Marine Policy 94 (2018) 71–80

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

The economic value of the deep sea: A systematic review and meta-analysis

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ARTICLE INFO

Keywords:
Deep sea
Ecosystem value
Deep sea mining
Systematic review
Meta-analysis
Ecosystem services

ABSTRACT

The deep sea has become an area of increasing interest due to the potential for mining the seafloor for valuable minerals. However, a critical knowledge gap in terms of understanding the economic value that the deep sea provides to societies makes it extremely difficult to estimate the long term economic impacts of mining activities. This article conducts a systematic review and meta-analysis of previous literature on the economic value of the deep sea, with the objective of integrating the findings of previous literature and identifying areas for future research. 25 studies were included in the systematic review, of which 15 were included in the meta-analysis. Although the systematic review reveals a lack of sufficient data to accurately estimate the economic value of the deep sea, the meta-analysis indicates that the functioning of the deep sea as an ecosystem significantly influences the economic value that it provides to society. The limited number of studies identified, along with the broad variety in their methods, scope, valuation perspective and purpose, emphasizes the need for future research into economic value-aspects of the deep sea. More importantly, this study reveals an urgent need for further scientific research into the deep sea's ecosystem in order to ensure the resource is managed sustainably in the long-term.

1. Introduction

The deep sea, defined as that part of the ocean deeper than 200 m and beyond the shelf break, forms the largest ecosystem on the planet, providing ecosystem goods and services that are deemed crucial to supporting and sustaining human wellbeing [1–3]. For example, deep sea marine environments are crucial for nutrient cycling, carbon absorption and contain a diverse set of genetic resources and biological substances, many of which are unique to these environments [4–6]. Further, deep sea marine environments contain significant deposits of valuable minerals such as zinc, copper, gold and silver [7,8]. Until relatively recently it was neither technologically nor economically feasible to extract these deposits, leaving the ocean floor substantially unblemished by mining activity. This, however, is rapidly changing. Increasing mineral prices and the development of a process known as Deep Sea Mining (DSM) has opened the deep sea to mining exploration and exploitation [9]. DSM is an attractive proposition for investors, as mineral deposits are of a higher grade than those found on land and contain rare earth elements, which are an important component in new technologies within the clean energy, military and consumer electronics sectors [10].

DSM can be undertaken to extract different forms of minerals from different types of ecosystems on the ocean floor. The most common source is high-grade polymetallic Seafloor Massive Sulphide (SMS) deposits found in the ecosystem of hydrothermal vents, which have been identified in the Manus Basin of Papua New Guinea, in the Atlantic Ocean and in the Red Sea [8,11,12]. Hydrothermal vents are most likely to be mined because of their high concentration of copper, zinc, gold and silver [13]. Other sources of minerals in the deep ocean floor include polymetallic nodules, manganese crusts and metalliferous muds [7], many of which are found in the ecosystem of abyssal plains, at depths of 4000 – 4200 m [14].

In response to investor demand, a large number of DSM exploration licenses have been granted in international waters governed by the International Seabed Authority (an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea) as well as within the exclusive economic zones of many coastal nations. The current extent of exploration licenses is difficult to ascertain, however reports suggest that exploration licenses have been granted for more than 1.5 million km^2 of the Pacific Ocean floor alone [15,16].

While to date only one country (Papua New Guinea) has granted a license to mine the deep sea, the rapid development of the industry is cause for much concern given the importance of the deep sea as an ecological asset, and given the myriad of uncertainties that surround DSM and its environmental and social impacts. As noted by The World

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https://doi.org/10.1016/j.marpol.2018.05.003
Received 2 February 2018; Received in revised form 2 May 2018; Accepted 3 May 2018
Available online 11 May 2018

Table 1
Search terms and engines.

Databases/Search Engines	Search terms
Google Scholar (GS)	Deep sea AND value: GS, G, SD, EL (no date, and 2016)
ScienceDirect (SD)	Deep sea AND benefit: GS, G, SD, EL (no date, and 2016)
EconLit (EL)	Deep sea AND cost: GS, G, SD, EL (no date, and 2016)
Google (G)	Deep sea AND monetary: SD, EL, G, GS (no date, and 2016)
	Deep sea AND dollar: G, GS, SD, EL (no date, and 2016)
	Ocean AND value: G, GS, SD, EL (no date and 2015, 2016),
	Ocean AND benefit: G, GS,SD, EL (no date and 2015)
	Ocean AND cost: EL, SD, G, GS (no date and 2015)
	Ocean AND monetary: GS, G, EL, SD (no date and 2016)
	Ocean AND dollar: G, GS, SD, EL (no date and 2016)

Bank in their report on the management of DSM in the Pacific [10]:

> In response to suggestions of large potential revenue streams, many nations have granted exploration permits even as regulatory and institutional capacities remain weak and environmental and social impacts are still yet to be fully understood. There are material information gaps, for which economic, environmental and social impacts remain uncertain and that carry an element of risk into these development schemes.

