HERMIONE
Hotspot Ecosystem Research and Man's Impact on European seas

Ecosystem goods and services of the deep sea

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How and why we value ecosystem goods and services, related challenges and recent developments

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Acronyms

BT	Benefits transfer
CBD	UN Convention on Biological Diversity
CWC	Cold Water Coral
DSWC	Dense Shelf Water Cascading
EEZ	Exclusive Economic Zone
ESF	Ecosystem Goods and Services Framework
FAO	United Nations Food and Agricultural Organization
GHG	Greenhouse gas
GtC	Gigatonnes of carbon
HERMES	Hotspot Ecosystem Research on the Margins of European Seas
HERMIONE	Hotspot Ecosystem Research and Man's Impact on European Seas
MA	Millennium Ecosystem Assessment
NGO	Non-Governmental Organization
RV	Revealed preferences
SP	Stated Preferences
tCO_2e	Tonne of CO_2 equivalent
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total economic value
UN	United Nations
UNEP	United Nations Environment Programme
VT	Value transfer
WTP	Willingness to Pay

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1. Introduction

The deep sea, defined as water and sea floor areas below 200 meters, comprises 90% of the biosphere, but until recently humans knew relatively little about it. Since little or no light penetrates to these depths, it had been assumed that deep-sea life was sparse. But in fact life is abundant, and highly diverse, and the ecosystems of the deep seas are very different from the uniform and desert-like plains described by pioneer expeditions. (Koslow 2007)

Though the deep sea is still relatively uncharted territory, national endeavours and international research programmes are rapidly expanding our knowledge. In Europe, projects such as HERMES have broadened our knowledge base, giving us more "in depth" knowledge of deep-sea ecosystems and their abiotic environment, a legacy which HERMIONE is continuing. For some private enterprises, no publicly funded stimulus has been necessary, and the knowledge of the deep sea and especially the sub-sea bed accumulated by oil and gas companies in particular is substantial.

As a result of this work, we now know that the deep sea and the deep marine floor form an extensive and complex system which is linked to the rest of the planet in exchanges of matter, energy and biodiversity[1], and the functioning of deep-sea ecosystems is crucial to global biogeochemical cycles (Cochonat et al 2007; Dell'Anno and Danovaro 2005, Suttle 2005 & 2007, Jørgensen and Boetius, 2007; Danovaro et al 2008a) upon which much terrestrial life, and human civilization, depends. But the deep sea is much less pristine and untouched than could be expected, considering its relative inaccessibility (van den Hove & Moreau 2007). Pressures on, and threats to, deep-sea ecosystems are increasing. And our knowledge of the deep sea remains piecemeal and partial. There are still huge knowledge gaps concerning the occurrence and functioning of deep-sea ecosystems and their precise roles in global biogeochemical cycles (Cochonat *et al.* 2007; Smith et al. 2009). The interactions between the different bio-chemical cycles, habitats, ecosystems, and species remain largely unknown. This means we know little about the resilience and vulnerabilities of the systems that provide deep-sea goods and services.

Therefore knowledge regarding the functioning of, and threats to, these deep-sea environments is important. We also need better understanding of exactly how deep-sea ecosystems function and how this supports the provision of ecosystem goods and services for humans. Measuring and valuing these functions and services is difficult, as our knowledge of goods and services, and the trade-offs among them, is highly limited (see Figure 1).

In this report we catalogue the goods and services of the deep sea as they are known today, given the degree of knowledge available regarding ecosystems and their functioning. We then explore the valuation of deep-sea goods and services and examples of values are presented. Throughout the report the questions how to and why value ecosystems goods and services and the related challenges and recent

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[1] Scientists now know of several examples of gene flow between deep and shallow, water and seafloor.

developments are discussed in a broad manner. The connections between the valuations and the governance and management of the deep sea are also discussed.

2. Theoretical framework

The approach taken in this report is grounded in frameworks of ecosystem goods and services and economic valuation methods.

2.1. Ecosystem goods and services: a (further) justification for action

In recent years, and in particular since the publication of the Millennium Ecosystem Assessment (MA 2005), there has been a strong emphasis on the theoretical and practical development of approaches based on identifying, measuring and in some cases valuing the goods and services provided by ecosystems (Costanza *et al.* 1997; Daily 1997; Boyd and Banzhaf 2007; Fisher and Turner 2008; Luck *et al.* 2009; Mace *et al.* 2009; Haines-Young *et al.* 2009). These arguments do not seek to replace ethical justifications for conservation, but rather to complement them. The concept of ecosystem services captures the dependence of human well-being on natural capital and on the flow of services it provides (Daily 1997; MA 2003; MA 2005; Turner and Daily 2008). This development has occurred alongside a progression in biodiversity science, policy and management over the last two decades, shifting from a relatively simple framing in purely conservation terms focusing mostly on species and habitats, to a framing in terms of conservation, sustainable uses and benefit sharing[2] and a more systemic approach in terms of socio-ecological systems (Young et al. 2006).

As discussed in the remainder of this report, the deep sea provides a whole array of ecosystem functions, goods and services, some of which contribute significantly to the global biogeochemical cycles, and hence to the well-being of humankind and ultimately to the suitability of planet Earth to our species. As recently as a couple of decades ago, the very existence of these services was either unknown or at best only suspected, but recent explorations and scientific advances have made us more aware of our dependency on these faraway ecosystems. Moreover, it is only in recent years that we have started directly to exploit goods from the deep to a significant level.

Increasing human populations and demands for resources, coupled with over-exploitation of many more traditional resource bases, and rapid technological advance, make further exploitation of deep seas both possible and attractive, even if it not exempt from serious risks, as illustrated by the catastrophic Deepwater Horizon oil spill in the deep waters of the gulf of Mexico in 2010.

[2] For instance, the objectives of the Convention on Biological Diversity are: *"the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources (…)"*. (CBD, Article 1)

But deep seas are often areas of limited or highly ineffective governance, in many cases lying outside national jurisdictions and potentially open to all the well-known problems of open-access resources (Gjerde 2006).

Today, to achieve both conservation and sustainable use of deep-sea ecosystems, we can – indeed we must – complement arguments based on intrinsic values and conservation ethics by more utilitarian arguments building on their usefulness. This requires more in-depth and systematic identification, qualitative description and quantitative measurements of the goods and services provided. And this is required in addition to, and as a key driver and input for, further work on improving deep-sea governance mechanisms.

Some critics of the ecosystem services framework stress that it is purely anthropocentric, putting humans at the centre of the reasoning, and that it is consequentialist, adopting an ethical stance whereby only the consequences count – services are directly or indirectly, actually or potentially influencing human welfare, with no direct consideration of the processes of delivery or the broader context.[3] It is not clear that these are really weaknesses – there is a lot to be said for an anthropocentric, consequentialist approach – but there is no need to attempt to resolve this debate in order to proceed with an ecosystem services analysis.

Our view is that the economic value of ecosystem goods and services can in some cases be used to construct a *sufficient* argument for biodiversity and ecosystem conservation, but the demonstration of the provision of valuable services can never be considered a *necessary* condition for conservation. Other arguments based on ethical positions are clearly legitimate, and can be used to promote conservation without any reference to human wellbeing or economic values. But, provided we agree that human welfare has some relevance to decision making, there can be a complementarity between analysis of ecosystem services and other approaches that argue for conservation on moral grounds (independently of any usefulness).

Even if we were to focus decisions just on economic values in a purely anthropocentric ethic (and we do not propose this), in the cases of those many aspects of biodiversity and ecosystems that do not (seem to) contribute anything useful to humans, a precautionary approach can still be justified by reference to substantial uncertainties about the relationships between diversity and resilience of systems and services, the existence of unknown thresholds, the value of functional redundancy and so on. These arguments are of course accepted by many of the main proponents of the ecosystem services framework.

So economic reasoning can be used to construct sufficient arguments for conservation, but the application of an ecosystem services framework, and *a fortiori* economic (monetary) valuation of impacts, cannot be considered necessary parts of decision making. In fact, in many spheres of political life, including environmental management, most decisions are taken without having full quantitative economic

[3] See O'Neill et al. (2008) for a discussion of these critics and more broadly of the ethical dimensions of environmental decision-making.

valuation of costs and benefits. But generally, there is wide recognition that the ecosystem services framework and environmental valuation, are useful tools for structuring and processing information for supporting the deliberative processes that are an essential component of decision making and environmental management. This is stressed in the Millennium Ecosystem Assessment, for instance: *"the [quantified] ecosystem values in this sense are only one of the bases on which decisions on ecosystem management are and should be made"* (MA, 2003, p.34).

It can also be argued that even decisions taken without explicit recognition of ecosystem service values hide implicit valuations, and that there is much to be gained from making them explicit, even if only in enhancing consistency between different decisions. Moreover, in practice the use of the framework can have profound effects, because in the absence of these heuristic structures and tools important impacts can be overlooked. Daily (1997, p365) notes that *"our primary focus here is on ecosystem service values because they are both very large and greatly underappreciated, if indeed they are recognized at all"*.

It must be acknowledged that simply recognising ecosystem services and values in the frameworks of assessment, decision-making and management can influence attitudes and behaviours. In the marine environment, and particularly in the high seas and deep seas, attitudes have in the past been split along a frontier mentality vs. preservationist dichotomy. Some actors seek to extract fish, fuels, or dispose of waste without consideration for wider environmental impacts or the long term; while others call for a strict hands-off approach to preserving these environments. This is in contrast to a more balanced approach common in terrestrial environments, where the intricate interactions between human activities and environmental quality has been more widely recognised.

One key advantage of the ecosystem services framework is its contribution to fostering greater understanding of trade-offs and a feeling of responsibility for actions with immediate and long-term consequences.

2.2. The ecosystem services framework: one component of the ecosystem approach

The governance and management of complex socio-ecological systems – by definition including both the environmental systems and the socio-economic / human cultural systems that are at the source of many pressures bearing on ecosystems – requires a 'paradigm shift' (Olsen *et al.* 2006) moving from sectoral and piecemeal tactics towards more holistic approaches. This realisation underlies current efforts at all levels to move towards ecosystem approaches to environmental management and governance.

Many definitions of the 'ecosystem approach' have been put forward. In the framework of the Convention on Biological Diversity (CBD) for instance, it is defined as: *"a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. […] It is based on the application of appropriate scientific methodologies focused on levels of biological* *organization, which encompass the essential processes, functions and interactions among organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of ecosystems."* Whatever the precise definition, the ecosystem approach is founded in the recognition of the interconnectedness of ecological processes and socio-economic processes. It is both a heuristic and a policy tool through which we endeavour to grasp the complexity of our relations to the socio-ecological system of which we are a part and attempt to render these relations more ecologically, socially and economically sustainable.

Today there is frequent confusion between the Ecosystem Approach and the ecosystem goods and services framework (ESF) (Daily 1999; MA 2003). The two are not equivalent. The ESF is an important component of an ecosystem approach, in particular as it brings the human dependency and uses into the picture, but there is far more to the ecosystem approach, in essence a mode of governance aiming to address complex socio-ecological systems in a holistic way. As such it goes beyond the reflection in terms of services provided by ecosystems and benefiting humans. It is in principle possible to apply the ecosystem approach to support a purely conservationist endeavour, independently of any ecosystem services. More generally, the ESF is only one possible way, though currently the dominant one, in which human dependence on ecosystems could be reflected in an ecosystem approach.

2.3. Biotic and abiotic resources in ecosystem services frameworks

Ecosystem services frameworks such as the MA (2005) and the UK National Ecosystem Assessment (Mace *et al.* 2009) generally focus on biotic resources and exclude purely abiotic goods such as minerals or aggregates extraction. This is also the approach taken in Beaumont *et al.* (2006) in assessing the services of the marine environment. Other frameworks however do make some recognition of abiotic factors, with CICES (Haines-Young et al. 2009) for example identifying abiotic materials and renewable abiotic energy sources (e.g. wind and wave power), but not including a category for fossil fuels. Swedish EPA (2009) also considers “space and waterways”. And many abiotic processes are included indirectly in ecosystem service frameworks, to the extent that these processes play important roles in supporting and regulating services.

In the case of the deep sea, there are certainly important abiotic features. Space for transport is not a significant issue, but space to host sea-bed pipelines and cables for telecommunications purposes is. Similarly, there is increasing interest in deep-sea oil and gas resources, in deep sea minerals, and in the scope for using areas beneath the deep seabed for injection and storage of carbon dioxide. Although these are not directly ecosystem services, they are uses of the space in ecosystems, and can compete with alternative uses and services. Also, there tends to be significant interest from business, management and policy communities in taking the values of these abiotic resources into account, and indeed in resisting a focus that is exclusively on biodiversity and services provided by the natural world.

Therefore in this report we have considered some goods and services that would not conventionally be treated as ecosystem services – notably oil, gas and minerals, but also less obvious examples such as the key role of (abiotic) dense water shelf cascading in maintaining (biotic) ecosystem productivity, and the importance of the deep seabed as a scientific record of past climate conditions. When considering the values of these goods and services, it is important to bear in mind the difference between stocks and flows of values. It is often natural to think about ecosystem goods and services in terms of flows – annual harvests of fish, annual carbon sequestration and so on. Some abiotic resources, on the other hand, may be more commonly discussed in stock terms – for example the total value of a given oil field.

Either approach may be appropriate for different purposes, but we should be careful never to add or compare stock values and flow values. We must also be careful about calculating stock values for biotic resources. The provisioning-service value of a stock of fish, for example, is not the net value of a harvested fish multiplied by the current stock: such a calculation would ignore a crucial feature of fish stocks: they reproduce. A better estimate of the value of a fish stock can be made by calculating the most profitable constant harvest that can be taken every year while keeping a stable stock capable of supporting that harvest indefinitely. Similarly, if comparing flow values, we need to keep in mind that while the flow from renewable resources (both biotic such as fish, or abiotic such as wave power) is in principle infinitely durable, any sustained flow from a non-renewable stock such as oil or gas must sooner or later exhaust the resource.

2.4. Economic valuation: part of a broader approach to assessment

The framework of ecosystem goods and services is an anthropocentric approach, based on the ways in which ecosystems contribute to human wellbeing. This blends well with the common, and equally anthropocentric, framing of environmental economics. Section 4 discusses in more detail how the ecosystem goods and services that provide several sources of value to humans can be represented in economics via the "Total Economic Value" (TEV) framework. This distinguishes among several different types of value:

- direct use, either consumptive (e.g. catching fish) or non-consumptive (recreation is a common example – of limited relevance to the deep sea, but e.g. whale watching above deep waters does take place)
- indirect use (e.g. watching film of deep-sea environments)
- option value (i.e. what it is worth paying now to maintain the option to carry out some currently unplanned activity in the uncertain future)
- non-use values, including altruistic, bequest and pure existence values.

The TEV framework is useful as a way of structuring information about values to humans, and in particular in recognising multiple sources of value, including non-material and non-selfish values.

It is worth noting that, since the concept of economic value is defined with reference to human individuals, the values are dependent on their views, tastes and preferences, and also on their knowledge. This means that if knowledge changes, values can change.

It is not always, or even generally, necessary to know about something in order for a value to exist – for example, we do not need to know exactly how the deep sea supports climate regulation in order for that service to have a value, though if we want to *measure* the value we do need the knowledge. But in many cases values can be latent/unrealised. For example, there was no value for deep-sea fish consumption before we realised there were fish to catch and started catching them. But the potential was always there. There are now deep-sea fish resources that are not currently exploited, but we cannot assume these have no value; rather, there is a latent value that may be classified either as a future use value (we plan to use the resource in future) or as an option value (we do not plan to use it, but value keeping the option open). Similarly, values may be latent because they are information-dependent. For example people will not hold non-use values for environments they do not even realise exist. A good example here is cold-water coral (CWC): until recently, we knew next to nothing about them. Now that we know more, a lot of people would agree that it is worth giving something up (for example cheaper fish or access to oil resources) in order to conserve these incredible habitats and the services they support (Armstrong & van den Hove 2008).

This can be interpreted as growing knowledge resulting in new value. And with the benefit of hindsight, we can see that past activities that have destroyed CWC and other habitats have led to loss of values that at the time we did not even know existed. There is also a substitution between different kinds of value: as our knowledge of deep-sea environments increases, there may be a reduction in value related to wonder or awe for the unknown, and an increase in value associated with marvelling at the intricacies of the natural world and our ability to decipher its secrets.

These changes in value associated with human knowledge also represent an additional motivation to and justification for research in deep-sea environments, though this is secondary to the primary justifications of better knowing these environments, better understanding the ways in which they contribute to global life support functions and recognised goods and services, and better assessing anthropogenic impacts on these environments and the underlying drivers.

2.5. Assessing and valuing ecosystem services

In Figure 1 we present an adapted version of the ecosystem goods and services pyramid presented in the interim report on 'The Economics of ecosystems and biodiversity' (TEEB 2008). The pyramid illustrates the increasing degree of non-specification as we move up the pyramid, starting from a listing of actual habitats and ecosystem goods and services, through a qualitative description of what we know regarding these services, a quantitative assessment of the goods and services, a pre-valuation review of knowledge about these goods and services, the characteristics of those who hold use and non-use values for them, any previous valuation attempts, suggested methods and priorities for valuation studies, potentially leading to monetary valuation of some ecosystem goods and services.

