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Services from the deep: Steps towards valuation of deep sea goods and services

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A B S T R A C T

Very little work has been done to identify and characterise the goods and services of the sea, and even less for the deep sea. We present a first categorisation and synthesis of deep-sea ecosystem goods and services, and review the current state of human knowledge about these services, the possible methods of their valuation, and possible steps forward in its implementation. Our conclusions highlight the nature and extent of research that is needed to overcome the gaps in knowledge that have been identified, and which have so far prevented the valuation of most deep-sea ecosystem goods and services.

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1. Introduction

Deep seas are defined as water and sea floor areas below 200 m. Oceans cover about 71% of the earth's surface: of that area, about 90% is above deep seas, and the deep seas also represent 90% of the oceans by volume. Despite this, until recently humans knew relatively little about them. 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, private enterprise, national endeavours and international research programmes such as INDEEP (International network for scientific investigation of deep-sea ecosystems), the Census of Marine Life and its successor, 'Life in a Changing Ocean', and the EU-funded HERMES and HERMIONE projects are rapidly expanding our knowledge. As a result of this work, we now know that the deep sea and the deep seabed form an extensive and complex system which is linked to the rest of the planet in exchanges of matter, energy and biodiversity, and the functioning of deep-sea ecosystems is crucial to global biogeochemical cycles upon which much terrestrial life, and indeed human civilisation, depends (Dell'Anno and Danovaro, 2005). But the deep sea is much less pristine and untouched than could be expected, considering its relative inaccessibility (van den Hove and Moreau, 2007; Benn et al., 2010; Ramirez-Llodra et al., 2011; Norse et al., 2012). Pressures on, and threats to, deep-sea ecosystems are increasing (Glover and Smith, 2003). And our knowledge of the deep sea remains piecemeal and partial. There are still substantial knowledge gaps concerning the occurrence and functioning of deep-sea ecosystems and their precise roles in global biogeochemical cycles (Cochonat et al., 2007). 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.

Increasing human population and demand for resources, coupled with over-exploitation of many more traditional resources, and rapid technological advances, make further exploitation of deep seas both possible and more attractive, despite practical difficulties and potentially serious risks, as illustrated by the Deepwater Horizon oil spill in the deep waters of the Gulf of Mexico in 2010. Deep seas are however 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, it can help, and might be necessary, to complement conservation arguments based on non-use values with utilitarian values. This requires more in-depth and systematic identification, qualitative description and quantitative measurements of the goods and services provided and their value to human populations. Understanding the importance of deep-sea ecosystems can lead to better governance. But although human dependence on marine environments is widely recognised, insuffiecient understanding makes accounting for this a major challenge. The recent TEEB (2010), for example, was not able to cover marine services at all—a key gap leading to research plans for a 'TEEB for Oceans'.[1] There are a few studies that consider valuation of marine ecosystem services on a broad scale, for instance the global synthesis of Costanza et al. (1997), Beaumont et al.'s (2008) and Saunders et al.'s (2010a, 2010b) studies of UK oceans, the Baltic sea report; "What is in the Sea for me?" (Anon, 2009), work by Plan Bleu for the Mediterranean (Anon, 2010) and the Guinea Current Large Marine Ecosystem (GCLME) valuation project (Interwies, 2010). The marine InVEST project is developing production function models for marine valuation (Ruckelhaus and Guerry, 2010). These initiatives illustrate both the policy need for valuation evidence for marine ecosystem services, and the present limitations in evidence available, which is primarily for coastal ecosystem services, food and energy provision, and certain aspects of the carbon and nutrient cycles.

The data gaps are especially large for the deep seas, and this work is to our knowledge the first catalogue of the goods and services of the deep sea. The UNEP-HERMES report "Deep Sea Biodiversity and Ecosystems" (van den Hove and Moreau, 2007) stopped short of providing a full catalogue relating services to current knowledge regarding ecosystems and their functioning. In this paper we 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 next section presents the classification system that we apply to the deep sea goods and services, followed by a catalogue of these goods and services, and a discussion of the methods of their economic valuation and the state of current knowledge of these values. In conclusion, we highlight the fact that deep-sea ecosystems are highly valuable and that research is needed to overcome the gaps in knowledge related to those ecosystems, that have made it difficult adequately to value all the goods and services they provide.