Of further cause for concern is that The World Bank considers a key driver of interest and investment in DSM to be [10]:

> …a significant likelihood that the environmental externalities that derive from DSM can remain undetected in the short run (across the short anticipated mine lives), or that their impacts will be felt further afield, and may not be immediately identified as resulting from DSM.

These concerns have led The World Bank to recommend that the precautionary principle be applied and that sound cost-benefit analyses of proposed DSM projects be undertaken before they proceed. Unfortunately, there are large information gaps that make undertaking a cost-benefit analysis very difficult, if not impossible. One critical gap is a lack of understanding of the value (in monetary terms) of the ecosystem services provided by the deep sea in its current state – it is this value that is potentially at risk from DSM. It should be emphasized that the environmental impacts from DSM differ considerably from the environmental impacts from deep sea fishing, e.g. deep sea trawling. These differences will be discussed in further detail in later sections.

The purpose of this paper is to conduct a systematic review and meta-analysis of the economic value of the deep sea in order to address three questions: (1) What is currently known about the economic value of the deep sea? (2) Do sufficient data exist to estimate the value of the deep sea in monetary terms? (3) What are the future research priorities in this area? To the best of our knowledge, no previous study has previously conducted either a systematic review or a meta-analysis on the economic value of the deep sea.

The paper is structured as follows: Section 2 describes in detail the methodological process of conducting the systematic review and meta-analysis, and summarises the included studies. Section 3 covers the meta-analysis, where the theoretical background for building the statistical model is outlined and explained, and the results of the meta-analysis are presented and interpreted. Section 4 discusses the results of both the systematic review and the meta-analysis, and draws lessons from these by identifying future research priorities for those seeking to better understand the economic value of the deep sea. Section 5 concludes.

2. Method: systematic review

The objective of this study is to integrate the findings of previous literature on the deep sea's economic value through a systematic literature review and meta-analysis. A systematic review is defined as a research method that "…attempts to collate all empirical evidence that fits pre-specified eligibility criteria in order to answer a specific research question" [17]. A systematic review is qualitative in nature and does not necessarily include a meta-analysis. However, it is common for a systematic review to include a meta-analysis, as this makes it possible to conduct a statistical summary of the literature identified in the review. Glass [18] defines a meta-analysis as "…the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings. It connotes a rigorous alternative to the casual, narrative discussions of research studies". The methodology adopted in this study reflects the main principles of the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-analysis) set forth by the Cochrane Collaboration [17,19].

The literature included in both the systematic review and the meta-analysis were identified through a three step process: (1) identification of literature via various databases and search engines; (2) screening of the identified literature to ensure appropriateness for the research questions of this study; and (3) eligibility assessment in which pre-specified eligibility criteria had to be satisfied in order to be included in the subsequent meta-analysis. These steps are described in detail below.

2.1. Identification of literature

First, all of the relevant literature was identified through an initial search. This was done by searching databases and search engines with the search terms [Table 1]. Literature available on-line as of September 2016 was included in the identification process, but literature published prior to 1990 was excluded. Because the economic value of the deep sea presents such a significant research gap in academic literature, the literature identified included peer-reviewed academic journal articles as well as grey literature, e.g. working papers, un-published Ph.D. dissertations and conferences proceedings from credible sources, e.g. government websites. However, internet- and news articles were excluded from further assessment, as were literature from sources deemed non-credible. Searches were organised by 'relevance', with the first 100 results of the search terms considered because search results beyond the 100th result led to literature of little relevance. The initial search led to the identification of 708 papers. Of these, 219 papers were duplicates.

2.2. Screening

The remaining 489 research papers went through a screening process. Special attention was given to studies that investigate the relationship between the environmental goods and services of the deep sea and economic outputs, e.g. cost, revenue, net benefits, etc. Studies that exclusively investigate non-economic aspects of the deep sea, such as geophysics, biology, oceanography, etc. were excluded from further assessment. Studies were included for further eligibility assessment if they specifically investigated an economic value- aspect of the deep sea or open ocean, e.g. the economic revenue of deep sea fishing in a

Table 2
Eligibility and exclusion criteria.