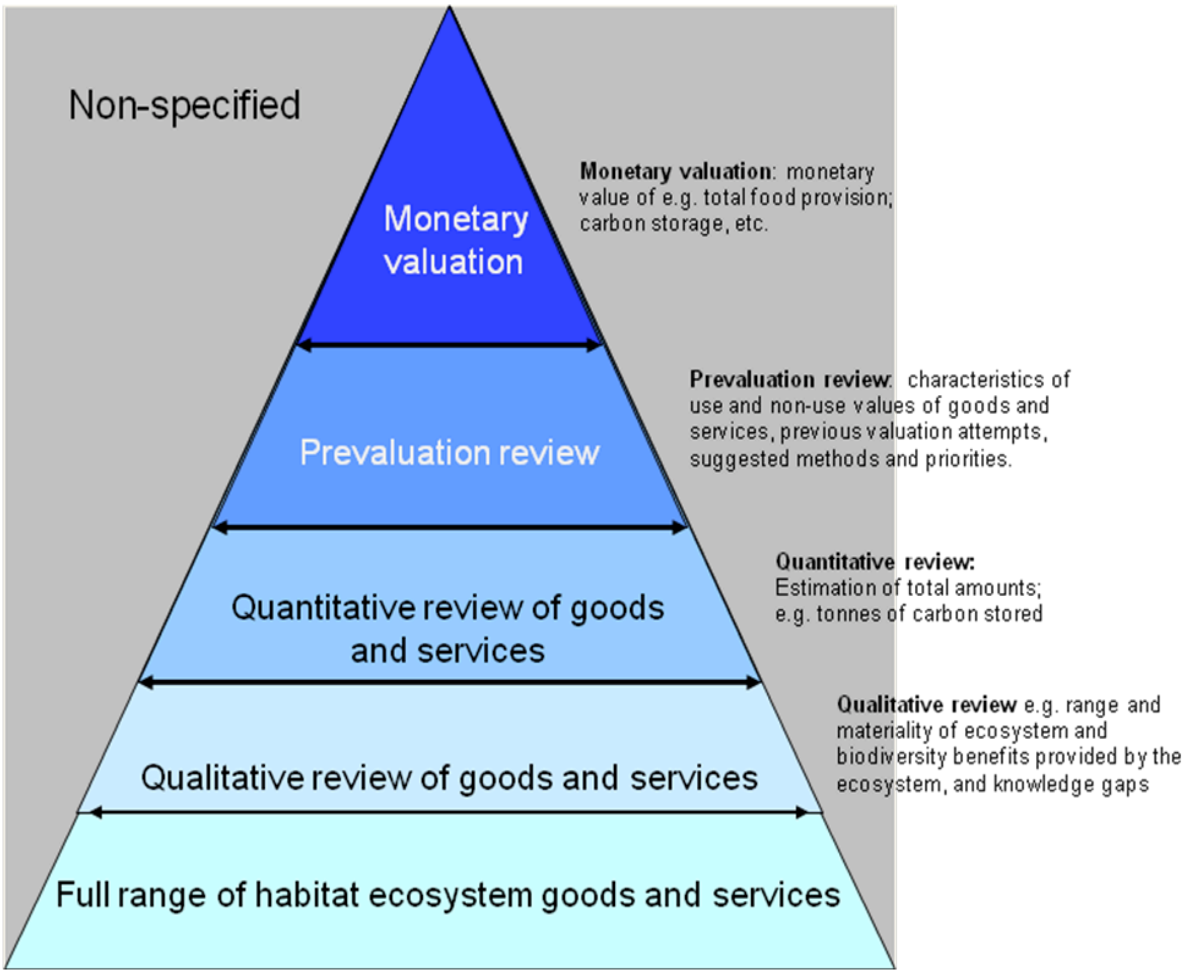


Figure 1. Identifying and valuing habitat and ecosystem goods and services – the knowledge pyramid of the deep sea (Source: adapted from TEEB 2008)

As we have only limited knowledge of deep-sea environments, at the level of identifying ecosystems we already have substantial non-specified entities. Furthermore, we do not know the extent or amount of different types of ecosystems in the deep sea, have limited understanding of their functions, and therefore we can quantitatively assess even fewer goods and services than we can identify. With regards to how we value those goods and services that are quantifiable, we know even less. Our economic tools are constrained and pose methodological problems, in particular in the context of remote environments of which most people have little or no knowledge or experience, hence the knowledge of our actual economic valuations is highly limited. Therefore, between the quantitative assessment and the monetary valuation, a pre-valuation review must be carried out, much of the kind that we are attempting in this report.

Studies of economic valuation of environmental goods and services have mainly been carried out for terrestrial regions (see e.g. Turner et al 2003). The ocean is a relatively unstudied part of our globe insofar as economic value is concerned, with the exception of fisheries and fossil fuel extraction. Valuation research on deep-sea habitat and ecosystem goods and services is particularly limited. There are a few studies that consider marine ecosystems on a broad scale, for instance the global synthesis of Costanza et al. (1997), Beaumont *et al*.'s 2008 study of UK oceans, the Baltic sea report; "What is in the Sea for me?" (Swedish EPA, 2009) and the UNEP report "Deep Sea Biodiversity and Ecosystems (van den Hove and Moreau 2007). In this report we aim to provide an overview and integration of existing knowledge about the value of deep-sea ecosystem goods and services, drawing on these earlier studies and other work.

The first step is to catalogue the ecosystem goods and services of the deep sea, following to a large degree the classification developed for the Millennium Ecosystem Assessment (MA 2005); this corresponds to identifying as much as possible on the qualitative level of Figure 1. The aim of this identification and cataloguing is to develop an overview of the many ways in which humans benefit from deep-sea ecosystems and environments, to make the role of deep-sea ecosystems more transparent and accessible, and in so doing to trigger the recognition of the wide range of potential effects on humans of the ecological responses to policies that affect that deep sea.

Moving up the pyramid (Figure 1), we discuss the quantitative side of the goods and services. Valuation of habitat and ecosystem goods and services is presented and discussed in an attempt to carry out a valuation review of the deep sea, as described further up the pyramid in Figure 1. In the process of the above, we identify the knowledge gaps both in an absolute sense, and in the sense of which gaps may most advantageously be filled.

3. Catalogue of goods and services in the deep sea

This report builds on the UNEP/HERMES report *"Deep-sea Biodiversity and Ecosystems: A scoping report on their socio-economy, governance and management"* (van den Hove and Moreau 2007) by giving a more in-depth and updated report on the deep-sea goods and services, the valuation of these, and how these values are or could potentially be accounted for in decision-making.

Following the framework of the Millennium Ecosystem Assessment (MA 2005), we classify the goods and services of the deep, with particular focus on the habitats and ecosystems studied in the HERMIONE project: canyons, seamounts, cold water corals, open slopes and basins and chemosynthetic communities on the sea-bed, as well as the water column above these ecosystems and the sub-seabed below them.

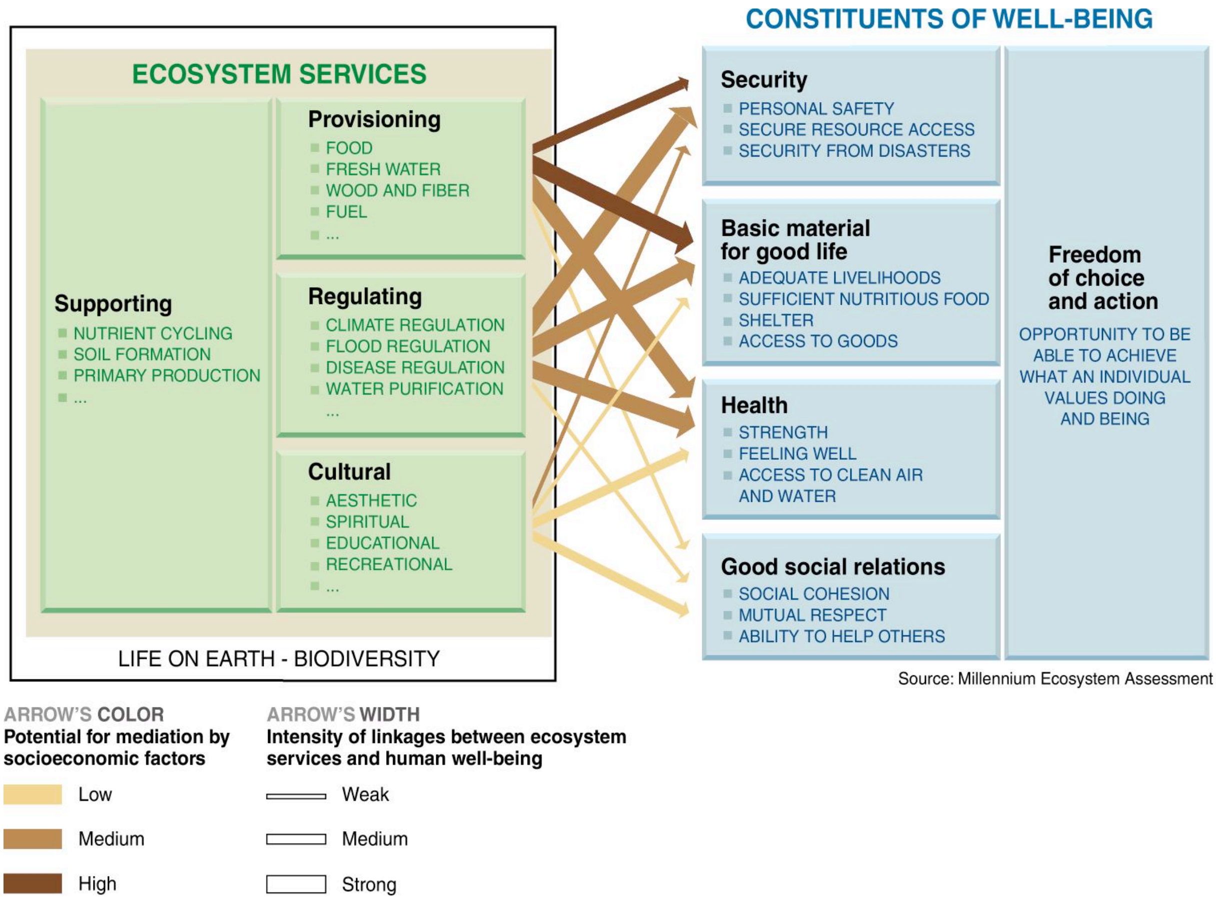


Figure 2. The Millennium Ecosystem Assessment presentation of Ecosystems goods and services. Source: MA 2005.

We follow the MA (2005) classification system, including so-called supporting services (Figure 2), rather than for instance the CICES (Haines-Young *et al.* 2009) solely focusing on provisioning, regulating and cultural services that supply benefits directly. Our reasoning is partly for presentational clarity, and partly because for the deep sea, the distance (both spatial and in some cases temporal) between the supporting services and services that give benefits directly to human well-being are substantial.

In the literature the difference between *function* and *service* is often made:

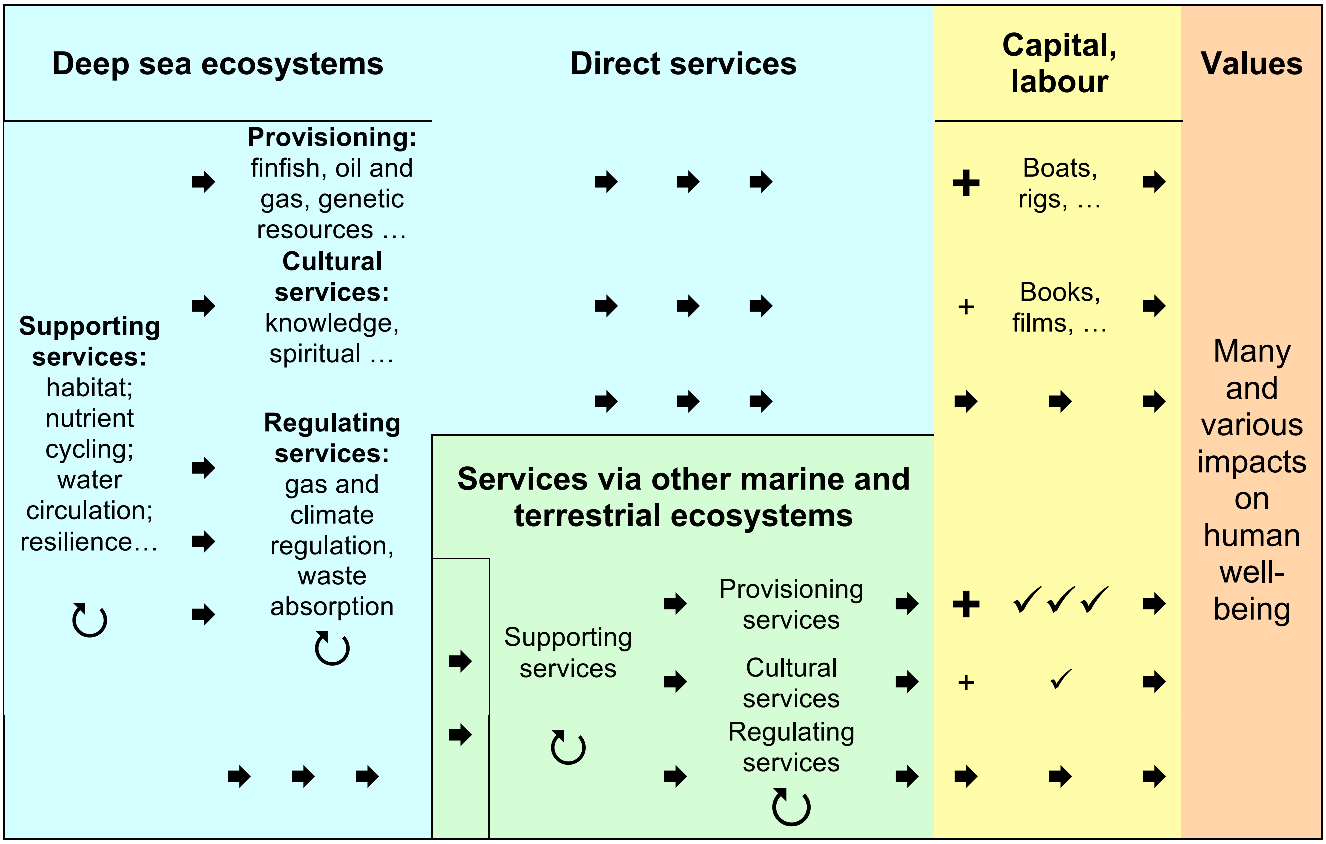
- *function* means a natural structure or process, that may generate services that ultimately provide human well-being, but that exist and can be measured independently of humans. Pacala and Kinzig (2002) distinguish three classes of ecosystem functions:
    - stocks of energy and materials (for example, biomass, genes),
    - fluxes of energy or material processing (for example, productivity, decomposition)
    - stability of rates or stocks over time (for example, resilience, predictability)
- *services* are the results of ecosystem functions that give benefits to human well-being, and they only exist as services by reference to human users of the service. They can be further divided into (see e.g. Boyd and Banzhaf 2007, Fisher and Turner 2008):
    - direct or final services: these provide direct value to human users
    - indirect or supporting services: these provide indirect value to human users, by supporting other direct/final services. Generally a supporting service is an ecosystem function, but in its role as a service it is defined with reference to the direct services it supports.

The rationale in CICES for focusing on direct services only is to avoid double-counting: since (the value of) a supporting service is defined with respect to (the value of) the final services it supports, including values for both supporting services and final services implies counting the same values twice. Avoiding this is clearly important for a comprehensive accounting framework. But there are two good reasons why it is not appropriate here.

Firstly, in order to present the role that the deep sea plays for human well-being in a transparent and accessible way, we need to describe the ecosystem functions or supporting services, and consider their importance or value. Of course we must also make the caveat, where appropriate, that the values of supporting services are only indicative of their importance to final services, and cannot be added to provisioning, regulating and cultural values.

Secondly, many of the final services supported by deep-sea functions create values distant in space or time from the deep sea. Table 1 illustrates how deep sea ecosystems support direct services to humans – often with a contribution from capital and labour, for example fishing vessels and crew – but also support services indirectly, both within the deep sea (supporting and regulating services that feed back into other deep sea services) and processed through other marine and terrestrial habitats (again with capital and labour investments). This applies, for example, to the services associated with nutrient cycling that support ecosystem services not just in the deep-sea but across the whole globe. The focus of this paper is on the deep sea, and we should not aim to consider the full values of all these other services; nor should we suggest that the whole of their value is due to deep-sea supporting services. But we should consider that some part of their value is due to the deep-sea, in particular in the important sense that these other services will be affected (change in value) if the levels of deep-sea supporting services change. Or in other words, since the values of the final services from non-deep-sea environments fall outside the boundaries of the present assessment, it would not entail double-counting to consider the values of the supporting services. Of course this conclusion is specific to this assessment: in particular, in a global assessment, that did cover all final services, it would be double-counting to include supporting services separately.

