
7. VLIZ, Oostende, Belgium
8. EcoServe, Dublin, Ireland
9. NERC - SOC, Swindon, UK
10. SNG, Frankfurt am Main, Germany
11. MPIMM, Bremen, Germany
12. DOP/UAz, Portugal
13. IOPAS, Sopot, Poland
14. AWI, Bremerhaven, Germany
15. AAU, Turku, Finland
16. USOU, Southampton, UK
17. MBS, Ljubljana, Slovenia
18. DIFRES, Charlottenlund, Denmark
19. IOW, Rostock, Germany
20. ICM, Madrid, Spain
21. UG, Gent, Belgium
22. CoNISMa, Roma, Italy
23. SAHFOS, Plymouth, UK
24. UCD, Dublin, Ireland
25. IFM-GEOMAR, Kiel, Germany
26. RUG, Groningen, The Netherlands
27. CNR, Napoli, Italy
28. MHSC, Hull, UK
29. CMRS, Esbjerg, Denmark
30. APN, Tromsø, Norway
31. RIVO, Ymuiden, The Netherlands
32. CIIMAR, Porto, Portugal
33. UO, Oslo, Norway
34. KU CORPI, Klaipeda, Lithuania
35. IFREMER, Issy les Moulineaux, France
37. UvA, Amsterdam, The Netherlands
38. CEFAS, Suffolk, UK
39. IOUG, Gdansk, Poland
40. ETI, Amsterdam, The Netherlands
41. RIKZ, The Hague, The Netherlands
42. HCMR, Crete, Greece
43. MBA, Plymouth, UK
44a. CNRS-DIMAR, Marseille, France
44b. CNRS-OOB, Banyuls, France
44c. CNRS-SBR, Roscoff, France
44d. CNRS-LOV, Villefranche, France
44e. CNRS-MNHN, Paris, France
45. NATURALIS, Leiden, The Netherlands
46. UGOT, Goteborg, Sweden
47. ICIS, Maastricht, The Netherlands
48. UWB-SOS, Gwynedd, UK
49. WU, Wageningen, The Netherlands
50. UP, Pisa, Italy
51. NIOZ, Den Burg, The Netherlands
52. IMR, Bergen, Norway

Associate members

BIOGES, Canary Islands, Spain
English Nature, Peterborough, UK
MEI, Pärnu, Estonia
FIMR, Helsinki, Finland
IBSS, Crimea, Ukraine
IZOR, Split, Croatia
IO-BAS, Varna, Bulgaria
ISMAR CNR, Venice, Italy
IEO, Santander, Spain
IMC, Oristano, Italy
MSU, Moscow, Russia
NERI, Roskilde, Denmark
NIMRD, Constanta 3, România
UnivPM, Ancona, Italy
IO-RAS, Moscow, Russia
Uniovi, Oviedo, Spain
CESAM, Aveiro, Portugal
LBEM, Université de la Rochelle de Cedex, France
University of Aberdeen, UK
UTU, Turku, Finland
University of York, York, UK
ZIN RAS, St Petersburg, Russia
CRELA, L'Houmeau, France
SAMS, Oban, Scotland
UOM, Msida, Malta
ZMH, University of Hamburg, Germany
FEI, Helsinki, Finland
QUB, Belfast, UK
TCD, Dublin, Ireland
URJC, Madrid, Spain
Universidad de Cádiz, Cádiz, Spain
University of Bologna, Ravenna, Italy
UCC, Cork, Ireland
University of Kalmar, Sweden
Unicomarine Ltd, Herts, UK
FEEM, Milano, Italy
University of Padova, Italy
PUM, Ancona, Italy
ONMU, Odessa, Ukraine