Criterion	Eligibility criteria	Exclusion criteria
Timeline or period	After 1990; Before 30 Sept 2016	Before 1990; After 1 Oct 2016
Language	English	Non-English
Literature Type	Peer-reviewed in academic journals, grey literature, working papers from credible institutes and sources; un-published PhD dissertations or working papers, conference proceedings	Internet articles; power point presentations, non-credible sources, news items
Publication Status	Published and/or available on-line	Others, e.g. published but unavailable sources
Sector	Deep sea, open ocean[a]	Coastal marine ecosystems, such as mangroves or coral reefs; terrestrial ecosystems
Locations	Global, region- and country-specific	Coastal locations, such as mangroves, coral reefs etc.
General Topics	Monetary estimates of deep sea-value, or of an aspect of the deep sea or open ocean	Failure to estimate or identify a new monetary value based on research methodology[b]
Methodologies (e.g. quality of research)	Discrete choice experiments, contingent valuation, cost-benefit analysis, economic impact assessment, net value, present value	Non-economic methodologies related to (e.g.) Geophysics, biology, geography, chemistry, oceanography, politics, topography etc.; or secondary estimates reported from other literature

[a] A few studies that estimate the economic value of the open ocean, including the deep sea as an ecosystem.
[b] Except for Foley, et al. [20].

particular area [20]. Studies that assess the economic value of coastal ecosystems, such as coral reefs and mangroves, were excluded from further eligibility assessment as these ecosystems lie outside of the realm of the deep sea. From the screening process, 65 papers included economic value assessments relevant to the research questions, whereas the remaining 424 papers were excluded as these did not produce economic value estimates relevant for the research questions. Next, the 65 papers were assessed for eligibility.

2.3. Eligibility and exclusion

The 65 papers assessed for inclusion in the systematic review and meta-analysis went through several stages of eligibility assessment [Table 2]. The results are depicted below [Fig. 1]. First, papers were deemed eligible for inclusion if they estimated a monetary value of one or more marine ecosystems related to the deep sea. Papers that estimate the economic value of broader aspects of marine systems, e.g. the pharmaceutical value of global marine biodiversity [21] were excluded for further assessment. However, the authors would like to acknowledge that the exclusion of papers that estimate the value of marine biodiversity may have led to the exclusion of important monetary estimates. It is almost impossible to separate the 'deep sea' from the remaining part of the ocean in terms of the biodiversity-value the deep sea generates because marine ecosystems exchange vital ecosystem goods and services. Nonetheless, the ambiguity of ecosystem limits and the difficulty of separating the economic values of the deep sea from other marine ecosystems can also lead to important insights. The difficulty of deciding where the value of the deep sea 'starts and stops' is reflected in papers that estimate the value of global marine biodiversity, or simply aspects of marine biodiversity [2,21,22], these papers make it clear that the limits of biodiversity are ambiguous, i.e. the marine biodiversity of the deep sea contributes to the marine biodiversity of other marine ecosystems, and vice versa. Whereas coastal areas can be excluded from further assessment, a few studies that estimate the economic value of the open ocean have been included as the deep sea constitutes the majority of the open ocean. The merits and shortcomings of this inclusion will be discussed later.

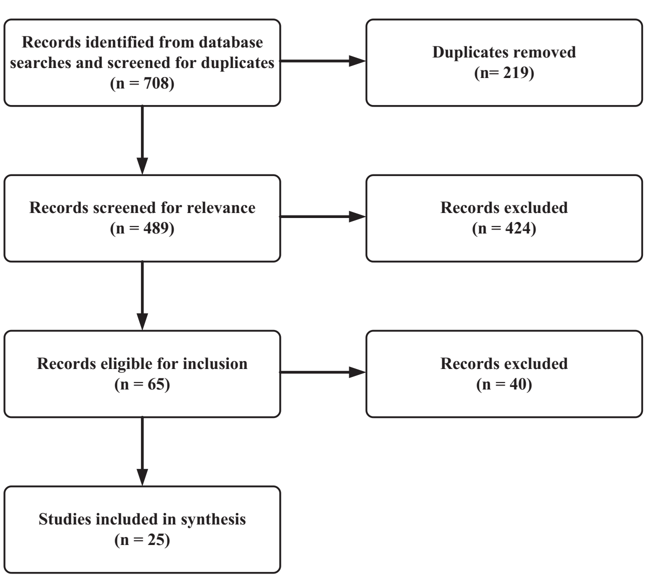

Fig. 1. Screening of studies. This diagram was constructed according to American Psychological Association Meta-Analysis Reporting Standards [21].

Second, papers were excluded from the systematic review and meta-analysis if they discussed aspects of marine ecosystem values without also estimating a monetary value of marine ecosystems. However, some of the excluded papers discuss relevant aspects of the value of marine ecosystems in relation to their quality, importance or functioning [21,23]. Even though these papers were excluded from further assessment, their viewpoints and qualitative findings have been included in the discussion of the results of this paper (Section 4) in order to draw lessons on the implications of the findings, put results into perspective and identify important research gaps for methodological advancement in ecosystem valuation.