Table 1: Deep sea ecosystem services and human well-being



3.1. Supporting Services

Supporting services are those functions that are necessary for the production of all other ecosystem services, i.e. they feed into provisioning, regulating and cultural services, and thereby only enter into human well-being indirectly.[4] They differ from regulating, provisioning, and cultural services in that their impacts on people are usually indirect, both physically and temporally, whereas changes in the other categories have relatively direct impacts on people. Some services can be categorized as either a supporting or a regulating service, depending on the time scale and immediacy of their impact on people, this is the case for instance with

[4] There is an on-going (and probably endless) debate on whether supporting services would be better described as supporting functions. In our view, the key distinction is between functions that would exist on a planet devoid of humans, and services that are defined with reference to impacts on humans (albeit indirect in the case of supporting services). In this report, we are focusing on the human impacts, so we use the terms 'supporting services'.

nutrient cycling as explained below. Examples of supporting services are habitat, nutrient cycling, water circulation and exchange, primary production, and resilience.

3.1.1. Habitat

The deep sea is the largest habitat on Earth. It hosts some of the most diverse ecosystems on the planet (e.g. Koslow 2007) in a wide variety of habitats such as seamounts, cold water coral reefs, hydrothermal vents, cold seeps, submarine canyons, open slopes and basins. With such a diversity of habitats and features the seabed is thought to be home to 98% of all marine species, and more species may live in deep seabed environments than in all other marine environments combined (Gjerde 2006). The wide variety of habitats gives rise to unique organisms and life forms with amazing adaptations to these harsh environments.

Although original assumptions suggested the biodiversity of the deep sea may be low, Grassle & Maciolek (1992) proposed that the number of deep-sea species could exceed 10 million; May (1992) suggested this was nearer 500,000, but estimates as high as 100 million have been reported (Gianni 2004). These estimates do not include microbial life, which would increase these figures by at least an order of magnitude. The recent 'source-sink hypothesis' (Rex et al 2005) suggested that abyssal biodiversity is a subset of the bathyal biodiversity (in particular the biodiversity of the slopes at depths typically comprised from 1000 to 2500m). Further studies are therefore needed to understand the link and interconnection between shallow, bathyal and abyssal ecosystems. In particular these studies would be of paramount importance for planning a correct management of human interactions with deep-sea biodiversity. There is evidence that continental shelves, slopes and basin ecosystems are interconnected. The enhanced levels of biodiversity along slopes are a source for biodiversity of deeper basins and shelves, through radiation and dispersal processes, closely coupled with benthic topography and the hydrodynamic, physical and biogeochemical characteristics of the deep-sea.

The biodiversity patterns in the deep-sea reflect not only the capacity of the environment to support species' coexistence but also the historical origins and diversification of genetic clades (Ricklefs 2004). Much of the research into biodiversity over environmental gradients has concentrated on changes in species richness and evenness. However, discerning how the environment regulates species diversity requires an understanding of the variation in phenotypic properties of species, dispersal mechanisms (McClain 2004), cues for larval settlement, reproductive timing and life cycles, competition and cooperation between species and communities, physiological thresholds with regards to population distribution, as well as long-term aspects of biogeography and evolution. To understand the resilience of ecosystems, it is critical to determine the interconnection between ecosystems and their communities. The deep sea provides habitat for vertebrate and invertebrate species, including some commercially important fish and crustaceans. This high species diversity (both in terms of local "alpha" and turnover "beta" diversity) encompasses mega-, macro- and meio-fauna. Recent genetic analyses revealed a huge diversity of deep-sea organisms even at regional scale (Brandt et al. 2007), and an even higher diversity is related to the microbial biosphere (Sogin et al. 2006).

Megafauna include sea cucumbers, sea stars, brittle stars, sea urchins and crustaceans but also fish and squid. In some energy-rich habitats such as hydrothermal vents and seeps, giant tubeworms and bivalves dominate. Macrofauna consist of polychaetes and other worms, amphipods, tanaids, isopods, bivalves and gastropods, while meiofauna include nematodes, copepods, ostracods and foraminiferans (Gage and Tyler 1991; Gubbay 2002). It is thought that species diversity of deep-sea macrobenthos (organisms that live at the seafloor) rivals that of tropical rainforests and coral reefs (Gubbay 2002). The high species diversity within the deep-sea is probably a function of the unexpected habitat heterogeneity found within the deep sea. Different habitats such as cold-water corals, canyons, cold seeps, hydrothermal vents or seamounts all contribute their own biodiversity of the high overall biodiversity. Disturbances such as e.g. food fall events, cold water cascades, turbidites, contribute to the evolution of diversity. The HERMIONE project is explicitly targeting research in all of these high-diversity habitats and also includes the study of disturbance events.

The *density* of specific types of organisms is also great in some deep-sea environments. The sub-sea floor may represent the largest habitat on Earth for Bacteria and Archaea despite apparent extreme conditions of high pressure, broad temperature ranges and low energy supply (Cochonat *et al.* 2007). Deep sub-surface microbial habitat may account for greater than 90% of the global biomass of Bacteria and Archaea (Head, Jones and Larter 2003). Viruses are the most abundant biological entities of the world's oceans and their production in deep-sea benthic ecosystems worldwide is extremely high and responsible for the abatement of 80% of bacterial heterotrophic[5] production (Danovaro et al 2008a). Viruses play an important role in global biogeochemical cycles, in deep-sea metabolism and the overall functioning of the largest ecosystem of our biosphere. At the same time viruses, through their infection and lysis of the host cells can contribute to gene exchange and to promote the evolution of deep-sea organisms. (ibid.)

Box 1 Example of Supporting Service: Cold Water Coral (CWC) Habitat

Biotic supporting services refer to the functional values associated with CWC reef biodiversity and the role of CWC as an essential fish habitat in supporting specific fisheries. For example, coral grounds appear to act as a habitat for many species; including fish of commercial value. The branches of corals act as a refuge for many deep-water species species and are populated by distinct microbial communities. Invertebrates such as brittle stars, sea stars and feathery crinoids live directly on the coral colonies, and smaller animals burrow into the skeletons.

Deep-water coral reefs coincide with areas where higher concentrations of fish can be targeted. Fishermen have observed that more fish are located in coral areas than adjacent areas. Redfish (Sebastes) are found in high abundance in *Lophelia* reef areas. Aggregations of orange roughy are also found in deep water coral environments. Demersal species such as ling and tusk appear to be more common around corals than on the surrounding seabed. The ivory tree coral, *Oculina varicosa*, located off the coast of Florida was found to be associated with grouper, snapper and amberjack and Koenig (2001) observed a relationship between grouper, snapper, sea bass, and amberjack and the health (dead, sparse and intact) of Oculina colonies. Oculina reefs off Florida have been identified as essential fish habitat for federally-managed species, as have gorgonian-dominated deep coral communities off Alaska. Studies by Fosså et al. (2002; 2005) and Husebø et al. (2002) found that

[5] Heterotrophs are organisms that use organic carbon as a carbon source, in contrast to autotrophs (e.g. plants) that use inorganic carbon.

there was a greater abundance of species in coral areas than in non-coral areas. There are possibilities that coral grounds act as spawning grounds and nurseries to juvenile fish; this evidence is however inconclusive.

Much attention has recently been given to what has been coined essential fish habitat (EFH). EFH is defined as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity”. Though definitive results are not yet available the research so far indicates that fish species exhibit facultative habitat use of cold-water coral. Facultative habitat use is defined as the use of habitat for many important life processes, but that the absence of these habitats does not result in extinction of the species in question. Hence, coral may not be essential habitat, but there seem to be indications that it may be a preferred habitat for many life processes, which infers that the destruction of such preferred habitat may result in losses connected with having to settle for second-best, reducing the value of the ecological good supplied.

Sources: USA (1996); Rogers (1999); Peterson et al (2000);Rosenberg (2000) ;Fosså et al (2002) ; Husebø et al (Husebø *et al.* 2002);Reed (2002);Koslow (2003); Auster (2005); Costello et al (2005); Fossa et al (2005); Puglise et al (2005), Schöttner et al. (2009) .

3.1.2. Nutrient Cycling

As well as energy, life requires the availability of certain chemical elements known as nutrients. These include in particular carbon, hydrogen, nitrogen, oxygen, phosphorus, sulphur, potassium, calcium, iron and magnesium. Nutrients cycle through the environment (land, ocean, sediments, and atmosphere) and ecosystems, and the specific cycle for each nutrient can be considered separately – the carbon cycle, the nitrogen cycle and so on – though these may interact in complex ways. Each cycle is a sequence of flows of a chemical element, in various compounds and forms, between land, ocean and atmosphere (and plants and animals). The cycles involve biotic and abiotic (water, land, air) processes and are therefore also referred to as ‘biogeochemical’.

The ecosystem service 'nutrient cycling' is defined by Costanza *et al*. (1997) as the storage, and recycling of nutrients by living organisms. Marine organisms play a crucial role in almost all biogeochemical processes that sustain the biosphere, and marine micro-organisms in particular are a major component of global nutrient cycles (Heip *et al.* 2009). Deep-sea microbial processes are essential to sustain primary and secondary production in the oceans, driving nutrient regeneration and global biogeochemical cycles (Arrigo 2005). Across the globe, microbes account for almost half of primary production and in the marine environment they form a major part of ecosystem respiration and nutrient recycling (Danovaro *et al.* 2008b; Jørgensen and Boetius 2007). Without deep-sea processes that support these cycles on geological time scales, the primary production in the photic zone of the oceans, ultimately the basis for most life on Earth, would significantly decline. Moreover, a biodiversity loss in deep-sea ecosystems might be associated with exponential reductions of their functions, including nutrient regeneration (Danovaro et al 2008b). This indicates that the biodiversity the deep sea seems to play a key role in the sustainable functioning of the world's oceans and in the ecological and biogeochemical processes at a global scale, hence biodiversity itself is likely to be a fundamental contributor to function and resilience and to the provision of supporting and regulating services.

Nutrient cycling therefore supplies both supporting and regulating services. Nutrient cycling feeds into resources that provide provisioning services, for instance commercial fish resources, and is in this sense a supporting service. As a regulating service, nutrient cycling balances and controls nutrient levels at different points in the cycle. An important example is the carbon cycle, which provides carbon absorption, reducing the CO_2 in the atmosphere and thereby diminishing the rate of anthropogenic climate change. Figure 3 illustrates this cycle, and highlights the importance of the deep sea as the single largest pool of carbon in the cycle.

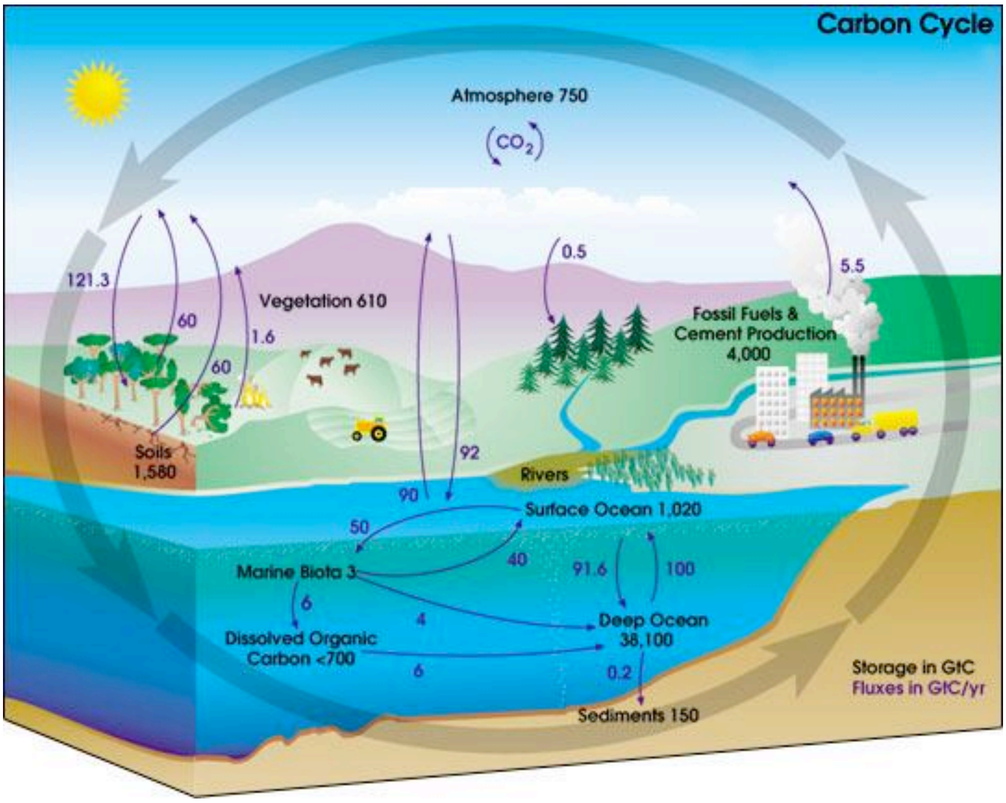


Figure 3. The Carbon Cycle. This carbon cycle diagram shows the storage and annual exchange of carbon between the atmosphere, hydrosphere (ocean) and geosphere in gigatonnes – or billions of tonnes – of carbon (GtC). The illustration shows total amounts of stored carbon in black and annual carbon fluxes in purple (figures are circa 2004). Source: NASA Earth Science Enterprise.

3.1.3. Water circulation and exchange

Water circulation and exchange is vital for productivity in the ocean. Ocean currents, for instance upwelling, have been shown to be of vital importance for the high productivity of many fisheries. Another such process is dense shelf water cascading, a type of marine current driven exclusively by seawater density contrast (Ivanov *et al.* 2004; Canals *et al.* 2006; Canals *et al.* 2009). Dense water masses flow 'over the edge' of the continental shelf into the deep sea, often using and carving submarine canyons. This margin exchange process provides an essential exchange between shallow and deep waters (Heip *et al.* 2009) and provides ecosystem services (See Box 1).

Box 2 Example of Supporting service: Transport of Nutrients by Dense Shelf Water Cascading (DSWC)

Dense shelf water cascading, the late winter and spring occurrence of sinking surface water that flows fastly over the bottom while carrying large amounts of organic matter and sediment, is one of the main mechanisms of matter and energy transfer from the surface to the deep ocean in some ocean regions. These seasonal events profoundly impact slope and basin ecosystems through the massive injection of fresh, highly nutritive organic matter and sediment on short time scales (normally several weeks). These events have a potentially important role in global carbon budgets. Dense shelf water cascading:

- contributes to the ventilation of intermediate and deep waters;
- modifies the seabed along its path by eroding and depositing sediments;
- efficiently transports pollutants and organic matter accumulated in the shelf sediments towards the slope and the basin;
- is suspected to sustain the deep ecosystems and enhance biological diversity by intermediate disturbance.

Source: Canals et al (2006; 2009); Nellemann et al (2008), Ulses et al (2009)

3.1.4. Chemosynthetic primary production

Primary production is the formation of biological material through assimilation or accumulation of energy, nutrients and inorganic carbon by organisms. In the deep sea, in the absence of sunlight, some organisms can utilize chemical energy in the form of hydrogen, methane, hydrogen sulphide, ammonium and iron to fix CO_2. This is referred to as chemosynthesis, and chemosynthetic bacteria and archaea use chemical energy for the conversion of inorganic carbon to biomass. These energy sources occur only in a few places: along mid oceanic ridges or other tectonically active sites where seawater interacts with magma or with reactive minerals (Jørgensen and Boetius 2007); on continental margins, associated with gas hydrates, gas seeps or mud volcanism where deep subsurface fluids transport chemical energy to the seafloor (Sibuet and Olu 2002; Levin et al. 2005); associated with large food falls such as whale carcasses, kelp or woods (Treude et al. 2009); and in organic rich oxygen minimum zones (Levin et al. 2003). In addition, chemosynthetic microbial primary production is known to fuel highly productive invertebrate communities on the seafloor (Cochonat et al. 2007). Most intriguing are the symbiotic associations between chemosynthetic bacteria and invertebrate hosts such as tubeworms, bivalves, snails and crustaceans (Dubilier et al, 2008), which provide food and niches to other organisms.

Another important function of some of the microorganisms inhabiting these reduced habitats is the consumption of toxic or climate-relevant substances such as sulfide or methane, respectively (Jørgensen and Boetius 2007). For the ocean floor, which covers 70% of the Earth's surface, an annual rate of methanogenesis of 85-300 Tg CH_4 per year has been estimated, of which more than 90% are consumed by seafloor microorganisms (Knittel and Boetius 2009). These microorganisms oxidize methane anaerobically with sulfate and are commonly found at cold seeps. The anaerobic oxidation of methane (AOM) efficiently controls the atmospheric methane efflux from the ocean (<2% of the global flux), because almost all of the methane produced in ocean sediments is consumed by AOM within the sulfate penetrated seafloor zones. Likewise, sulfide-oxidizing microorganisms consume almost all the sulfide released from reduced habitats, by oxidation with oxygen or nitrate. These microorganisms use the energy from methane or sulfide to fix CO_2.