2. Classification of ecosystem goods and services

MA (2005) sets out a framework for assessing ecosystem goods and services with four main categories:

Provisioning services are the products used by humans that are obtained directly from habitats and ecosystems. In the context of the deep sea, important goods provided include in particular fish, oil and gas; minerals/chemical compounds are likely to become important.[2] Of these, only fish would conventionally be considered as provided by a (current[3]) ecosystem service, though the fossil fuels and minerals are accessed via marine habitats, using processes that may damage the marine environment, and many 'ecosystem service' assessments do include them in analysis. 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.

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.

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).

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

[1] http://www.teebweb.org/InformationMaterial/TEEBUpdates/tabid/1137/Default.aspx.

[2] We will be studying both biotic and abiotic goods and services, with further explanation later in the text.

[3] Oil and gas come from ancient ecosystems, but timescales are such that there is little point in considering them to be ecosystem services.

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

Since the Millennium Ecosystem Assessment (MA, 2005), numerous studies have used or adapted this classification scheme in order to value the environment or aspects of it. Many authors distinguish between 'intermediate' and 'final' services (Balmford et al., 2008; Haines-Young et al., 2009a). Another common distinction is between natural functions or ecosystem processes, that exist independently of humans (for example nutrient cycling), and 'services' that only exist with reference to humans beneficiaries (for example recreation). Ecosystem services frameworks such as the MA (2005) and the UK National Ecosystem Assessment (Mace et al., 2009; Bateman et al., 2011) generally focus on biotic resources and exclude purely abiotic goods such as minerals or aggregates extraction. This is also the approach taken by 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., 2009a) 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 (Anon., 2009) also considers "space and waterways"; Saunders et al. (2010a, 2010b) include abiotic resources, space for shipping, cables, pipelines, and energy infrastructure. Furthermore, 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 (Benn et al., 2010). 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, including by causing damage to the ecosystems. 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 living world. Therefore 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.

We follow the MA (2005) classification system, including so-called supporting services, rather than for instance the CICES (Haines-Young et al., 2009b) approach that focuses only on provisioning, regulating and cultural services that supply benefits directly. 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. Fig. 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 does not entail double-counting to consider the values of the supporting services. Of course this conclusion is specific to this assessment: in a global assessment, that did cover all final services, it would be double-counting to include supporting services separately.

3. Catalogue of goods and services in the deep sea

In the following we present a catalogue of goods and services from the deep sea, starting with the presumably most important services in the deep; supporting services.

3.1. Supporting services

3.1.1. Habitat

The deep sea is the largest habitat on Earth. It hosts some of the most diverse ecosystems on the planet (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. The Census of Marine Life reports[5] that there are only about 250,000 known marine species at present, with expectations of at least 750,000 more to be described (excluding 'more than a billion' types of microbe). Estimates of the number of species living in the *deep* sea vary greatly, from 500,000 to 10 million, according to CeDAMar (Census of the Diversity of Abyssal Marine Life), who also report that for any sample taken at any point in the deep sea, at least half of all animals are new to science.[6] It is even possible that more species may live in deep seabed environments than in all other marine environments combined (UNEP, 2006)—we simply do not know yet. The wide variety of habitats gives rise to unique organisms and life forms with amazing adaptations to these harsh environments. Recent genetic analyses revealed a huge diversity of deep-sea organisms

[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 paper, we are focusing on the human impacts, so we use the terms 'supporting services'.

[5] http://www.coml.org/media-resources/frequently-asked-questions-faq.

[6] http://www.cedamar.org/#jqtabs-205-0, accessed 9 May 2012.