2.4. Overview of included studies

As a method for organising the literature, this review groups studies according to the type of ecosystem service that the study is seeking to value, as developed by the Millennium Ecosystem Assessment [24]. The Millennium Ecosystem Assessment groups ecosystem services according to the following four categories: (1) Provisioning services – the products used by humans that are obtained directly from habitats and ecosystems (e.g. fish, minerals); (2) Regulating services – the benefits obtained through the natural regulation of habitats and ecosystem processes (e.g. climate regulation, carbon sequestration); (3) Cultural services – the non-material benefits people obtain from habitats and ecosystems (e.g. recreation, aesthetic enjoyment); and (4) Supporting services – nutrient cycling, primary production etc. [3]. However, none of the included studies produce monetary estimates for supporting services. For that reason, this paper groups the monetary values in the studies according to provisioning, regulating and cultural services – but not supporting services. In addition to these three groups, one additional category of 'total' ecosystem service value is included which is for value estimates that represent two or more ecosystem service categories. It should be emphasized that economic value estimates from studies that estimate the loss or cost of certain deep sea activities are categorised as “provisioning” services, as these value estimates represent losses in provisioning services. An overview of the studies included in the systematic review, describing the type of ecosystem services being valued and the method of valuation is provided as [Appendix A].

2.5. Review of studies included in the systematic review

The existing literature on the monetary valuation of deep sea values is extremely diverse and differs in scope, purpose and methodology. A few studies have estimated the monetary value of the open ocean[1] [25–28]. These studies estimate either the total monetary value of the global open ocean in a particular year, or the unit-value of the open ocean, e.g. the open ocean's ecosystem flow-value per hectare per year. Other studies estimate people's willingness to pay (WTP) for specific features or aspects of the deep sea. For example, Ressurreição, Gibbons, Dentinho, Kaiser, Santos and Edwards-Jones [29] and León, Araña and Melián [30] employ the contingent valuation method to estimate the WTP of visitors to the Azores and Spain, respectively, to preserve marine species in the countries' deep seas. Employing choice experiments, Jobstvogt, Hanley, Hynes, Kenter and Witte [1] and Aanesen, Armstrong, Czajkowski, Falk-Petersen, Hanley and Navrud [31] estimate people's WTP for protecting or preserving ecologically important aspects of the deep sea, e.g. cold-water corals or deep sea-biodiversity, in Scotland and Norway respectively.

Several studies investigate the market value of country-specific areas of the deep sea, either by estimating the present value, or net value added, of ecosystems goods and services provided by the deep sea. Most of these studies are concerned with the market value of landed deep sea-ecosystem goods, such as fish species, bottled deep-sea water and cold-water corals [20,32–37]. However, a small number of studies estimate the potential market value of ecosystem goods, e.g. the market value of the existing (non-landed) krill stock in the Southern Oceans [38] or the possible gross revenue from DSM operations [12,39,40] in specific locations. Another group of studies [2,41,42,43] assess and estimate the economic cost of environmental damage in the deep sea, e.g. the cost of oil spills, or the cost of restoring ecosystem services following environmental damage from DSM activities.

A few studies provide more specific estimates of particular actions or value potentials of human interaction with deep sea resources. For instance, Armstrong, Foley, Tinch and van den Hove [32] estimate the annual CO_2 tax money saved by injecting CO_2 into deep sea grit formations in Norway; along with the global economic value of carbon absorbed by the deep sea's ecosystem and the potential market value of deep sea-enzymes. In two recent studies, Vendeville, Fadhel, Magraoui and Sacchi [44] estimate the annual increase in economic profit and rent from better environmental management of the deep-water rose shrimp trawl fisheries in Tunisia, and Mangi, Kenny, Readdy, Posen, Ribeiro-Santos, Neat and Burns [45] estimate the economic reduction in vessel wages and gross value added from changes to deep sea fishing regulations in the EU, using the UK as a case study.

Most of the studies included in the systematic review of the economic value estimates of the deep sea are restricted to a country or a regional area, i.e. their economic analysis is not applicable to the global deep sea-area. The results of the studies are extremely varied, and the monetary estimates they produce are influenced by the area studied, methodology and purpose of conducting the economic valuation. The monetary estimates are typically expressed either as a total cost, revenue or net-benefit,[2] or as a unit-value, e.g. economic output / ha / year. A variety of methods are employed, such as cost-benefit analysis, empirical analysis of economic values, data interpolation, non-market valuation methods and economic impact assessments.

2.6. Value perspectives in the context of ecosystem services

It should be emphasized that the environmental damage from DSM activities on the deep-sea environment differ substantially from the environmental damage from deep-sea fisheries on deep-sea cold water corals and sponges. The DSM process involves several types of direct damages to the deep-sea environment, including direct damage to benthos organisms,[3] resedimentation and discharges of particulates, and potential upwelling and ocean pollution [9,46,47]. Environmental damage to cold water corals in the deep sea can occur because of DSM activities, but also because of deep-sea trawling (deep-sea fishing) and ocean acidification [48]. Therefore, the economic values derived from DSM and deep-sea fisheries differ substantially, as do the environmental costs associated with each of these activities.