Box 3 Chemosynthetic Ecosystems: Methane Absorption, a service from Mud Volcanoes

Active deep-sea mud volcanoes and other types of cold seeps such as pockmarks, gas chimneys and hydrate fields play a role in methane emission to the hydrosphere. Methane emission from the seafloor can be recorded in the form of gas bubble escape (geophysical signals), upward floating of hydrates (observation), and diffusive transport of dissolved methane (chemical measurements). Modern in situ tools allow us to quantify methane emission from different deep-water habitats, as well as the microbial consumption of methane.

Methanotrophic micro-organisms act as a filter against the active greenhouse gas methane. As such they provide a service by preventing this greenhouse gas from entering the atmosphere. In most types of seabed, the biological filter against methane is 100% efficient (0% methane escape). However, at some cold seeps, because of the high upward fluid flow, the efficiency of the microbial filter can be reduced to less than 20%. The reason for this reduction could be lack of electron acceptors, chemical composition of the fluids, or high mass transport of methane (bubble escape).

Today, the total number of mud volcanoes and other sites of methane emission on Europe's margins remain unknown. When methane reaches the mixed upper water layer, it will enter the atmosphere and act as greenhouse gas. Moreover, global warming will cause increased methane release from the upper continental margin, as is currently observed around Svalbard. For this reason, there is a need to increase our knowledge and to monitor methane hydrate-rich regions on the European margins.

Sources: HERMES, 2009; Foucher et al. 2009 ; Vanreusel et al. 2009 ; Knittel and Boetius 2009

3.1.5. Resilience

There exists a multitude of different descriptions of what resilience entails, and the concept has become "vague and malleable", making it difficult to apply and measure (Brand and Jax 2007). Resilience may refer to the amount of disturbance or stress that a system can absorb and still remain capable of returning to its predisturbance state (Cochonat *et al.* 2007). Alternatively resilience may be the capacity of an ecosystem to adapt to an external shock either by recovering to its original state or settling at a new equilibrium level. Carpenter et al. (2001) stress that applying the concept requires clear specification 'resilience of what, to what?'. The multitude of possible definitions, and the multiple possible interpretations/measures of "biodiversity", mean that the old idea (MacArthur 1955 ; Elton 1958) "complexity enhances stability" is difficult to test unambiguously. In general, however, ecosystems with higher biodiversity are usually thought to exhibit higher resilience than low biodiversity ecosystems, in the sense that high biodiversity ecosystems are better able to withstand unpredictable change than less diverse ecosystems (MA 2005), in particular being able to maintain consistency of ecosystem functions across a wider range of conditions, due to the wider diversity of species and species traits able to perform important roles under different conditions. Marine ecosystems are thought generally to have a higher level of resilience than terrestrial ecosystems (Holling 1973; Holling *et al.* 1995). A recent meta-analysis (Balvanera *et al.* 2006) showed that, in general, evidence supports the contention that for various measures of biodiversity there is a positive association with a number of different measures of ecosystem functioning, including primary and secondary productivity and nutrient cycling, and with indices of resilience.

With regards to the resilience of deep-sea environments, there are several questions of interest. In particular, how resilient are deep-sea habitats and environments and what is the role of their biodiversity in providing their resilience? Deep-sea species and habitats have been thought to be intrinsically more vulnerable and less resilient than their shallow water counterparts (Holling *et al.* 1995). The traditional view of the life history characteristics of deep-sea macro and megafauna, including fish, is for slow growth, longevity and late reproduction, all characteristics associated with stable environments. But there is not a single deep-sea species where we understand the entire life history from conception through to death. Although slow growth and longevity would appear to be the most common characteristics, there is strong evidence that in a limited number of species growth and reproduction are seasonal (Tyler *et al.* 1982; Gage and Tyler 1991; Gooday 2002), with growth and gamete development tuned to the availability of phytodetritus flux from surface production. Other taxa show evidence of rapid growth and early reproduction: deep-sea barnacles (Green *et al.* 1994) and the wood boring bivalve genus Xylophaga (Tyler *et al.* 2007), for example. In these last two cases, rapid life history characteristics are a response to the transient nature of suitable habitats. Large protozoans in the deep sea show evidence of 60-day quiescent periods followed by rapid growth and then another period of quiescence (Gooday, Bett and Pratt 1993). Even at vents and seeps where energy is believed to be available all year round, there is evidence of seasonal reproduction in seep mussels, the necessity of the larvae to feed on seasonal sinking phytoplankton blooms overcoming the year-round availability of energy for the adult (Tyler, Young and Dove 2007). Hence the picture is complex, and further research is needed to improve our understanding of the resilience of deep-sea habitats and species. This includes in particular better understanding of connectivity and organism dispersal which are essential to the resilience of a system after disturbance.

Secondly, what role does the deep sea play in the resilience of the Earth? The deep sea is clearly an important contributor to marine and terrestrial resilience, due to its important function in (for instance) carbon sequestration and temperature regulation, and in particular as a large, relatively slow-changing store of carbon and heat. “Ocean thermal lag”, for example, is a well-recognised factor slowing the rate at which the Earth heats or cools in response to changing atmospheric conditions. However not enough is known about possible thresholds and tipping points within deep-sea systems, including for example the rates of mixing between deeper and shallower waters, the impacts on global circulation patterns, and the consequences for the supporting and final services provided by the deep sea and the ecosystems influenced by it. There are major uncertainties here, for example the debate over the likely fate of the Gulf Stream under changing global conditions, and it is important to develop better knowledge both of the possible biotic processes feeding in to these processes, and the likely impacts on biotic processes, ecosystem goods and services, of changes in them.

3.2. Provisioning Services

Provisioning services are the products used by humans that are obtained directly from habitats and ecosystems. In the context of the deep sea, these include in particular fisheries, oil and gas, waste disposal sites, and chemical compounds. In most cases, the exploitation of provisioning services involves a significant input of man-made capital and labour, for example in the form of fishing boats, oil rigs, and their crews.

3.2.1. Finfish, shellfish, and marine mammals

Fishing fleets have shifted to fishing further offshore and in deeper waters to meet global demand since the 1960s (Morato *et al.* 2006, Cochonat *et al.* 2007) (see Figure 4). The deep sea, despite its limited primary productivity, is a source of several commercial species. There are deepwater fisheries for species such as orange roughy, roundnose grenadier, redfish, oreos and blue ling. A third of shark and ray species spend most of their life in the deep sea (Morato *et al.* 2006). In addition there are deep-sea fisheries for shellfish such as crab and shrimp.

Gordon (2001) classifies the three main categories of deep-water fish: mesopelagic, bathypelagic and benthopelagic. Mesopelagic fish occupy the water column from beneath the photic zone to approximately 1000m depth. Many species migrate towards the surface at night and descend to depth during the day. Examples of mesopelagic fish are the lantern fish and cyclothones. Bathypelagic fish live below 1000m and are usually highly adapted to life in a food-poor environment. Examples are deep-water angler fish and gulper eels. The benthopelagic fish can be compared to the demersal fish of the continental shelf and live close to the bottom. It is the benthopelagic species that are currently being exploited in the deep-water fisheries. Examples are roundnose grenadier, blue ling and Greenland halibut. In addition, many commercially exploited marine species recruit in the deep and then move upwards to where they are more easily targeted by fisheries. Many deep water fish species are long lived, slow growing, have a low reproductive capacity and are adapted to live in an ecosystem of low energy turnover in which major environmental changed occur infrequently (Roberts *et al.* 2005; Morato *et al.* 2006). Deep water stocks can be rapidly depleted and recovery can be very slow, although this will not apply to a few deep-water species with life history traits comparable to shallow water species (Gordon 2001).

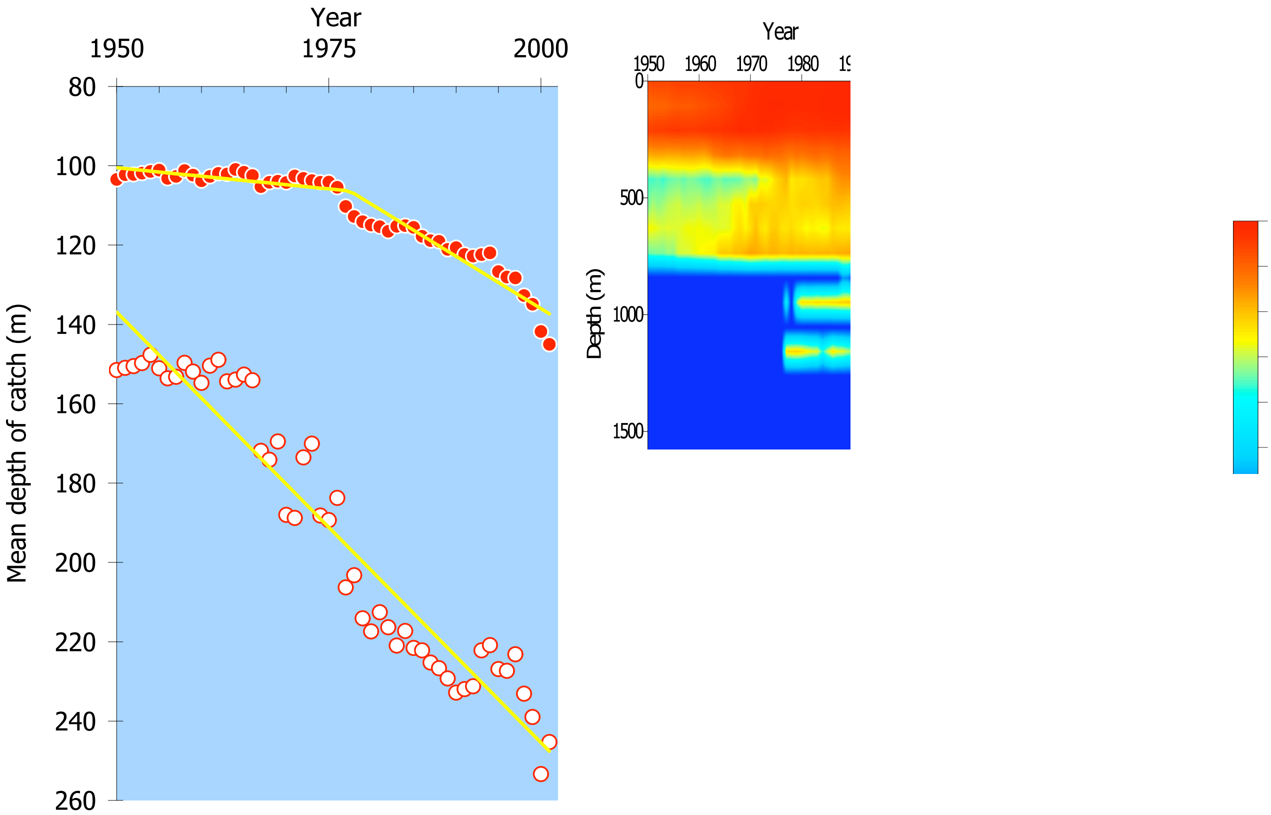


Figure 4. (a) Global trend of mean depth of world marine fisheries catches (Red dots: Bottom marine fishes only; white dots: high seas areas only; bottom fish). **(b) Time series of world marine bottom fisheries catches by depth strata** (Catch in tonnes log10 transformed). Source: Morato et al. 2006.

The increasing depth of catches as shown in Figure 4 is interesting from a valuation perspective. Firstly, catches are now being taken from deeper areas from which few fish were previously harvested. Hence what was always a *function* in the deep sea (fish populations) is increasingly becoming a *service* (fish catches). This increases the value to humans of the deep sea, through a combination of technological development (making it cheaper to access these deep resources) and mismanagement of shallower fisheries (making the shallower alternatives less available /more costly).

Some years ago there was little realised use value for deep-sea fish, but we can see (with the benefit of hindsight) that there was substantial option value associated with preserving the ability to catch fish when other resources decline. Though it must be added that deep sea fishing has often been heavily subsidised (Large *et al.* 2003; Pauly et al. 2003; Sumaila et al. 2010), making the creation of an actual service at least questionable in many cases. The slow growth of many deep water fish species has also lead to critique of their commercial utilisation being more similar to mining than sustainable harvesting (Clark 2001). Nonetheless, in principle an ecologically sustainable utilisation of fish resources in the deep could enable us to continue a fishing industry while allowing other stocks to recover. But whether this is doable in practice still remains to be shown. There could also be option values now associated with conserving even deeper stocks that are not yet exploited. These examples show that both use values and option values are dependent on management, and that mismanagement can seriously reduce both.

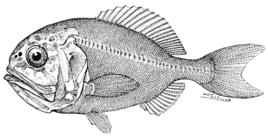
Box 4 Provisioning service: deep-sea fisheries

Commercially important deep-water species are targeted within the 200 nautical mile limits and also in the high seas (areas beyond national jurisdiction). The North East Atlantic hosts a diverse range of deep sea target species including; orange roughy, blue ling, redfish, Greenland halibut, ling, tusk, deepwater sharks deep-water red crabs, hake and monkfish.

Example of deep water species

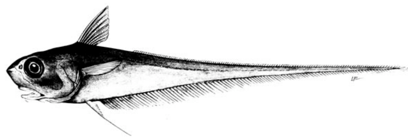
Orange roughy

(*Hoplostethus atlanticus*)



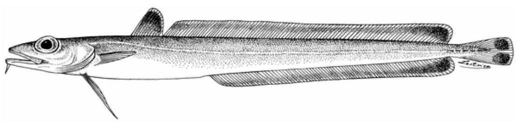
Roundnose grenadier

(*Coryphaenoides rupestris*)



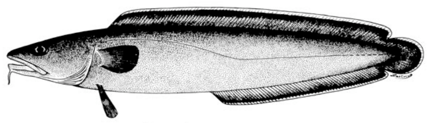
Blue ling

(*Molva dypterygia*)



Tusk

(*Brosme brosme*)



Black scabbardfish (*Aphanopus carbo*)

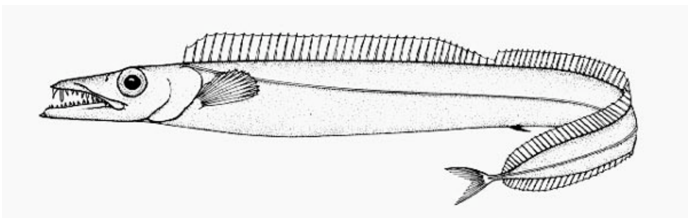


Image Source: FAO

3.2.2. Oil, gas and minerals

Oil, gas and minerals under the ocean floor are ecosystem goods created over geological time periods[6]. Oil and gas exploration and production are increasingly

[6] Most submarine oil and gas reserves occur on the continental shelves and slopes, where continental crust is present. These oil and gas resources were formed by the degradation of organic matter that accumulated over millennia in sedimentary basins on the bottom of the ocean. Buried by sediments in an anaerobic environment, the organic matter was subjected to gradual decay through bacterial and chemical action while sediments continued to accumulate above. The resulting conditions of pressure and temperature led to the breaking down of complex biological molecules into simpler hydrocarbon chains. The resulting oil and gas migrated upwards through the rock layers in which they were

taking place in deeper waters, and the pace of oil and gas exploration and production at depths greater than 300m has accelerated rapidly in some areas (Large *et al.* 2003)). Deep-water oil and gas operations are far from risk less from and environmental, societal and economic perspective, as dramatically illustrated by the 2010 Gulf of Mexico oil spill.

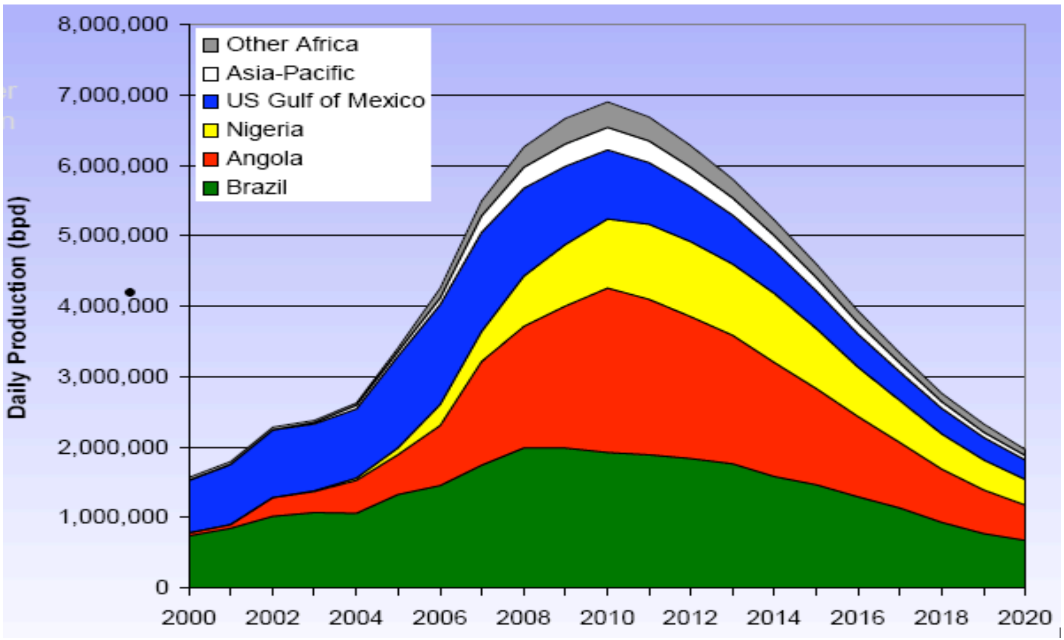


Figure 5. Worldwide Deepwater (>400m depth) Oil Production (kbbl/d). Commercial reserves only. Includes onstream fields, fields under development and probable developments. Source: Wood Mackenzie 01/2007.