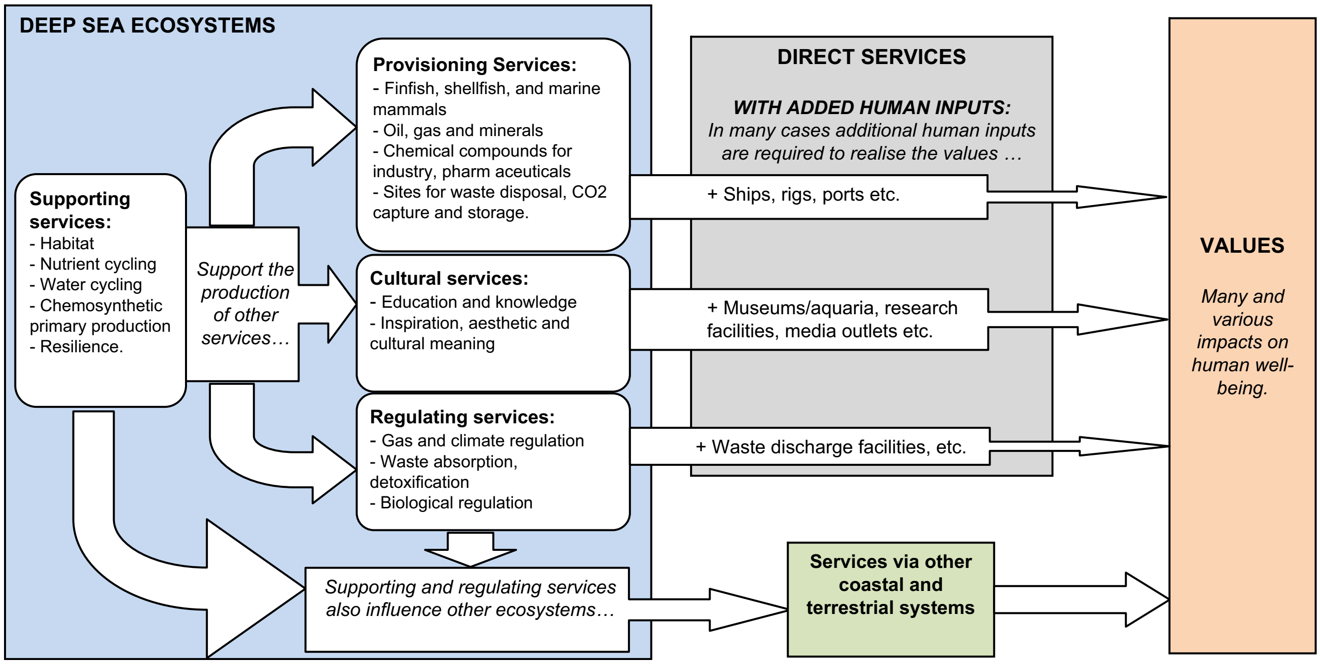

Fig. 1. Deep sea ecosystem goods and services.

even at regional scale (Brand and Jax, 2007), and an even higher diversity is related to the microbial biosphere (Sogin et al., 2006).

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 – including areas below land and below sea – may account for over 90% of the global biomass of Bacteria and Archaea (Head et al., 2003).

3.1.2. Nutrient cycling

The ecosystem service 'nutrient cycling' is defined by Costanza et al. (1997) as the storage and recycling of nutrients by living organisms within ecosystems. These cycles play an important role in global biogeochemical cycles. 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 nutrient cycling acts both as a supporting service (feeding into resources that provide provisioning services, for instance commercial fish resources) and as a regulating service (for example providing carbon absorption, reducing the CO_2 in the atmosphere and thereby diminishing the rate of anthropogenic climate change). 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 (Jorgensen and Boetius, 2007; Danovaro et al., 2008b). 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.

3.1.3. Chemosynthetic primary production

In the deep sea, in the absence of sunlight, chemosynthetic bacteria and archaea can use chemical energy from hydrogen, methane, hydrogen sulphide, ammonium or iron to fix inorganic carbon and produce biomass. These energy sources are widespread and abundant in reducing environments, such as the sub-sea floor, but occur in high concentrations in seawater only in a relative few places: along mid oceanic ridges or other tectonically active sites where seawater interacts with magma or with reactive minerals (Jorgensen 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-LeRoy, 2002; Levin, 2005); associated with large food falls such as whale carcasses, kelp or wood (Treude et al., 2009); and in organic rich oxygen minimum zones (Levin et al., 2003). 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 in turn provide food and niches to other organisms.