The literature generally reports use- and/or non-use value(s) of regulating, provisioning and cultural ecosystem services delivered by the deep sea ecosystem. These ecosystem services deliver benefits to society by changing human wellbeing, either through direct use (e.g. fisheries catch for final consumption), indirect use (e.g. krill catch and deep sea enzymes as inputs to the production process) or non-use (e.g. knowledge that deep sea biodiversity is conserved via improved environmental management) pathways [49]. The benefits of these ecosystem service deliveries could be valued from an economic welfare perspective or from an accounting value perspective. From an economic welfare perspective, consumers' surplus and producers' surplus in combination provides the appropriate measure of the total net benefit delivered to consumers and producers [50–52]. Consumers' surplus comprises consumers' total willingness to pay net of total expenditure, and producers' surplus comprises producers' total revenue net of total costs. From a national accounting perspective, the value that ecosystem services deliver is reported as the product of exchange prices and exchange quantities for the goods and services concerned. These exchange prices and quantities are usually derived from market transactions for marketed good and services [53]. The product of exchange prices and exchange quantities, or exchange values, are defined as “the total value of income, production and expenditure as evidenced by transactions” [54].

The distinction between the economic welfare and accounting value perspectives is retained in the subsequent meta-analysis. Replacement cost is also included as a third valuation perspective. Replacement cost assigns a value to an ecosystem service by determining the minimum cost that would be required to replicate the function delivered by the ecosystem service if the service ceased to provide that function (e.g. the cost of replacing or restoring the damaged deep-sea bed following DSM activities). Replacement cost adopts the ‘price multiplied by quantity’ perspective of exchange value, but the ‘price’ used is that associated with the unit cost of the least expensive alternative mechanism for delivering the desired function in the absence of the original ecosystem service.

3. Meta-analysis

The purpose of the meta-analysis in this paper is to investigate potential systematic trends that may be present amongst the wide ranging studies on the economic value of the deep sea, and to identify if there are factors that influence these values. From the outset it should be acknowledged that the broad variety of the studies included in the systematic review makes it difficult to standardize and compare their results in statistical terms. The following sub-sections explain how the

[1] “Open ocean” refers to the part of the ocean that does not include coastal areas, i.e. it includes the deep sea and the non-coastal epipelagic zone at depths lesser than 200 m.

[2] Net benefit = revenue - cost.

[3] Benthos refers to the collection or organisms that live on or in the ocean floor, including flora and fauna.

values, as reported in primary studies, are standardised, followed by descriptions on moderator variables, and the meta-regression models. The final sub-section presents results.

3.1. The value of the deep sea

The 25 studies identified [Fig. 1] for further review report a wide range of values as either (welfare-consistent) net benefits, exchange values or replacement costs for the deep sea ecosystems. To conduct a meta-analysis, there is a minimal requirement that the dependent variable is measuring the same economic concept across observations [55]. This is to ensure 'effect-size' consistency in terms of uniformity in both the definition and type of the good being valued [56]. Previous meta-analyses on the value of marine and coastal resources [26,57] and wetland resources [58,59], take into account differences in reported time periods, areas of study and currencies by standardising the values into a common spatial, temporal and currency unit expressed as International dollars per area per time period – e.g. Int. $ / ha / year.

This paper follows this approach by restricting primary studies for inclusion in the metadata to those reporting the monetary value at a spatial scale that can be easily defined. This requirement eliminates 5 of the 25 primary studies from inclusion in the metadata. Some of the remaining 20 primary studies report valuation of the deep sea resources in terms of WTP [1,29–31]. These WTP (either per person or per household) require information on the relevant population and size of the study area, which is currently unavailable. Thus a further 5 studies are excluded leaving only a subset of 15 primary studies that are deemed to be reporting value estimates that would meet the minimal level of 'effect-size' consistency or uniformity. The 15 primary studies together yield 35 observations to be included in the meta-analysis. A summary of the primary studies is shown below [Table 3].