In the Gulf of Mexico exploratory activities for oil and gas are conducted down to 3000m water depth (Cox 2003; Sumaila *et al.* 2010). The exploitation of oil and gas in deeper waters is expected to continue to grow in the coming years, unless the Deepwater Horizon spill triggers some restrictions or bans on some activities.

The marine minerals industry has seen unprecedented expansion, though this is limited in the deep sea. In waters deeper than 1000m potential mineral resources include manganese nodules and cobalt-rich crusts, polymetallic sulphides and phosphorites (Roberts *et al.* 2005; van den Hove & Moreau 2007). The Toronto based company Nautilus Minerals is already operating a major seabed sulphide-mining exploration and resource evaluation project in the waters of Papua New Guinea (http://www.nautilusminerals.com/s/Projects-Solwara.asp). While in 2010, the Chinese government has lodged the first application to mine for minerals under the seabed in international waters, in this case on a ridge in the Indian Ocean 1,700 metres below the surface. (The Independent, 2 July 2010).

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enclosed until they reached the impermeable surface, which concentrated them into an exploitable accumulation.

The seabed is a giant anaerobic bioreactor in which vast amounts of methane is produced (DWL 2005). Methane gas, frozen at ocean depths between roughly 500m and 1200m, is conservatively estimated to hold over twice the combustible carbon known from all other fossil fuels on the planet (Glover and Smith 2003). The most significant mining resource from the deep sea could in the future be methane hydrates, though there are a multitude of technological challenges and hazards, including in particular the risk of destabilisation that could trigger massive slides, not to mention the climate change impacts of emitting yet more CO_2.

3.2.3. Chemical compounds for industrial and pharmaceutical uses

Industry sectors involved in bioprospecting include biotechnology, waste, agriculture, and the pharmaceutical and cosmetics industries (Cochonat *et al.* 2007). The uses of marine derived compounds are varied, but the most exciting potential uses lie in the industrial and medical realms (Glover and Smith 2003). The majority of marine derived compounds to date have been obtained from either microorganisms or stationary bottom dwelling organisms such as corals and sponges (*op. cit.).*

The deep seas represent the largest reservoir of genetic resources and biological substances, including some of major biotechnological interest. A recent study (Yooseph *et al.* 2007) reports the discovery of thousands of new genes and proteins in just a few litres of water, promising many potential new functions. The unusual characteristics of deep sea organisms, their unique adaptations that enable them to survive in dark, cold and highly pressurized environments, offer unique opportunities, making them the subject of considerable excitement in the scientific community, with many potentially interesting commercial possibilities (Arico and Salpin 2005, HERMES 2006).

It is thought that several species known to be associated with cold water corals may be a source of knowledge of new biochemical resources which can be synthetically emulated (Maxwell *et al.* 2005). As early as the 18th centuries Norwegian fishermen collected and used deep water corals for ‘powerful medicaments’ (Arico and Salpin 2005; Maxwell *et al.* 2005), indicating some value in those days – whether medicinal or placebo – from these resources.

Scientists are studying a number of deep sea compounds to develop new pharmaceutical products to fight cancer, Alzheimer's disease, asthma, viral infections and for bone grafting (McAllister 1988; Witherell and Coon 2001; Grehan *et al.* 2003). Organic compounds such as antibiotics found in shallow water gorgonians may also be found in the deep-water species (Pitcher *et al.* 2000) (see Table 2 for some of the deep sea species under scrutiny). .

	Deep sea species	Function	Reference
Marketed	*T. thermophilus* enzymes - deep sea bacteria	Enzymes; Skin protection products (UV-resistant)	Arico (2005)
	T. thermophilus, Thermus aquaticus and *Thermatoga maritime* - deep sea bacteria	DNA polymerases; enzyme that builds new strands of DNA	Arico (2005)
Clinical trials	*Discodermia dissolute** - deep water sponge	Discodermolide; cancer treatment	Maxwell (2005)
	*Lissodenroyx sp** - deep sea sponge	E7389; lung cancer and other cancer treatment	Maxwell (2005)
	Salinospora tropica – deep sea bacteria	Salinosporamide-1; antibiotic and anti-cancer agent	Maxwell et al (2005)
Research	*Lithistida* (family: *Coalistadae*) - deep sea sponge	Dictyostatin-1; Cancer treatment	Maxwell (2005a)
	Spongosporites ruetzleri - deep sea sponge	Topsentin; Anti-inflammatory agent for arthritis and skin irritations	Isbrucker et al (2003)
	Isidae – deep sea bamboo corals	Bone grafts	Maxwell (2005)
	Vibrio diabolicus – deep sea hydrothermal vent bacteria	HE 800 Exopolysaccharide; bone grafts	Zanchetta et al (2003)

**This species can be found at < 200m depth, but is defined as a deep-sea organism (Maxwell et al. 2005)*

Table 2: Examples of products derived from deep-sea species and materials.

3.2.4. Waste disposal sites

The deep sea is been used for the purposeful or *de facto* disposal of high quantities of waste that cannot be disposed of by other means (Maxwell *et al.* 2005, Benn et al. forthcoming). For instance, all plastic material disposed in the sea will not be decomposed but accumulates. In some areas with high ship traffic like the Mediterranean, plastic litter can be found on every 100 m^2 at all depths, including in the deepest areas. The deep sea has been used as a repository for sewage sludge, dredge spoil and radioactive waste (McAllister 1988). It has been used as a dumping ground for dangerous wastes such as munitions and chemical weapons, for example nerve gas (Thiel 2003; Tyler 2003; Foglini et al. 2010). In addition, there has been interest in the disposal of large man made objects such as ships and oil rigs (Glover and Smith 2003; Tyler 2003). Carbon capture and storage will be discussed below.

Current international regulations prohibit deep-sea dumping of structures, radioactive waste and munitions. Future disposal activities that could be significant include carbon-dioxide sequestration, sewage sludge emplacement and dredge-spoil disposal (Tyler 2003), as well as illegal dumping of all sorts of toxic chemical and radioactive materials. To varying degrees, these waste disposal activities could damage other ecosystem functions, goods and services, now and in the future, and this needs to be considered in any accounting.

3.2.5. CO_2 capture and storage

Capture of CO_2 emitted from fossil fuel combustion and storage of CO_2 in the deeper areas of our oceans and in sub-seabed geological formations is currently envisaged and various techniques have been considered or are already being tested. These include direct injection into deep seawater; storage of CO_2 as a liquid or a hydrate on the seafloor in water depth below 300m and CO_2 injection into geological formations below the seafloor (Schubert *et al.* 2006; Davies, Roberts and Hall-Spencer 2007). (IPCC 2005). The first two options, injection on the seabed or in the water column, are contested by many on the grounds that since the ocean is in permanent exchange with the atmosphere, they do not mitigate the long term consequences of CO_2 emissions and only lead to a postponement of the consequences (Schubert *et al.* 2006). Today, only the third option, injection in subseabed geological formation, is allowed under the 2006 amendment of the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and there are significant research efforts in this direction (Schubert *et al.* 2006) and commercial operation already exist, such as Sleipner in the North Sea (See Box 5) and Snoehvit, in the Barents Sea.

If scenarios of large scale carbon capture and storage under the deep seabed become a reality, the deep sea would supply an important provisioning service to mitigate climate change. However, the risk of CO_2 leakage from the deep subsurface and potential effects on deep-sea ecosystems needs to be assessed (Inagaki et al. 2006).

Box 5 Waste Disposal: CO_2 Storage in the Sleipner Field

In the offshore gas field Sleipner, located 240km south-west of Stavanger in the middle of the North Sea, 1 million tons of CO2 per year has been successfully injected since 1996. The Sleipner project, operated by the Norwegian oil and gas company Statoil, is a commercial project which involves several different groups, including energy companies, research institutions and environmental authorities.

Natural gas that is brought up from the Sleipner field contains about 9% CO_2. In order to meet export specification and customer requirements, the concentration of CO_2 must be lowered to 2.5%. With the introduction of offshore carbon tax in Norway in 1991, it proved more efficient for Statoil to develop a method to store the CO_2 that is separated from the natural gas.

CO_2 is stored in a 200m thick grit formation from 800 to 1000 meters down in a saline aquifer. Above the grit, there is a 700m thick layer of hard rock. The storage capacity of the aquifer is estimated to be about 42 trillion tons of CO_2.

The Sleipner licence has saved about 300 million Norwegian Crones per year in reduced CO_2 tax.

Though carbon storage such as is carried out in the Sleipner field has been heralded as one option for climate change mitigation, the security of the method has been questioned and still needs further investigation.

Sources: Bellona.org, Greenpeace.org, Solomon, Tyler (2003), Zero.no, HERMES 2009

3.3. Regulating Services

Regulating services are the benefits obtained through the natural regulation of habitats and ecosystem processes such as gas and climate regulation, natural carbon sequestration and storage, waste absorption and biological control.

3.3.1. Gas and climate regulation

Gas and climate regulation include in particular the maintenance of the chemical composition of the atmosphere and oceans. An important mechanism in this regard is the so-called 'biological pump' (Figure 6), a series of biologically-mediated processes that transport organic material (hence carbon and other nutrients) from the ocean surface to deeper layers.

The biological pump recycles nutrients and providing food for deep-dwelling species. It also plays an important role in the Earth's carbon cycle, carrying carbon away from the atmosphere and upper ocean layers. Marine organisms act as a reserve or sink for carbon in living tissue and by facilitating burial of carbon in seabed sediments. Through this natural carbon sequestration and storage process, it provides a climate regulation service.

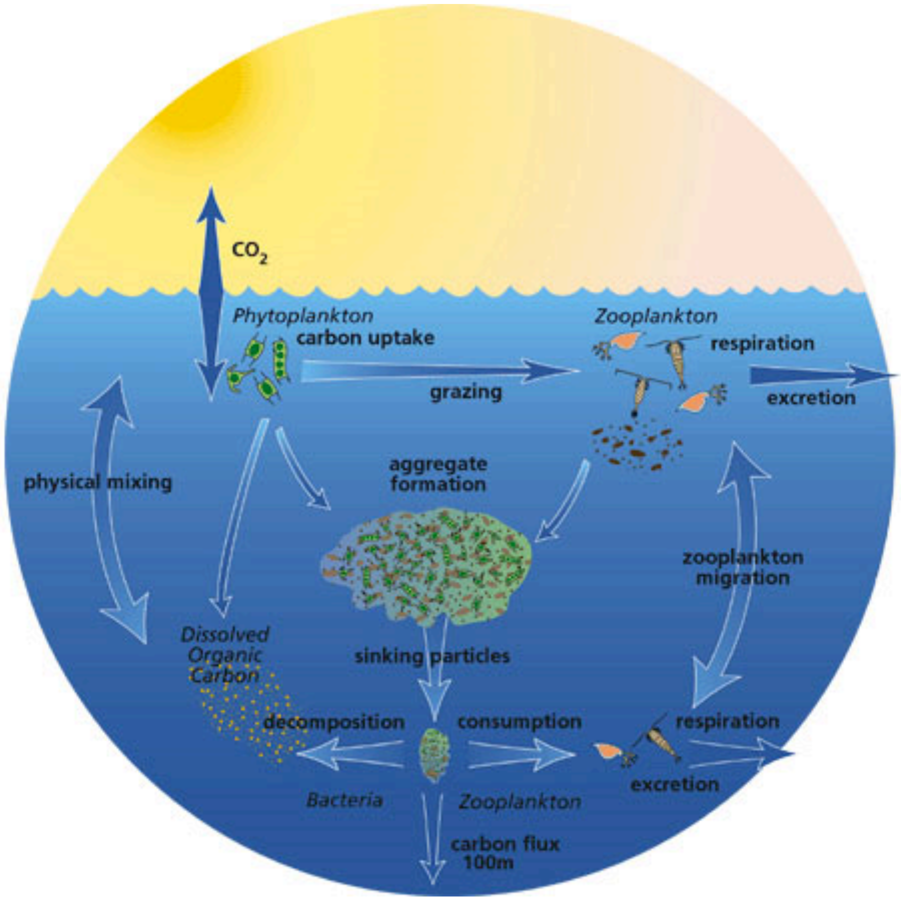

Figure 6. The biological pump. Source: © United States Joint Global Ocean Flux Study, http://www1.whoi.edu/general_info/gallery_modeling/slide4.html.

As explained in Box 3 above, methanotrophic microbes in the ocean floor and waters consume almost all of the methane entering the oceans through various processes such as coastal runoff, diffusion from organic-rich anoxic sediments, or through seeps, vents, and mud volcanoes emitting methane-rich fluids or methane-rich bubbles (Glover and Smith 2003). Hence these microbial systems provide an important gas regulation service by maintaining most of the ocean volume in a state of undersaturation in methane compared to the atmosphere (ibid.).

3.3.2. Waste absorption and detoxification

Waste absorption and detoxification are important regulating services as marine organisms store, bury and transform many waste materials through assimilation and chemical transformation, either directly or indirectly. Oceans have a unique (though not infinite) ability to clean up sewage, waste material and pollutants. In particular, bioturbation – the biogenic mixing of sediments on the seafloor by burrowing organisms (Solan *et al.*, 2004) – and accumulation regulate the processes of decomposition and/or sequestration (e.g. by burial) of organic wastes.

Due to their proximity to land areas, continental shelves are the locus of input, transit and accumulation of land born particulate substances, including pollutants. Dense shelf water cascading transports these particulate substances for recycling into the deep sea (Reeburgh 2007). Canyons function as transport vectors for large amounts of sediment and organic matter to the deep sea, where the above mentioned processes take place (Canals et al., 2006). See Box 2 above.

3.3.3. Biological regulation

Biological regulation and control services are the services that result from interactions between species or genotypes, that is the services linked to biodiversity itself. They include the trophic-dynamic regulation of populations (www.coastalwiki.org), biological control of pests, and the supporting ecosystem services provided by biodiversity that are necessary for the production of all other – more direct– ecosystem services, including for instance biodiversity influence on primary production, and nutrient cycling (MA 2005b, Ch. 11).

For instance, deep-sea biodiversity can contribute to the biological controls of pests. There are evidences that several pathogenic organisms (including pathogenic bacteria) are increasingly spread over the globe (including through ballast waters). Most of these are able to produce cysts and remain stored within the sediment. Benthic organisms contribute to the control of these potential pests by removing them (by ingestion) or averting their outbreak (by competing for available resources). In this sense, a high biodiversity represents a buffer for environmental changes and ecological shifts and this reduces the probability that these forms will develop (Danovaro, personal communication).

Another example of biological regulation is viral infection. It plays an important part in the functioning of the largest ecosystem of the biosphere by controlling benthic prokaryotic biomass (top down, predatory control) . Increasing evidence indicates that viral infection may be responsible for the high mortality of autotrophic and heterotrophic organisms in surface oceans (Suttle et al 1990, Suttle 2007), with cascading effects on carbon cycling and nutrient regeneration (Wommack & Colwell 2000). Viral lysis of infected microbes transforms their cell contents and biomass into organic detritus (both dissolved and particulate), which can then be used again by non-infected prokaryotes (that is, viral shunt) (Suttle 2005, Fuhrman 1999). This process supports prokaryotic heterotrophic production, but it also decreases the efficiency of the carbon transfer to higher trophic levels (Fuhrman 1999) and influences the carbon budget of the oceans, thereby modifying the amount of carbon transferred by sinking particles from the surface waters towards the ocean floor (Suttle 2007). Therefore, the integration of the viral component into trophodynamic and biogeochemical models is of primary importance for an improved understanding of the function of the world's oceans and the services associated with these functions.

3.4. Cultural Services

Cultural services are the often non-material benefits people obtain from habitats and ecosystems through recreation, aesthetic enjoyment, 'inspiration' (the material for artistic inspiration, reflection and cognitive development) and 'awe' (whether interpreted as marvel at the emergent properties of natural processes, or as a sense of 'spiritual' wonder).

There are many people, and significant investment, involved in studying and learning about the marine environment, including the deep sea, i.e. the deep sea provides educational and scientific services. There are some estimates of numbers and expenditures (see e.g. Pugh 2008) and some attempts to convert these into values (see e.g. Austen et al. 2009; Beaumont et al. 2007, 2008)), though not specifically for the deep sea. These calculations are interesting indications of the importance of marine research and education. Although they are not true value estimates in the sense of the economics frameworks applied here – because expenditures on these activities represent costs not benefits - the willingness to incur the costs can be taken to suggest that the benefits are considered greater. On the other hand this is of no use whatsoever in determining whether or not investments in marine research and education are justified.