Another important function of some of the microorganisms inhabiting these oxygen poor or anoxic habitats is the consumption of toxic or climate-relevant substances such as sulphide or methane (Jorgensen 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% is consumed by seafloor microorganisms (Knittel and Boetius, 2009). 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 sulphate penetrated seafloor zones. Likewise, sulphide-oxidising microorganisms consume almost all the sulphide released from reduced habitats, by oxidation with oxygen or nitrate. These microorganisms use the energy from methane or sulphide to fix CO_2.

3.1.4. Resilience

How resilient are deep-sea habitats and environments and what is the role of their biodiversity in providing their resilience?

There is not a single deep-sea species where we understand the entire life history from conception through to death, but 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). In many cases, the life history characteristics of deep-sea macro and megafauna, including fish, include slow growth, longevity and late reproduction. These are all characteristics associated with stable environments and there is abundant evidence of deep sea species that match this description, including invertebrates with direct development, fishes with low number of eggs or young, fishes that live centuries and corals that live millennia. So slow growth and longevity would appear to be the most common characteristics, but there is also 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., 2007a), 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-d quiescent periods followed by rapid growth and then another period of quiescence (Gooday et al., 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 because the larvae feed on seasonal sinking phytoplankton blooms (Tyler et al., 2007b).

Hence while many deep sea species and systems may have low resilience, 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. 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, 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. It seems likely that while the deep seas make a substantial contribution to the resilience of the global system, buffering against anthropogenic impacts on the biosphere including climate change, at the same time the deep sea ecosystems may have quite limited resilience to direct impacts from threats such as pollution and overfishing. Further research is required to understand the scaling properties of resilience, and whether the global scale buffering properties of the deep seas could indeed be at risk from more localised threats.

3.2. Provisioning services

3.2.1. Finfish, shellfish, and marine mammals

Since the 1960s, fishing fleets have shifted to fishing further offshore and in deeper waters to meet global demand (Cochonat et al., 2007; FAO, 2010). The deep sea, despite its limited primary productivity, is a source of several commercial species of both fish and shellfish.

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 1000 m depth. Bathypelagic fish live below 1000 m and are usually highly adapted to life in a food-poor environment. The benthopelagic fish can be compared to the demersal fish of the continental shelf and live close to the bottom. Benthopelagic species that are currently being exploited in the deep-water fisheries include roundnose grenadier, blue ling and Greenland halibut. Several pelagic species that feed below 200 m are also exploited, including bigeye tuna, swordfish and black scabbardfish. In addition, many commercially exploited marine species recruit in the deep and then move upwards to where they are more easily targeted by fisheries. A few deep-water species have life history traits comparable to shallow water species (Gordon, 2001), but in general deep water fish species are long lived, slow growing, and have a low reproductive capacity, being adapted to live in an ecosystem of low energy turnover in which major environmental changes occur infrequently (Roberts et al., 2005; Morato et al., 2006). These deep water stocks can be rapidly depleted and recovery can be very slow.

The increasing depth of catches 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 of the deep sea to humans, 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 actual or planned *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 opportunity to catch deep sea fish when other resources decline. Though it must be added that deep sea fishing has often been heavily subsidised (Large et al., 2003; Cochonat et al., 2007), making the creation of a *profitable* service at least questionable in many cases. The slow growth of many deep water fish species has also led to critique of their commercial utilisation being more similar to mining than sustainable harvesting (Clark, 2001). Nonetheless, in theory at least, 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 practicable 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.

3.2.2. Oil, gas and minerals

Oil, gas and minerals under the ocean floor are ecosystem services created over geological time periods. Oil and gas exploration and production are increasingly taking place in deeper waters, and the pace of oil and gas exploration and production at depths greater than 300 m has accelerated rapidly in some areas (Large et al., 2003). Deep-water oil and gas operations can involve significant risks from the environmental, societal and economic perspectives, as dramatically illustrated by the 2010 Gulf of Mexico Deepwater Horizon oil spill. Though the long-term effects of the spill remain uncertain, the most recent research suggests some severe damages, including a loss of US$8.7 billion in revenue, profit, and wages from fisheries, and close to 22,000 jobs, over 7 years (Sumaila et al., 2012), as well as Woods Hole Oceanographic Institution research showing widespread damage to coral and associated species[7] and NOAA research showing severe impacts on dolphins.[8]

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[7] Woods Hole Oceanographic Institution (2012, March 26). Unprecedented impact of Deepwater Horizon on deep ocean revealed. *Science Daily*. Retrieved May 10, 2012, from http://www.sciencedaily.com/releases/2012/03/120326160825.htm.