Study sources include journal articles, reports and working papers, conducted between 2003 and 2016. Just under half of the primary studies provide multiple estimates of the deep sea value, and the inclusion of multiple observations from the same study to increase the sample size is a common practice in meta-analysis [55]. Aiming to achieve effect-size consistency criterion at the minimum, the categorisation by value perspective is retained in this meta-analysis section. The *net benefits* group consists of net benefit estimates (i.e. net present value of a proposed project, or net values of deep sea ecosystem services delivered to society). Included within this group is a paper by Sumaila, Cisneros-Montemayor, Dyck, Huang, Cheung, Jacquet, Kleisner, Lam, McCrea-Strub, Swartz and Watson [6] who produce estimates of the loss in revenue, profit and wages as a result of the Deepwater Horizon oil spill in the Gulf of Mexico. This loss in revenue, profit and wages is assumed to indicate the (foregone) net benefit of the deep sea natural resources to society, and therefore is recorded as a positive value in the metadata, i.e. 1.37 billion rather than − 1.37 billion. It is however, worth noting that the net benefits from this study is biased upward from the true welfare-consistent value because wages indicate the cost of using labour as an economic input.

The *replacement cost* category of value refers to the costs of undertaking rehabilitation activities to restore the flows of ecosystem services which may be impaired as a result of natural resource exploitation. Given the extremely sparse primary valuation studies on the economic value of the deep sea, the cost of restoration (i.e. *replacement cost*) is used as an estimate of the value, assuming that society would be willing to pay those costs to restore the functions of the deep sea ecosystem. In this instance, the cost of restoration is recorded in the regression dataset as a positive value, i.e. 23,172 rather than − 23,172. Similarly, studies which report the value of ecosystem services lost or impacts following a DSM operation are also recorded as a positive value in the regression dataset [42,43].

The *exchange value* category refers to estimates of the market value of extracted natural resources that are traded in commodity markets such as commercial fish catch [35], krill catch [38], minerals [12,40],

Table 3
Primary studies included meta-data (15 studies, 35 observations).

Author & year	Title	Valuation perspective	Site	Obs	Type of publication	Value range (Int. $ 2011)
Armstrong et al. [32]	Ecosystem goods and services of the deep sea.	Net benefit	Norway, Europe, Global	2	Report	51.65–112 billion
Batker and Schmidt [42]	Environmental and Social Benchmarking Analysis of Nautilus Minerals Inc. Solwara 1 Project.	Replacement cost	PNG	2	Report	23,172–18.58 million
Bertram et al. [12]	Metalliferous sediments in the Atlantis II Deep—Assessing the geological and economic resource potential and legal constraints.	Exchange value	Red Sea (Saudi Arabia/ Sudan)	1	Journal article	362 billion
Binney and Fleming [43]	Counting the Potential Cost of Deep Sea-bed Mining to Fiji.	Net benefit	Fiji	2	Report	1.18–24,314
Cardno [39]	An Assessment of the Costs and Benefits of Mining Deep-sea Minerals in the Pacific Island Region: Deep-sea Mining.	Net benefit, Replacement cost	PNG, Cook Islands, RMI	5	Report	235,351–42.87 million
Costanza et al. [25]	Changes in the global value of ecosystem services.	Net benefit	Global	1	Journal article	7.01
de Groot et al. [26]	Global estimates of the value of ecosystems and their services in monetary units.	Net benefit	Global	1	Journal article	1.43
Grant et al. [38]	Ecosystem services of the Southern Ocean: Trade-offs in decision-making.	Exchange value	Southern Ocean (Antarctic)	1	Journal article	473 million
Jin, Hoagland and Wikgren [35]	An empirical analysis of the economic value of ocean space associated with commercial fishing.	Exchange value	Gulf of Maine, U.S.	1	Journal article	145,643
Li and Fang [27]	Global mapping and estimation of ecosystem services values and gross domestic product	Net benefit	Global	1	Journal article	5.28
Murillas-Maza et al. [28]	The value of open ocean ecosystems: A case study for the Spanish exclusive economic zone.	Net benefit	Spain	8	Journal article	29.5 million to 5.05 billion
Pendleton et al. [36]	Assessing the value of marine and coastal ecosystem services in the Sargasso Sea.	Net benefit	Sargasso Sea	6	Working paper	33,385–274.25 million
Seidel and Lal [40]	Economic Value of the Pacific Ocean to the Pacific Island Countries and Territories	Exchange value	Pacific Islands	1	Report	1.39 trillion
Sumaila et al. [6]	Impact of the Deepwater Horizon well blowout on the economics of US Gulf fisheries	Net benefit	Mexico	1	Journal article	1.37 billion
Van Dover et al. [2]	Ecological restoration in the deep sea: Desiderata	Net benefit	PNG, Scotland	2	Journal article	1.13–1.26 million

and enzymes [32].