It is also possible to consider the value of the knowledge that can be gleaned from deep-sea environments. For example, the deep seafloor constitutes the largest archive of climate data. Marine paleoclimatology provides the opportunity to gain access to climate data over timescales that extend the short instrumental period, across the onset of anthropogenic perturbations and far beyond. Paleoclimatic profiles from deep-sea sediments enable the investigation of the Earth's climate and its dynamics over a wide range of timescales (Nellemann, Hain and Alder 2008). In the context of the pressing problem of climate change, this opportunity to derive a fuller understanding of the long-term dynamics of global systems is clearly very important.

With regard to more aesthetic services, there are an increasing number of books and documentaries discussing deep-sea ecosystems and habitats. For example documentaries like David Attenboroughs *The Blue Planet – Into the Deep* or books and exhibitions such as Claire Nouvian's *The Deep* introduce people to some of the deep-sea ecosystems and habitats and allow people to see and appreciate them. The deep sea is a relatively unexplored area and is likely to provide an ongoing flow of discoveries of scientific, educational and entertainment value over a long period. The fascination for the deep is by no means a recent phenomena; the deep sea has inspired and awed humans for centuries, from Poseidon in the Greek myths, to literature such as *Moby Dick* and *20,000 Leagues under the Sea*.

More direct aesthetic uses of deep sea environments are limited, since we do not access them directly. However structures such as seamounts have been shown to aggregate marine life, and certain whales and dolphins appear to aggregate around seamounts during spawning (Pitcher *et al.* 2007). The growing tourist industry of whale watching may depend to a large extent on supporting services from deep sea environments. And in some cases, such as around seamounts, the service may be direct enough to be considered as a final cultural service

With regard to more spiritual services, in many societies, creatures from the deep sea played and to some degree still play a role in spiritual life. Indigenous societies both in North America and Asia still carry out traditional spiritual ceremonies connected to for instance marine mammals. Modern western societies generally do not hold direct spiritual or ceremonial values associated with marine life, but in many cases do have ethical values associated with marine conservation, especially for marine mammals. Willingness to pay (WTP) for the protection of marine mammals is reflected in environmental NGO memberships and in quite widespread rejection of human use of whale meat or seal fur. These values reflect the non-use or existence value that some people may have in the sense of experiencing mental satisfaction from knowing that certain deep-sea animals or ecosystems exist, even if they will never physically experience them. Within an economic framework, this satisfaction would be represented and measured via individual willingness to pay for their conservation. People may also hold bequest values related to the continuing provision of deep-water ecosystems in certain forms for future generations. Box 9, further discusses this subject.

3.5. Quantification of goods and services in the deep sea

As stressed above, the deep sea is still highly unknown, and the research effort in the deep still entails significant components of discovery and identification, as exemplified by the Census of Marine Life, and other national projects. But research is now increasingly looking at issues such as ecosystem functioning and the role of biodiversity, connectivity between ecosystems, and anthropogenic impacts, as exemplified in Europe by the HERMES and HERMIONE projects. In this context, quantifying the goods and services of the deep is still highly tentative and requires further research. Some quantification is available, for instance in provisioning services from the deep sea. Fisheries statistics reveal some information about deep-sea fish provision (see Box 6) though care is required to distinguish sustainable harvests from stock depletion, for example through use of catch-per-unit-effort and catch-at-age data for stock modelling. On the other hand, the supporting services for the fisheries are still largely unknown and hence unquantifiable, though research is being carried out to identify for instance the importance of cold water coral in deep-water fish life cycles (see the EU project CoralFISH[7]).

4. Economic Valuation

One of the main drivers for describing and measuring ecosystem goods and services is to clarify the extent to which human societies depend on, and benefit from, these services. Whether used directly for consumption or production processes, or regulating and supporting global conditions functions, or through cultural importance, ecosystem goods and services are important sources of value to humans. There are many possible ways of considering these values. One approach that is particularly useful in the context of comparing ecosystem values with other sources of value is to express the values in economic terms, although this covers only a particular subset of value, namely values that individual humans are prepared to trade-off with other influences on their well-being.

[7] See http://eu-fp7-coralfish.net/.

"Value" covers a wide range of related concepts. For example, many people consider the natural environment and/or its constituent parts to have "intrinsic" value, value in their own right. However by definition these values are beyond human knowledge – we can acknowledge that they may exist, and debate how to moderate our behaviour in order to reduce any damage we might cause to intrinsic values, but we can not sensibly talk of measuring these values, or of comparing them with values to humans.

Table 3: Classification of environmental values

	Anthropocentric	**Non-anthropocentric**
Instrumental	Use and non-use (bequest, altruistic, existence) values; (including values related to others' potential or actual use). These are the values included in the concept of "total economic value".	The values of other animals, species, ecosystems etc. (independent of humans). For instance, each species sustains other species (through different types of interactions) and contributes to the evolution and creation of new species (co-evolution).
Intrinsic	Values relating to humans existing and interacting with the natural world, but not to any human benefit from using nature. Sometimes referred to as 'stewardship values'.	Value an entity possesses independently of any valuer.

Source: adapted from Turner et al 2002

The part of value which is the most amenable to measurement and the most relevant to policy-making is the contribution to human well-being, captured in the cell containing "anthropocentric" and "instrumental" values. These values may be assessed within a framework based on individual preferences, as the various components of "Total economic value" (discussed in section 4.3 below).

4.1. Valuing the natural environment

There are many senses in which the natural environment may be considered valuable. It underpins and supports all human activity, and in this sense is of immeasurable total value. More pertinently for policy, small changes in environmental conditions, goods and services will have consequences for human welfare, now and in the future. Humans may also ascribe value to possible states of the natural environment over and above any personal or societal human use that may be made of those environments. There may also be senses in which environments are of intrinsic value over and above any value they have for human welfare.

The fact that intrinsic values can not be measured does not mean they do not exist, and the fact that the environment is valuable to humans does not in itself justify the need to measure this value. The need to value the natural environment arises rather from the need to better integrate natural and social sciences in communicating and articulating values, managing the natural environment, and helping decision-making processes. Economic valuation aims to provide means by which the contributions that the natural environment makes to human welfare can be better taken into account in decision-making procedures so that more efficient, effective and/or equitable decisions can be made.

So although we can talk of “the value of the natural environment” (see e.g. Costanza et al. (1997)), the value concept of most practical interest and policy relevance is not the value of the entire world, which is difficult to define let alone measure, but rather the much more tractable value of relatively small changes in the quality or quantity of natural goods and services. Specifically, value evidence for ecosystem goods and services can be useful for a range of purposes:

- as one part of a process of structuring information about the ways in which humans benefit from, impact on, and depend upon ecosystems;
- as a means of measuring and accounting for these impacts;
- as one element in an ecosystem approach, helping the understanding and resolution of value conflicts;
- to support more efficient, effective and/or equitable decisions;
- as a means of exploring consequences of changing management strategies and practices:
- as a powerful heuristic for understanding and communicating our dependence on natural environments.

Parts of the above reasoning only hold if methods are available that are sufficiently reliable, and sufficiently inexpensive, to inform decisions on the natural environment in a useful and non-wasteful way; but it is clear from the discussions in this report that the scope for providing reasonably accurate economic valuation for deep-sea ecosystem goods and services is somewhat limited at present, due to fundamental uncertainties regarding key relationships and variables. However, this does not mean that all attempts at valuation are misguided. For one thing, valuation is merely one step in a broader process of identification, description, qualitative assessment, measurement and valuation, and each of these successive steps, and their integration within an overall framework of assessment, is important and useful even if the subsequent steps are difficult or impossible. Secondly, it is always useful to set down clearly what we do and do not know, and an appreciation of the gaps in value evidence can be important in structuring research agendas and also in understanding where the key uncertainties lie when making decisions on the basis of imperfect information.

Of course there are also many caveats and limitations to economic valuation. There are ethical implications to focusing on anthropocentric and consequentialist interpretations of value – though as noted earlier, this approach can be taken as complementary to arguments based on other ethics. There are also practical and ethical issues acting within the anthropocentric consequentialist paradigm, since economic valuation methods derive expressions of value that are dependent on existing income distributions. If these are thought to be inequitable then this unfairness will carry through to the values derived; there exist methods for adjusting values to account for distributional objectives, but they are rarely applied. This criticism can be partly countered by a separate consideration of distributional issues, again considering valuation as one component in a broader suite of assessments.

There may also be particular types of value that are thought to be beyond the economic value framework – intrinsic values, clearly, but there may be human values that are nonetheless qualitatively of a different nature: for example spiritual values, or moral imperatives. Often, however, it is not truly possible to avoid trading-off such values with economic values: we may resist the calculus, but the decisions are taken, and the valuations are implicit in the decisions. The fact that values are implicit need not necessarily mean that they can be deduced and expressed in simple, monodimensional terms, however, and there are cases of irreducible complexity or multidimensionality of values that we can not simplify with available techniques of analysis (O'Neill et al. 2007).

There are additional problems associated with uncertainty and thresholds, which may not be adequately reflected in valuation, and in particular with the assumed substitutability of different resources. This reasoning applies particularly to indispensable life-support functions, and cases of irreversible loss or change. As the TEEB report notes, there is a fundamental ethical question "about the extent to which some life-supporting functions of biodiversity can be fully addressed by economic valuation and be considered as part of possible trade-offs instead of being dealt with as ecological constraints" (TEEB 2008, p. 35). Again, this can be viewed as a reminder that valuation is only part of a wider framework, and assessments can be augmented by the inclusion of sustainability constraints or precautionary approaches, specifying limits and thresholds to set boundaries for the valuation exercise, in the form of minimum levels of environmental quality, or maximum levels of acceptable impacts. Sustainability constraints can take weak or strong forms. Weak sustainability focuses on total capital and assumes substitutability between natural, human and physical/technical capital. Strong sustainability considers these categories separately and does not permit trade-off between natural and other forms of capital. There has been much debate in the environmental economics literature regarding the distinction, and no clear agreement: see for example Pearce (1997), Neumayer (2003). Ayres (2006; 2008) summarises that, although there remains room for dispute regarding very long-run possibilities for substitution, it is rather clear that substitutability between sectors as well as between factors of production is extremely limited in the short to medium term. The practical implication of this, coupled with application of the precautionary principle in light of our uncertainty regarding future options for substitution, is that we would be well advised to include sustainability constraints in assessments, and to take strong measures to protect natural resources that we suspect might turn out to be "critical natural capital" (Ekins et al 2003).

Valuation should therefore be seen as one step in a continuum of ways of better organizing information to help guide decisions, but it is not an end in itself, and is only *"one tool in the much larger politic of decision-making"* (Daily et al., 2000, p. 396).

4.2. Economic value

A key strand of economic analysis is concerned with measuring changes in the wellbeing of individuals and of society overall. The concept of economic value is concerned with what is 'given up' in order to obtain something, and choices (trade-offs) between different goods and services reveal their economic value, and their contribution to wellbeing, at the margin. The value of larger changes can be estimated by mathematical integration of marginal values, and in principle this can allow estimation of total values. However for key ecosystem goods and services at a global scale this may not be feasible since the marginal value tends towards infinity as we approach the limits of life-support. The scarcity of resources is central to the concept of economic value, because scarcity leads to situations of choice or trade-off. A resource that is abundantly available – oxygen to breathe for example – will have low or zero *marginal* economic value, even if the *total* value is essentially infinite.

The potential to derive total values for a resource is to a significant extent dependent on scale. It is conceptually straightforward to value the totality of a resource within a small area, if in a global context the contribution of that area to the global resource is trivial. As the scale becomes larger, this assumption breaks down. This means that we might be able to assess total values for particular small areas of the deep sea, but we probably could not assess "the total value of the deep sea" because there are certain aspects of deep-sea processes that are essential to life on the planet, so their total value is infinite. On the other hand, we can attempt to assess the value of small to moderate-sized changes in these critical life support services.

Estimating economic values is a matter of determining marginal trade-offs between resources. For goods and services traded in well-functioning markets, these trade-offs are revealed by market prices, in terms of a common unit of money. Where the markets are characterised by market failure – for example, by monopoly power, asymmetric information, or external costs associated with pollution – the prices are biased away from values, and need to be corrected to reveal true value estimates. For goods and services not traded in markets (including a wide range of ecosystem services), economic valuation techniques attempt to estimate the marginal economic value by measuring in the monetary unit the trade-offs that people make (either in reality, or in hypothetical situations).

The concept of economic value given by this framework is individualistic (though not necessarily selfish). It considers individuals as best placed to know their own welfare, and assesses value via the trade-offs (real or hypothetical) made by individuals, and social welfare as the sum of individual welfares. Clearly this is only one possible conception of social welfare. To some extent other conceptions can be reconciled with the economic framework, for example via the inclusion of compensatory weights in economic appraisal to give greater weight to the values of the poorest individuals, but this is beyond the scope of this paper.

4.3. Total Economic Value framework

Ecosystem goods and services contribute to human wellbeing in several ways and individuals have several motivations for placing a value on these resources. It can be helpful to tease these motivations out, as in the "Total Economic Value" (TEV) framework (Pearce and Turner, 1990), the components of which are shown below (see also the top-left cell in Table 3 above). It is important to note that the "Total" in TEV does not imply the "value of the totality of the resource", but rather the "sum of all types of economic value" for this resource. In other words, the Total Economic Value framework, despite the name, operates at the margin.

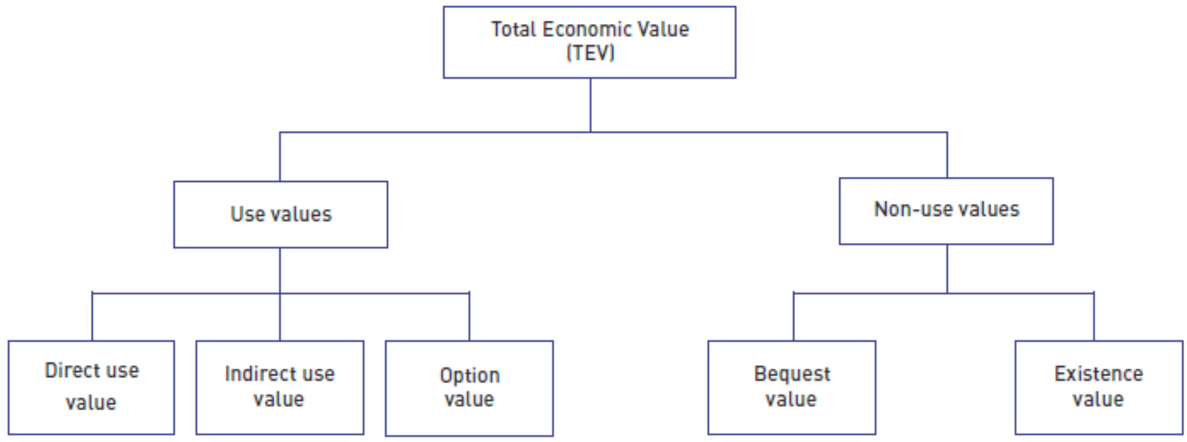

Figure 7. Total Economic Framework (TEV) (Source: Beaumont and Tinch 2003, reproduced in van den Hove and Moreau 2007, inspired by Pearce and Turner 1990)

Use value involves some interaction with the resource, either directly or indirectly:

- **Direct use value:** the use of the deep sea in a consumptive manner (fishing) or in a non-consumptive manner (there are few example for deep-sea environments because by and large we do not go there; whale watching on the surface above deep sea areas is arguably a rare example). (See e.g. Box 6)

- **Indirect use value:** The role of the deep sea in providing or supporting key (ecosystem) services, such as nutrient cycling, habitat provision, climate regulation. (See e.g. Box 7)

Box 6 Direct use value: Deep-sea fishing on the High Seas

Commercially important deep-water species are targeted within the 200 nautical miles Exclusive Economic Zones (EEZ) of nation states and also in the High Seas (areas beyond national jurisdiction). In the following we focus on the high seas fishing activity.

A recent worldwide FAO review of bottom fishing in the High Seas estimated the value of High Seas fisheries to be €447 million for 2006. Total High Seas catch by EU fishing vessels using bottom gears had an average value of €126 million per year for 2004 – 2006, making the EU a substantial harvester of the High Seas.

The North Atlantic is the main High Seas fishing area of the EU high seas fishing fleet. The fleet harvests a diverse range of deep-sea species including; orange roughy, blue ling, redfish, Greenland halibut, ling, tusk, deepwater sharks deep-water red crabs, hake and monkfish.

Deep sea species are characterised by high longevity, slow growth, late maturity and low fecundity, often leading to high vulnerability to exploitation. Depletion can be rapid, and recovery slow. This makes valuation difficult: even if we know what is coming out of the deep sea in any given year, we do not know to what extent this harvest is sustainable as an on-going flow of value, and to what extent it represents unsustainable stock depletion, giving only a short-term provisioning service, but with long-term costs in terms of reduced options for future provisioning, and perhaps reduced ecosystem function and biodiversity.

For the EU as a whole, landings of deep-sea species in the High Seas made up 1.5% of landings of all species by volume and 0.25% by value of the total landings into EU ports for the period 2004 – 2006. Though the high seas catch is a small part of total EU catches, the importance of this catch for some regions, such as Galicia in Spain, is substantial.

Sources: Bensch et al (2008); Morato et al (2006); MRAG et al (2008).