[8] http://www.gulfspillrestoration.noaa.gov/2012/03/study-shows-some-gulf-dolphins-severely-ill/.

In the Gulf of Mexico exploratory activities for oil and gas are conducted down to more than 3000 m 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. There is also pressure to allow exploration under the ice sheet in the Arctic, including in deep waters. So it seems that the Deepwater Horizon incident has done little to slow deep sea oil and gas exploration.

The marine minerals industry has seen unprecedented expansion, though this is limited in the deep sea. In waters deeper than 1000 m potential mineral resources include manganese nodules and cobalt-rich crusts, polymetallic sulphides and phosphorites (Roberts et al., 2005). 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, 2011). 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 1700 m below the surface (McCarthy, 2010). Since then also the Russian Federation has applied for permission to carry out exploratory mining on the Mid-Atlantic Ridge (van Dover et al., forthcoming).

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 500 m and 1200 m, 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 applications. The unusual characteristics of deep sea organisms, their unique adaptations that enable them to survive in dark, cold and highly pressurised 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).

It is thought that several species known to be associated with cold water corals may be a source of new biochemical resources which can be synthetically emulated (Maxwell et al., 2005). 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).

3.3. *Regulating services*

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', a series of biologically-mediated processes that transport organic material (carbon and other nutrients) from the ocean surface to deeper layers.

The biological pump recycles nutrients and provides 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, the deep sea provides a climate regulation service. 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 (Knittel and Boetius, 2009; Boetius and Knittel, 2010).

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 – 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. Cascades of dense shelf water transport 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).

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, 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, 2005).

For instance, deep-sea organisms can contribute to the biological controls of pests. There is evidence 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, these species represent a buffer for environmental changes and ecological shifts and this reduces the probability that the pathogens develop.

3.3.4. 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 300 m and CO_2 injection into geological formations below the seafloor (IPCC, 2005; Schubert et al., 2006; Davies et al., 2007). 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 sub-seabed 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. There are significant research efforts in this direction (Schubert et al., 2006) and commercial operation already exists, such as Sleipner in the North Sea and Snoehvit, in the Barents Sea.

If scenarios of large scale carbon capture and storage under the deep seabed become a reality, the locations beneath 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 need to be assessed (Inagaki et al., 2006).

3.4. Cultural services

Exploration of the deep sea was accelerated by the desire for communication, exemplified by the need for sea floor knowledge in order to lay submarine cables, for instance between the US and Europe in the mid-1800s (Rozwadowski, 2008). The endeavours of Beebe and Barton in the submersible Bathysphere in the first half of the 20th century produced great interest and learning from the deep sea. Today there are many people, and significant investment, involved in studying the marine environment, including the deep sea. There are some estimates of numbers and expenditures (see e.g. Pugh (2008)) and some attempts to convert these into values of 'educational and scientific services' (see e.g. Austen et al. (2009) and 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. 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 (Nellemann et al., 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 aesthetic services, fascination with the deep sea can be traced way back, for instance to the biblical story of Jonah and the whale, and in literature such as Jules Verne *Twenty Thousand Leagues under the Sea*. Today 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 on-going flow of discoveries of scientific, educational and entertainment value over a long period. 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 (Danovaro et al., 2008a). Even the growing industry of whale watching may depend, to some 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 widespread rejection of human use of whale meat or seal fur. Actual bequests to environmental NGOs have been used in the UK NEA as a proxy for part of non-use values (Bateman et al., 2011). 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.