Of the 35 observations included in the meta-analysis, 25 observations reflect net benefit estimates, and the remaining 10 observations reflect replacement cost and exchange values equally. Net benefit, replacement cost and exchange values for all studies are standardised to 2011 International dollars per km^2 per year (I$/$km^2$/year), following similar procedures described in de Groot et al. [26]. Local currencies are standardised to International dollars using official datasets on exchange rates, GDP deflators and purchasing power parity conversion factors based on World Bank Development Indicators [60] for all countries in the dataset with the exception of Taiwan, where the relevant statistics are based on the International Monetary Fund's World Economic Outlook [61]. If net benefits and replacement cost values are reported as a 'total', these values are annualised using the discount rate and number of periods reported in the primary valuation study [57,58] or a 7% rate in the two primary studies (3 observations) that did not state a discount rate [58].[4] Finally, annual deep sea values are converted into annual value per km^2 using the area provided in the studies. Values are wide ranging spanning between 0.01 I$/$km^2$/year to 6 billion I$/km^2/year with a median value of 337 I$/$km^2$/year. The majority of observations (69%) have values less than 5000 I$/$km^2$/year.

3.2. Moderator variables

Like the systematic review, the value-observations in the meta-analysis dataset are categorised according to the ecosystem service categories of provisioning, regulating, cultural and total services. This categorisation, *ES*, expressed as dummy variables, forms the first group of moderators, which is similar to a meta-analysis by Reynaud & Lanzanova [59].

The second group of moderator variables, *SC*, control for specific characteristics of the primary studies, namely, valuation perspective (net benefit, replacement cost or exchange values) and whether or not the study is published in a peer-reviewed academic journal article.[5] The final group of moderator variables, *OTH*, refers to the scale (country, regional or global), whether the primary study is about deep sea mining, and whether the study is strictly referring to ecosystem services arising from deep sea ecosystems stocks, i.e. excluding open ocean-studies. All moderators are represented as dummy variables, noting that *replacementcost* is a baseline value for the valuation perspective moderators. A summary of descriptive statistics of the dependent and moderator variables are shown below [Table 4].

3.3. The meta-regression model

The dependent variable in the regression model is the natural logarithm of deep sea values measured in 2011 I$/$km^2$/year, labelled *lny*. The estimated regression model for the meta-analysis is specified as follows:

$$lny_{ij} = \alpha + \boldsymbol{\beta ES}_{ij} + \boldsymbol{\gamma SC}_{ij} + \boldsymbol{\delta OTH}_{ij} + \eta_{ij} \quad (1)$$

where the subscript i is an index for the value observation in study j; α is a constant term; $\boldsymbol{\beta}$,γ and $\boldsymbol{\delta}$ are vectors containing the coefficients to be estimated for the moderator variables ***ES*** (ecosystem service categories), ***SC*** (study characteristics) and ***OTH*** (other relevant drivers), respectively, η represents the usual error term.

As recommended in the meta-analysis literature [55], the model in Eq. (1) is estimated following a random-effects panel data approach with robust standard errors to accommodate potential correlation among observations belonging to the same primary study [56,59] as well as to accommodate between-study autocorrelation [59]. Under the random-effects panel data approach, the error term in Eq. (1) is split into two components, μ_j and ε_{ij}, to represent study-level and observation-level error terms, respectively. It is assumed that these two error components are uncorrelated with zero means $\{E(\mu_j) = 0$ and $E(\varepsilon_{ij} = 0\}$ [59] and separate estimable variances $\{Var(\mu_j) = \sigma_\mu^2 \text{and} Var(\varepsilon_{ij}) = \sigma_\varepsilon^2\}$.

3.4. Results of the meta-regressions

The results of the meta-regressions with and without the vector ***SC*** of study characteristics moderators are presented below [Table 5]. Model 2 (with SC moderators) delivers a somewhat better fit based on overall R^2. Both models identify statistically significant increases in valuation estimates if provisioning, regulating, cultural and 'total' ecosystem services are included in the valuation assessment. Whether or not the study is strictly about the deep sea (i.e. excluding open ocean-studies) also has a significant effect. The variable representing the scale of the study changes from being statistically significant at 10% level in Model 1 to not being statistically significant in Model 2; otherwise the signs of significant coefficients are similar between the two models. Since the *SC* moderator variables are individually and jointly not statistically significant based on a Wald test of joint significance of a subset of regressors (p-value = .2856), Model 1 is considered superior to Model 2 because more efficient estimates are obtained without the inclusion of the *SC* variables.

Three of the four ecosystem service categories, provisioning, regulating and cultural, have similar coefficient estimates, particularly in Model 1. This suggests that inclusion of any one of these ecosystem service categories increases the estimated value of the deep sea, by an approximately equivalent amount, all else remaining unchanged. This increase in the estimated value of the deep sea when ecosystem services are included in the valuation is much greater for Model 2. Specifically, the coefficient for *provisioning* ES in Model 1 implies that primary studies which include an estimate of the provisioning value of the deep sea are, on average, 123%[6] higher than comparable primary studies which do not. Similarly, across both models, studies that focus strictly on the deep sea are found to generate a substantially higher valuation compared to studies that do not. Increasing the scale of the study (national to regional to global) decreases the predicted value of the deep sea.