Box 7 Indirect Use Value: Dense Shelf Water Cascading and Submarine Canyons - The Rose Shrimp fishery in the Mediterranean

Indirect use values add to, or support, direct use values such as fisheries. An example of deep sea indirect use value is the effect of dense shelf water cascading (DSWC) on the rose shrimp fishery in the Mediterranean.

DSWC is a type of current that is driven solely by a seawater density contrast. It is a seasonal phenomenon that results from the formation of dense water by cooling and/or evaporation. The influence of seafloor topography on the path followed by DSWC is best illustrated by submarine canyons. At specific locations, canyons are the main conduits for the cascading shelf waters, and from this developed the concept of 'flushing submarine canyons'.

The deep water rose shrimp (*Aristeus antennatus*) is a target species of Mediterranean fisheries and is both abundant and economically valuable. Company et al studied the impact of DSWC on the rose shrimp fishery. Initially the strong currents associated with intense cascading events displace the shrimp from the normal fishing grounds, causing a temporary fishery collapse of the species. The spatio-temporal co-occurrence between major cascading events and the temporary fishery collapse of rose shrimp suggest that the physical disturbance by such strong deep currents of cold and turbid dense water probably displaces the species from the fishing grounds, presumably towards greater depths. Despite the initial negative effect from cascades, harvest of red shrimp appears to increase 3 – 5 years after major cascading events. Company *et al* conclude that the large transport of dissolved and particulate organic matter associated with this phenomenon appears to enhance the recruitment of rose shrimp, mitigating the general trend of overexploitation. DSWC can be compared to regenerative fires in forests.

Sources : Company et al (2008); Sarda et al (2009); Roberts et al (2005); Canals et al (2009); Puig et al (2008) ; Cochonat et al (2007)

- **Option value:** the benefit of keeping open the option to make use of deep-sea resources in the future even though such use is not currently planned or conceived. A related concept is quasi-option value which arises through avoiding or delaying irreversible decisions, where technological and knowledge improvements can alter the optimal management of a natural resource. A key example in the deep sea is bioprospecting: there is a value *now* to delaying or avoiding decisions that could reduce deep-sea genetic diversity, due to the unknown *future* potential for these genetic resources to contribute to human wellbeing. Option values are *additional* to any utility that may arise if and when the good is actually consumed. (Perman et al. 2003). There is some debate regarding the categorisation of option value: it has sometimes been considered non-use as it does not relate to any current use; but more commonly it is included as a form of use value, since it relates to values associated with uncertainty regarding future direct or indirect use. It has also been considered a separate value category capturing values associated with uncertainty regarding both use and non-use benefits in the future. (See e.g. Box 8)

Box 8 Option Value: Bioprospecting

Because of the high biodiversity and richness of ecosystems in the deep sea, the longevity and long history of many deep-sea species as well as the extreme conditions of pressure and temperature in which deep-sea species thrive, deep-sea ecosystems and their genetic resources offer great potential in terms of bioprospecting for industrial and medical applications. These resources can be seen as option values.

In particular deep-sea bioprospecting has focused on microbial communities associated with hydrothermal vents. The associated biological communities are highly diverse and thrive in extreme conditions. Hydrothermal vents genetic resources are being used for the development of novel enzymes for use in a range of industrial and manufacturing processes. The full potential of the enzyme market is valued at a minimum of $50 billion dollars a year.

Studies of bioprospecting companies have shown that their stock market values far exceed the value of the products they have developed. Clearly the market is factoring in the option values of the activities carried out by these firms.

Sources: Arico and Salpin (2005); Leary et al (2009)

Non-use value is associated with benefits derived simply from the knowledge that the natural resources and aspects of the natural environment are maintained. It is not associated with any *personal use* of a resource. For example, individuals may value knowing that iconic locations such as Challenger Deep in the Mariana Trench, or specific ship-wreck sites, would be protected, even though they have no intention to make any use of the site.

Non-use value can be split into three categories:

- **Altruistic value:** Derived from knowing that contemporaries can enjoy the goods and services related to the deep sea (this is human use, but not personal).
- **Bequest value:** Associated with the knowledge that the deep-sea resource will be passed on to future generations: this is human use, but not personal (Krutilla 1967). (See e.g. Box 9)

- **Existence value:** Derived simply from the satisfaction of knowing that the deep sea or specific bits of it (e.g. CWCs), continue to exist, regardless of the uses by oneself or others, now or in the future. Although this is not related to human use of the environment, it is a direct value to humans and so falls within the "instrumental" category (see Table 3) (Pearce and Turner 1990). (See e.g. Box 9)

Box 9 Existence / Bequest Value: Cold Water Corals (CWC)

Existence values are the values held by individuals that do not relate to any personal use or use by other contemporary or future humans. The evidence for such values comes from many sources, including direct questions (surveys, interviews, stated preference valuation studies) and revealed behaviour (conservation activism, contributions to conservation NGOs). A number of international environmental organisations and NGOs have been particularly vocal in pressing for cold water coral (CWC) conservation, for example UNEP, WWF, and Oceana. Although this has not been quantified, this provides some evidence of the importance of non-use values in relation to CWC. It is clear from these organisations involvement, and increasing public support for these organisations in campaigning to conserve CWC, that CWC have both existence and bequest values.

A choice experiment was applied in order to elicit people's preferences and willingness to pay (WTP) for the protection of CWC in Ireland. It was found that a large percentage of those surveyed valued cold water corals and would like to see them protected for future generations, for their role as essential fish habitats, for their pure existence value and also for the option to use or see them in the future.

Sources: Glenn et al (2010)

4.4. Economic valuation techniques

4.4.1. Current valuation techniques

Economic valuation techniques can in some cases be used to estimate the above values. The methods seek to answer the question "what would the price be if there was a market for this?" – or more accurately, "what would the demand curve be?", because generally we need to know how price changes with quantity of a good or service. Often we are interested in the value of sizeable changes in quantity and/or quality (at least on a local scale, and though the caveats noted above regarding total values apply) and the assumption of a constant price or value will often be inadequate. There are three main types of valuation techniques:

Market-based techniques: using evidence from markets in which environmental goods and services are traded, markets in which they enter into the production function for traded goods and services, or markets for substitutes or alternative resources. These can be applied for example to deep-sea fish, for which there exist direct markets, or for the greenhouse gas (GHG) regulation service of the deep sea, which is not traded directly, but which could be valued at prices from carbon trading markets since GHGs are global pollutants.

Revealed preference (RP) techniques: based on interpreting actual behaviour with both environmental and market elements. There is limited applicability to deep-sea environments as people do not go there. However they could be useful for some indirect values supported by the deep sea, for example whale watching.

Stated preference (SP) techniques: based on stated behavioural intentions in hypothetical markets created through surveys. These methods are very widely applicable, and are the main techniques capable of capturing non-use values[8]. Their success does depend on the extent to which respondents understand the resource and this can limit applicability to unfamiliar goods and services, such as those provided by deep-sea ecosystems, though it may be possible to reduce problems significantly through careful presentation of information and options, and other aspects of survey design.

Benefits transfer (BT) or Value transfer (VT) is an alternative to primary research. BT uses value evidence from existing literature applied to a different good or service, closely related to the original study or studies: eftec (2010) gives a comprehensive overview and guidelines. The simplest forms involve “point” value transfer, generally with adjustment for income and sometimes other aspects. Value function transfer is more sophisticated, involving the transfer not of a specific value but rather of a function expressing value as a function of one or more other variables. Full meta-analysis function transfer derives such a function from regression analysis of several existing studies and is therefore statistically more robust, but also more data demanding. BT is normally applied where the ecosystems, goods or services are very similar, and where the characteristics of the valuing population (users and non-users) are similar. Success depends on the data available: the quality and quantity of previous studies, and their appropriateness in the context of the specific characteristics of the population and good/service under consideration. BT is cheaper and quicker than primary studies. It may also be less accurate, but this is not axiomatic: BT based on several good studies could be better (unbiased and lower variance) than a single good study (unbiased but high variance).

The main problem for application of this methodology to the deep sea is that there are few existing studies from which to transfer. But could we transfer from other environments? This is likely to depend on the good or service in question. For provisioning and regulating services, it is probably acceptable. A shallow pelagic fish may be a pretty close substitute for a deep-sea fish, in culinary terms. Greenhouse gas regulation is the same service irrespective of where it occurs. The main need here is to control for scientific variables – differences in rates of carbon flux, or of fish stock growth. For cultural and non-use values, however, BT from different environments is on shakier ground. It may be defensible – in the absence of alternative evidence – to transfer cultural values from shallow coral reefs to deep-sea coral reefs, if it is possible to remove recreation and other direct use values. It may even be defensible to transfer non-use values from studies of remote terrestrial environments that are considered in some sense to be of similar ecological value. But there can be little doubt that such transfers would be gross approximations, acceptable only to the extent that primary study were not feasible.

[8] It is also possible to infer non-use values via donations and memberships for environmental NGOs, but converting this to a value estimate is very difficult.

4.4.2. Key aspects of value

Before discussing the value of deep-sea goods and services, it is worth stressing some key aspects of value that will come to bear on the way values may be articulated.

Value depends on location

Ecosystem services generally do not have a single uniform value but rather a value that varies with the details of the location and level of provision. Location in relation to human populations is often particularly important, both because the number of beneficiaries matters, and because key value-determining variables (such as tastes and incomes) vary greatly across space. There may also be spatial variability through ecological factors, even to the extent that ecosystem processes providing benefits in one area may have undesirable effects in another area (Silvestri and Kershaw, 2010). For example a species might be a valuable resource in one area but an ecologically-destructive invasive species in another.

Interdependence of values

One problem often arising in valuation and appraisal relates to the interdependence of values, whether across different categories, or within a single category across space. Across categories, some values may be complementary while others may be substitutes or incompatible, and this makes it difficult to assess the values in isolation. For example, whale watching and whale catching are to a large extent alternative uses for the same resource; if both activities occur, a valuation model is likely to require some spatial modelling, or recognition that the values conflict and the uses cannot arise simultaneously in the same area.

This can also occur between different resources / services: for example, there may be a trade-off between high whale populations (aesthetic/recreation and non-use values) and certain fish stocks eaten by whales (fishery values).

More generally resource management valuation requires bioeconomic models reflecting the trade-off between current and future harvests of renewable resources, or extraction of non-renewable oil, gas and mineral resources.

Nonlinearity of values

Within a single category, substitution effects may be very important, and failure to take account of diminishing marginal value for goods and services can lead to significant overcounting. This can arise in particular for conservation, where for example the marginal value of the 10th cold water coral area conserved may be very much greater than the marginal value of the 100th. The value of increasing populations of a species is similarly unlikely to be linear. This is not really a problem for global assessments, provided we can estimate the way in which values vary with different levels of provision, though this can be complex in practice (see e.g. Koch et al 2008). It is a potential problem for specific local assessments, where the value can not be taken as independent of what happens outside the boundaries of the assessment.

Thresholds and tipping points

The "extreme" of non-linearity in values arises where systems are liable to discontinuous change at thresholds or tipping points. Here the system, and/or the services it provides, can undergo major changes in state. As noted in Silvestri and Kershaw (2010), in non-linear systems, small perturbations can become magnified and lead to qualitatively unexpected behaviours at macroscopic levels. If we do not know about these risks, or fail to take them into account, analysis of ecosystem services (including but not limited to economic valuation) may be misleading.

4.5. Valuation of deep-sea ecosystem goods and services

4.5.1. Steps in valuation

Figure 8 below gives a partial illustration of how valuation techniques might be applied to deep-sea environments, through a sequence of considering the resource, the intermediate and supporting services it provides, the final services provided to humans deriving from the resource and its intermediate services, and finally the valuation techniques that could be used to assess these values.

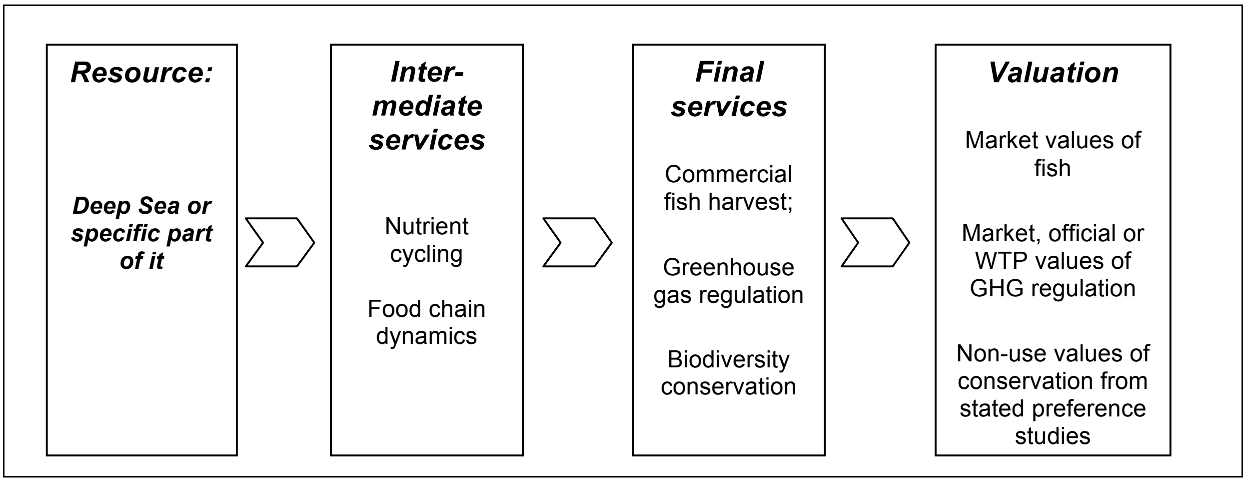

Figure 8. Steps in Valuation

Intermediate or supporting services do not necessarily need to be valued. However this depends on the boundaries of the assessment:

- Where the final services supported by the intermediate services are also "in scope", in the sense of being separately included for valuation within the boundaries of the assessment, then applying valuation to the intermediate services would involve double counting and should be avoided.
- On the other hand where the final services are "out of scope" – where distance in space or time means they are not included directly in the assessment – then the supporting services do need to be valued separately. For example, if the role of the deep sea is in supporting fish populations that are food for animals that are 'used' outside the deep sea (say for whale watching) then the

intermediate service (the contribution of deep-sea resources to supporting whale populations and thereby whale watching and conservation values) should be counted in an assessment focusing on the deep sea.

In principle, therefore, non-market valuation can be applied to changes in final or intermediate services, to changes in entire habitats or ecosystems, or even directly to changes in management practices. But the potential for valuation, and its accuracy, are crucially dependent on individuals' awareness of the ways in which the object of valuation influences their personal welfare. The closer we can get to final services, the better the valuation is likely to be. Where there is uncertainty about how a management change will influence services, deciding to apply non-market valuation techniques directly to the management change does not remove that uncertainty, but merely shifts it to the valuation exercise, and its respondents. So the first important step in appraisal is to use the best scientific information available to assess the likely physical and ecological impacts of the option under consideration. In Table 4, we present an assessment of the state of knowledge for the various ecosystem goods and services, for each of the key deep-sea habitat types under consideration in HERMIONE.[9]

[9] State of knowledge as represented in this table corresponds to our assessment of the situation. Opinion may of course diverge on whether some category should be labelled "some knowledge" rather than "little knowledge". The intention is to illustrate the immense work ahead in term of improving our knowledge of ecosystems, habitats, goods and services, and their values.

Box 10 Supporting Service and Use Value: Natural CO_2 Sequestration

Marine algae utilising CO_2 during photosynthesis create a deficit of CO_2 in the surface of ocean waters, leading to the dissolution of CO_2 from the atmosphere into the surface ocean in order to restore equilibrium. Perhaps as much as 30% of the carbon that is taken up in this primary production sinks into deeper water. There, it is mostly converted back to CO_2 by marine bacteria, with a small fraction reaching the bottom to be buried in the sediment. As illustrated in Figure 3 (The Carbon Cycle: NASA figures for 2004) the result is a net flow of carbon from the atmosphere and terrestrial environment into the world's oceans equal to approximately 2 GtC per year. Most of this increases the pool of carbon in the deep-sea, which is increasing at around 1.6 GtC per year, of which 0.2 GtC is buried in marine sediments. Both the storage in the deep-sea carbon pool, and the long-term burial in marine sediments, can be considered ecosystem services of the deep-sea.

Several studies have attempted to estimate the fixation of carbon in primary production in the ocean to determine the amount of carbon or greenhouse gas (GHG) sequestered. Beaumont et al (2008) for example estimate that the value of CO_2 sequestration in UK territorial waters is between £420 million and £8.47 billion. The estimation is based on the standing stock of phytoplankton locking up 0.07Gt carbon per year valued at £6-£121 per ton carbon.

Since GHGs are entirely fungible as a global stock pollutant, consistency in valuation suggests that the same values should be used irrespective of the source of emission or sequestration. Carbon values are much debated, with attempts to estimate the long-run damage costs of climate change, but since climate policy is largely target-driven, most policy and ecosystem service assessments use abatement cost estimates. In Europe values are related to the EU emissions trading scheme (ETS), which in 2009 valued carbon at around Euro 15 per tCO_2e, but these are likely to rise as the scheme expands and tighter targets demand stricter controls. The Department of Energy and Climate Change (DECC) in the UK provides official guidelines for valuing GHG emissions that envisage values per tonne reaching around 250 Euros within the next 40 years.