4. Valuation of deep-sea ecosystem goods and services

While it is clear that deep-sea ecosystem goods and services are extremely valuable, this does not in itself justify the attempt to express these values in monetary terms.[9] It is a difficult task, but there are several reasons why we might attempt it. These have slightly different requirements in terms of baselines and required accuracy.

- *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 developing overall political strategies. 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 – in order to explore possible consequences under uncertain futures, without attempting accurate prediction.
- *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. Accuracy is desirable, though it may be enough to demonstrate relative ranking of options.
- *Pricing decisions*: there are many situations in which pricing can be used as a tool for environmental management, even in

[9] For further discussion on valuation and marginal values see for instance *The Economics of Ecosystems and Biodiversity* (*TEEB*): *Ecological and Economic Foundations* report (TEEB, 2010).

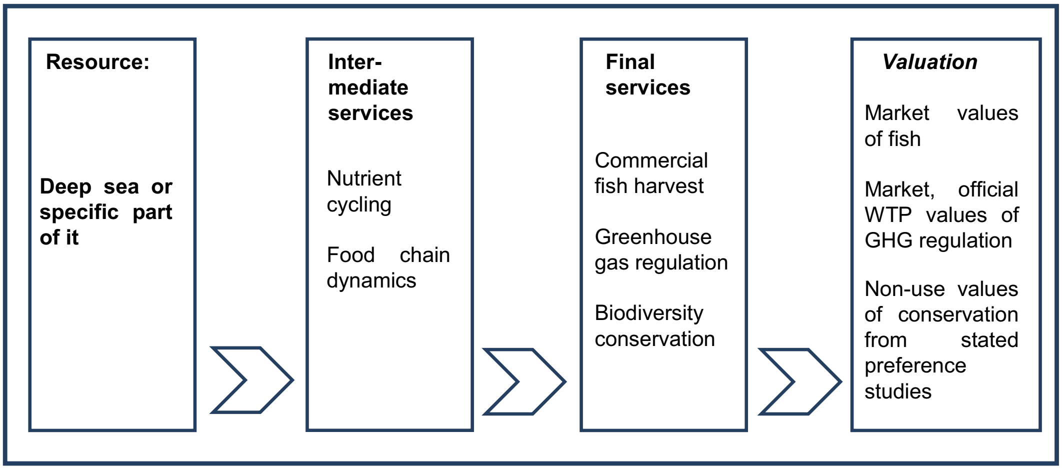

Fig. 2. Steps in valuation.

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 higher.

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 cannot 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.

4.1. Steps in valuation

Fig. 2 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.

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 1, we present an assessment of the state of knowledge for the various ecosystem goods and services provided by key deep-sea habitat types.[10]

4.2. Knowledge, values and valuation

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 use

[10] 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.

Table 1
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 and 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 and climate regulation	0	?	+	0	+	+	+
	Waste absorption and detoxification	0	+	+	0	0	+	0
	Biological regulation	?	+	?	?	+	+	0
Cultural services	Educational	+	+	+	+	+	+	+
	Scientific	+	+	+	+	+	+	+
	Aesthetic	+	?	?	?	+	+	0
	Existence/Bequest	+	?	?	?	?	+	?

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 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 and van den Hove, 2008).

This can be interpreted as growing knowledge resulting in new value: by improving knowledge, we gain not merely better understanding of the values created by deep sea environments, but also new types of value and new opportunities for 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.

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, direct use of deep-sea resources and other indirect impacts of human activities (e.g. contamination from land-based sources), and we are not able to make reliable assessments of the value changes 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 although 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.

From the perspective of valuation, Table 2 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., 2010).

As indicated in Table 2, there are several important gaps in our knowledge that prevent both non-monetary and 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

Table 2
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. (Key: blue = good knowledge; green = some knowledge; yellow = little knowledge; grey = no knowledge; white = irrelevant). SP refers to stated preference methods.

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

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 initially, 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 alternative 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[11]; research on rationality in the field of decision sciences; and research on (and implementation of) the precautionary principle and decision-making under uncertainty and ignorance.

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

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. Achieving this will require wide recognition – from scientists, funders and decision makers – of the importance both of sustained funding for interdisciplinary research in the deep sea, and of clear communication of deep sea knowledge at the science-policy interface.

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