Of course these values are intended to be marginal at current and presumed future atmospheric GHG concentrations, so while it is appropriate to use them for small changes in flux from the deep seas, large scale changes would call for separate valuation studies. In particular, the deep-sea contains the largest pool of carbon on the planet, over 38,000 GtC (see Figure 3) compared to 750 GtC in the atmosphere. If even a few percent of the deep-sea pool were somehow released to the atmosphere, that would result in catastrophic climate change. Hence the value of the deep-sea service of storing this stock of carbon is to all intents and purposes infinite.

It does however make sense to consider the value of the annual *flow* of carbon into the deep-sea pool and marine sediments. This net flow of approximately 1.6 GtC per year makes the atmospheric concentration of carbon less than it would otherwise be. Valued at a conservative 15 € per tCO_2e (which is 55 € per tC if all the carbon is in the form of $C0_2$*), this represents a value of 88 billion euros per year. This value could rise significantly as stricter GHG targets are applied, requiring more expensive abatement activities.

** Note that in our (back of the envelope) calculation, to convert from GtC to $GtCO_2e$ we have assumed that all the carbon is in the form of CO_2 and not CH_4.*

Sources: Costanza et al (1997); Feely et al (2001); Beaumont et al (2008); Stephens et al (2009); DECC 2009

Table 4: Knowledge of ecosystems and habitats, and their value. Cell colours indicate the state of natural science knowledge on the contribution of these ecosystems and habitats to the provision of goods and services (updated and expanded from table 2.2 of van den Hove & Moreau (2007) Key: **blue** = good knowledge; **green** = some knowledge; **yellow** = little knowledge; **grey** = no knowledge; **white** = irrelevant). Value is defined as being; present (+); not present (0); unknown (?); monetarily known (c.f. Beaumont et al (2008)).

Services	Ecosystems and Habitats	Cold Water Corals	Open Slopes and Basins	Canyons	Sea-mounts	Chemo-synthetic	Water Column	Sub-seabed
Supporting Services	Nutrient cycling	?	+	?	?	+	+	0
	Habitat	+	+	+	+	+	+	0
	Resilience	?	?	?	?	?	?	0
	Primary production	?	?	?	?	+	+	0
	Biodiversity	+	+	+	+	+	+	?
	Water circulation and exchange	0	+	+	?	0	+	0
Provisioning Services	Carbon capture and storage (artificial)	0	0	0	0	0	+	€
	Finfish, shellfish, marine mammals	+	+	+	+	+	€	0
	Energy: Oil, gas, minerals	?	?	0	?	?	0	€
	Chemicals compounds – industrial/pharmaceutical	+	?	?	?	+	?	?
	Waste disposal sites	0	+	+	0	0	0	+
Regulat -ing Service	Gas & climate regulation	0	?	+	0	+	+	+
	Waste absorption and detoxification	0	+	+	0	0	+	0
	Biological regulation	?	+	?	?	+	+	0
Cultural Services	Educational	+	+	+	+	+	+	+
	Scientific	+	+	+	+	+	+	+
	Aesthetic	+	?	?	?	+	+	0
	Existence / Bequest	+	?	?	?	?	+	?

4.5.2. Determining the baseline

A further issue arising in valuation is the definition of the baseline against which value is assessed. As noted previously, attempting to derive "total" values is fraught with difficulty. The baseline for a total value estimate is the complete removal of the good or service, and in many cases this is very unrealistic, and sometimes inconceivable. Total values estimated in such circumstances are not very meaningful. But the correct choice of baseline is important, and depends on the context/policy question:

- **Assessing the "importance" of the deep sea**: to answer the question "What does the deep sea do for us?", with the results being useful for general awareness raising or basic political strategy. This is fine for some services, or for specific areas, but when looking at the deep sea as a whole such assessments inevitably run into problems associated with the unrealistic baseline ("the deep sea stops existing").
- **Scenario evaluation for policy development**: this requires assessment of one or more future scenarios against an appropriate baseline – generally a "business as usual" management, though in some cases a "status quo" baseline may be more practical.
- **More detailed policy and project appraisal**: this requires a more careful definition of baselines, and a more realistic focus on potential changes in levels of goods and services. The objective here is to compare policy options in terms of service values. This is appropriate for example when considering options for siting offshore protected areas. We need to consider the state of the world without the project (the baseline) and compare it with the state of the world with the project and the values of interest are not "total" values of services but the values of the change in services between baseline and project.
- **Pricing decisions**: there are many situations in which pricing can be used as a tool for environmental management, even in the deep-sea. Possible applications include access payments or taxes for mineral or fossil fuel exploration, and payments for fishing permits. Valuation with a view to setting prices may need to take more account of how values vary over certain ranges of activity, since the level of the activity will be partly dependent on the price set.
- **Legal damage assessment**: for example for oil spills or seabed pollution, this is very similar to project appraisal in methods – comparing the state of the world with and without an event – though is retrospective rather than prospective. The burden of proof and level of accuracy required may be different.

In most of the above cases there is a choice between a static and a dynamic baseline. A static baseline (status quo or other) does not consider changes that would happen anyway, most importantly climate change; whereas a dynamic baseline (business as usual or other) attempts to consider what would happen without the policy or change under assessment, and therefore gives a more accurate assessment of the net value of the policy.

There is also a fundamental distinction between comparative static assessments and dynamic assessments. Static assessments compare equilibrium situations (for example “today” vs. “fish stocks recovered”) and are much simpler to model and assess. They include no consideration of how the system moves from “now” to “then” and therefore can not be used to calculate net present values, only comparisons of flows per period. This is useful for visioning and scenario building exercises. Dynamic assessments, which attempt to construct a full model of how the system evolves over time, are much more complex, but in principle can be used to estimate net present values, and are therefore more useful for specific policy development, appraisal and impact assessment.

4.6. Scenarios for deep-sea values

Although lack of physical, ecological and economic knowledge and data means we can not make precise estimates of the values of deep-sea goods and services (Table 4), it is nevertheless possible to make qualitative assessments of the likely relative magnitudes of different services of the deep sea, and to do this for different possible future patterns of exploitation. This is a first step in considering how the values of the deep sea may be dependent on decisions we make about how to exploit its resources and to conserve its habitats.

In Table 5 we present five different scenarios for utilisation of the deep sea. The first two are based on our knowledge of past and present uses of these environments, the remaining three represent future possible scenarios of differing management focus.

1. the preindustrial utilisation, i.e. prior to the technological possibility of directly utilising the deep sea;
2. the current situation with its increasing use of the deep sea;
3. an exploitative scenario with focus on utilising the provisioning services of the deep maximally as soon as possible and independently of the impact;
4. a sustainable use scenario assuming management that ensures environmentally sustainable utilisation of the deep sea over time; and
5. a conservationist scenario with focus on conserving resources in the deep.

The table presents educated guesses of how the different services contribute to human present value given these five scenarios. The supporting services are not marked with euro or value signs, as these services are generally functions that derive their value from underpinning final services under the different scenarios that we indicate.

We make the assumption that there were few values emanating from the deep sea prior to the availability of technology to utilise the resources in the deep. But the supporting services are of importance to the degree that a low technology world has any indirect use for these services via other supported services in marine and terrestrial environments. Also some cultural and aesthetic values are inherent in the cultural heritage, via the inspiration of art and literature.

In the current situation we observe there are a number of supporting services are highly important, and there is also some provisioning from the deep. Furthermore, we derive value from a number of cultural services.

The three future scenarios, exploitative, sustainable and conservationist, focus on different values. The exploitative scenario has high valuation of the provisioning services in the short term, but this level of exploitation results in reduced values from supporting services. The exploitative scenario is also likely to be ecologically and economically unsustainable, due to impacts on future provisioning and supporting services that are not fully reflected in the present values under an exploitative framework, and hence we anticipate that the service values may decline over time, both for non-renewable resources, which become exhausted, and renewable resources, which may be overexploited and in the mid- to longer term suffer low yields and stock collapses.

The conservation scenario derives higher values from supporting services and the cultural services, at the expense of reduced immediate provisioning, but we allow for the possibility that a conservation scenario could give higher value of the renewable fish resources in future years. Non-renewable such as oil, gas and minerals are expected to have much less immediate use value under the conservation scenario, due to trade-offs with the renewable and conservation values, but there could also be important option values associated with preserving opportunities to use these resources in the future – indeed, in the distant future, there could be greater use from these resources which may be rapidly exhausted under the exploitative scenario.

The sustainable scenario lies between the exploitative and the conservationist, but the real distinction lies in the fact that provisioning values are highly present, and these values do not decline over time, as in the case of the exploitative scenario. Non-renewable fuel and mineral resource values are also intermediate; conceptually, these are run down in a quasi-sustainable manner, with a gradual switch to backstop technologies.

Table 5: Contribution of the deep sea to human value under different scenarios; preindustrial, current, exploitative, sustainable and conservationist. Ticks in the supporting services show the importance of the different supporting services in provisioning, regulating and cultural service. The euro signs in the other services give an indication of the value of these final services, and the arrows in parentheses show the direction that these values may be expected to take over time (↓; decline in value, →; value unchanged, ↑; increase in value).

Services	Deep Sea Scenarios	Preindustrial	Current	Exploitative	Sustainable use	Conservation
Supporting Services	Nutrient cycling	√	√√√	√	√√	√√√
	Habitat	√	√	√	√	√√√
	Resilience	√	√√	√	√√	√√√
	Primary production	√	√√	√	√√	√√√
	Biodiversity	√	√√	√	√√	√√√
	Water circulation and exchange		√√		√√	√√√
Provisioning Services	Carbon capture and storage		€€€	€€€(↑)	€€€(→)	
	Finfish, shellfish, marine mammals	€€	€	€€€(↓)	€€(→)	€(↑)
	Energy: Oil, gas, minerals		€€	€€€(↓)	€(→)	
	Chemicals compounds – industrial/pharmaceutical		€	€€€(?)	€€€(→)	€(↑)
	Waste disposal sites	€		€€€(?)	€(→)	
Regulating Services	Gas & climate regulation	€	€€€	€€€	€€€	€€€
	Waste absorption and detoxification	€	€€	€€€(↓)	€€	€
	Biological regulation	€	€	€	€	€
Cultural Services	Educational		€€	?	?	€€€
	Scientific		€€	?	?	€€€
	Aesthetic/Spiritual/Inspirational	€	€	?	?	€€€
	Existence / Bequest		€	?	?	€€€

Table 6: Research agenda for valuation of deep-sea goods and service. Cell colours indicate the state of natural science knowledge on the contribution of these ecosystems and habitats to the provision of goods and services (as per Table 4 above). Key: **blue** = good knowledge; **green** = some knowledge; **yellow** = little knowledge; **grey** = no knowledge; **white** = irrelevant).

<table>
<tr><th colspan="2">Valuation
Services</th><th>State of knowledge</th><th>Key gaps in valuation evidence</th><th>Potential Monetary Valuation methods</th><th colspan="2">Research needs for valuing service</th></tr>
<tr><td rowspan="6">Supporting Services</td><td>Nutrient cycling</td><td></td><td rowspan="6">Understanding how these functions are provided, the key threats to them, and how they impact on other ecosystems, goods and services</td><td rowspan="6">Via impacts on other goods and services: production function approach</td><td rowspan="6">Further primary scientific research with involvement of economists: view to production function valuation</td><td rowspan="18">Research on non-monetary valuation of ecosystem goods and services and ways of bringing different value evidence into decision-making processes.</td></tr>
<tr><td>Habitat</td><td></td></tr>
<tr><td>Resilience</td><td></td></tr>
<tr><td>Primary production</td><td></td></tr>
<tr><td>Biodiversity</td><td></td></tr>
<tr><td>Water circulation and exchange</td><td></td></tr>
<tr><td rowspan="5">Provisioning Services</td><td>Carbon capture and storage (artificial)</td><td></td><td>Storage capacity , costs, risks</td><td>Carbon market or official values.</td><td>Cost-benefit analysis of options</td></tr>
<tr><td>Finfish, shellfish, marine mammals</td><td></td><td>Knowledge of stock dynamics and ecosystem interactions; understanding fisher behaviour, reliable data</td><td>Market based, with bioeconomic modelling</td><td>Data collection and modelling of stock dynamics and of management strategies</td></tr>
<tr><td>Energy: Oil, gas, minerals</td><td></td><td>Environmental impacts of exploitation</td><td>Market based</td><td>Monitoring and assessment of ecosystem service impacts</td></tr>
<tr><td>Chemicals compounds: industrial/pharmaceutical</td><td></td><td>Identification and function</td><td>Market based</td><td>Estimation of option value</td></tr>
<tr><td>Waste disposal sites</td><td></td><td>Ecological effects, risks, and capacity</td><td>Avoided cost</td><td>Monitoring and assessment of ecosystem service impacts</td></tr>
<tr><td rowspan="3">Regulating Services</td><td>Gas & climate regulation (Natural C sequestration & storage)</td><td></td><td>Methods to determine rates</td><td>Carbon market or official values</td><td>Further primary research into determinants</td></tr>
<tr><td>Waste absorption and detoxification</td><td></td><td>Rates, effects and capacity</td><td>Avoided cost</td><td>Assess costs associated with a decline in function</td></tr>
<tr><td>Biological regulation</td><td></td><td>Understanding the natural processes</td><td>Avoided cost / production function</td><td>Further primary scientific research with economist involvement</td></tr>
<tr><td rowspan="4">Cultural Services</td><td>Educational</td><td></td><td rowspan="4">Evidence on values to humans (expressed in monetary and non-monetary terms)</td><td>Market based or SP</td><td rowspan="2">Attempt production function valuation</td></tr>
<tr><td>Scientific</td><td></td><td>Production function or SP</td></tr>
<tr><td>Aesthetic</td><td></td><td>Stated preference</td><td rowspan="2">Deliberative research (focus groups …) and SP studies</td></tr>
<tr><td>Existence / Bequest</td><td></td><td>Stated preference</td></tr>
</table>

5. Conclusions

It is becoming clearer that deep-sea ecosystems are very valuable, even infinitely valuable, in the sense of supporting crucial biogeochemical processes and cycles that support much of life on Earth as we know it. But still relatively little is known about the ways in which these vital ecosystem services may respond to growing threats and pressures arising through the combined effects of global environmental change and direct use of deep-sea resources, and we are not able to make reliable assessments of the values arising through changes in these processes.

We also know rather little about the other values of goods and services of the deep sea. This is true even for provisioning services such as fisheries, because though we do have some estimates of levels of harvests, we do not know where these are sustainable, and where they are in effect “mining” out slow-growing, slow reproducing stocks. The overview in Table 4 shows the full extent of our ignorance of deep-sea ecosystem service levels.

From the perspective of valuation, Table 6 gives an overview of what we know, what the key gaps are, the potentially appropriate monetary valuation methods, and suggested next steps in researching the value of deep-sea ecosystem services. To value deep-sea ecosystems and their goods and services, we need knowledge about the biodiversity, structure and functioning of the systems, and the factors influencing these. And we need to know about the threats and pressures impacting on the systems, and how the systems and services respond over time. As human activities extend more into the deep seas, both in direct exploitation and in indirect impact through environmental change, we will need to know more about the benefits and values we can extract from the deep sea, but also more about the cumulative impacts our activities will have on both these direct values and the indirect supporting functions on which we all depend (Benn et al., forthcoming).

As indicated in Table 6, there are several important gaps in our knowledge that prevent both monetary and non-monetary valuation of most deep-sea ecosystem goods and services at present. The sources of gaps vary: for the cultural services, the important gaps are in how humans relate to, and value, the services, and the challenges are primarily methodological, for example in finding reliable ways of applying stated preference methods to environments with which people are not familiar or in developing appropriate deliberative value articulation methods. For the regulating and supporting services, we need better scientific understanding of the determinants of rates of processes and functions providing services, and the threats posed by human activity. In some cases there are substantial uncertainties on the economics side too – for example in the valuation of nutrient cycling – though in some cases generally accepted values are in use, or can be derived, notably for carbon capture and storage. For provisioning services, our level of understanding is generally better, but there remain important gaps in data, in understanding human behaviour in exploiting the resources, and in modelling dynamic interactions over time.

As indicated in section 2.5, there are limits to what can be expressed in monetary terms and, in particular for environments as remote as the deep sea, there is little prospect of ever being able to provide comprehensive monetary valuation for all ecosystem goods and services. So in addition to the research on monetary valuation of deep-sea goods and services, more research and practice are needed on other (non-monetary) ways of articulating values and of building different value evidence and evidence of human impacts in decision-making processes. This could build in particular on existing research on, and practice with, non-monetary valuation concepts and techniques[10]; research on rationality in the field of decision sciences; and research on the precautionary principle and decision-making under uncertainty and ignorance.

The valuation evidence gaps need to be addressed via a programme of interdisciplinary natural and social science research, simultaneously improving our knowledge of natural processes and dynamics, and our knowledge of the ways in which humans benefit from and value the goods and services derived directly and indirectly from deep sea environments.

[10] See Annex I of (DEFRA 2006) for a catalogue of non-monetary methods.

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