4. Discussion

The fact that the studies included in this systematic review are extremely diverse in terms of the geographical area of study, methodology employed, valuation perspective and motivation, makes it increasingly difficult to integrate the findings in order to answer the pre-specified research questions. Like previous meta-analysis studies [58,63] this study seeks to identify which factors influence the economic value of a specific ecosystem, i.e. the deep sea. However, the studies included in this systematic review are so varied that it is impossible with any confidence to estimate the (total) value of the deep sea in monetary terms, let alone determine how much (or how little) is known about the economic value of the deep sea as an ecosystem. Nonetheless, the systematic review and the meta-analysis results point to a few factors that influence the economic value of the deep sea.

[4] This discount rate is chosen as it is the most commonly employed discount rate in the studies contained within our dataset.

[5] There is a possibility that the dummy variable *refjournal* and the choice of *valuation perspective* variable are in some sense endogenous. This issue is problematic to address, however, because it is difficult to find valid instruments which are correlated to *refjournal* and *valuation perspective* but uncorrelated with the model error term.

[6] The exact percentage difference in the predicted value of the dependent variable given the two values of the binary variable is given by $100 \cdot [exp(\hat{\beta}) - 1]$. See [62] J. Wooldridge, Introductory Econometrics: A Modern Approach, 3rd ed., Thomson South-Western, USA, 2006.

Table 4
Descriptive statistics for meta-analysis.

Variable	Description	Mean	Std. Dev.
Dependent Variable			
lny	Value of the deep sea in millions of I$/km^2/year. The dependent variable is in natural log form (summary statistics are not in log form)	244	1059
Moderator Variables: Ecosystem Services (*ES*)			
provisioning	Provisioning ecosystem services is provided (=1)	0.371	0.490
regulating	Regulating ecosystem services is provided (=1)	0.143	0.355
cultural	Cultural ecosystem services is provided (=1)	0.114	0.322
total_es	Total ecosystem services is provided (=1)	0.086	0.284
Moderator variables: characteristics of the study (*SC*)			
Valuation Perspective			
netbenefit	Value is categorised as net benefit (=1)	0.714	0.458
exchangevalue	Value is categorised as exchange value (=1)	0.143	0.355
replacementcost	Baseline valuation perspective	0.143	0.355
refjournal	Study has been published in a refereed journal (=1)	0.457	0.505
Moderator variables: Other relevant drivers (*OTH*)			
deepsea	Whether study is strictly about the deep sea (=1)	0.486	0.507
scale	Categorical variable describing the scale of study (expressed in increasing order: national, regional, global)	1.571	0.739
dsmspecific	Whether study is about deep sea mining (=1)	0.342	0.481

Table 5
Meta-regression results with and without study characteristics (SC) moderators.

	Model	
Variable	1 (SE)	2 (SE)
Intercept	5.027 (4.84)	2.467 (6.36)
Moderator variables: Ecosystem Services (ES)		
Provisioning	4.819***(1.45)	7. 462*(4.13)
Regulating	4.906***(1.26)	6.737*(4.015)
Cultural	4.794***(1.47)	7.509*(4.48)
Total	12.705** (5.25)	12.181*(7.18)
Moderator variables: Characteristics of the study for valuation perspective (SC)		
Net-benefit		− 2.633 (4.27)
Exchange value		− 6.125 (5.10)
Refereed journal		3.080 (3.60)
Moderator variables: Other relevant drivers (OTH)		
Deep sea	13.158** (5.37)	13.876** (6.24)
Scale	− 5.469*(3.00)	− 4.248 (3.60)
DSM specific	− 0.173 (5.00)	1.005 (6.20)
n	35	35
R^2 within	0.131	0.098
R^2 between	0.553	0.634
R^2 overall	0.571	0.617
σ_μ^2	5.137	4.990

***,**,* are significant at the 1%, 5% and 10% levels, respectively. Values in parentheses represent the standard errors.

4.1. Insights from systematic review

The most obvious finding of the systematic review is that the economic value of the deep sea depends, by and large, on how societal and economic aspects interact with deep sea-resources. This is evident from several of the papers. First, Sumaila Cisneros-Montemayor, Dyck, Huang, Cheung, Jacquet, Kleisner, Lam, McCrea-Strub, Swartz and Watson [6] estimate the economic loss that society will experience as a consequence of the Deepwater Horizon oil spill in Mexico in 2012. This loss – or foregone net benefit – is created by human intervention, not by the deep sea's ecosystem services. Second, Hewamanage [20] estimates the economic efficiency of the deep sea fishing fleet of Sri Lanka by means of the annual net profit of deep sea vessels. This profit depends heavily on multiple economic aspects, such as (i) the capacity of vessels, (ii) capital costs, (iii) sales price of deep sea catches on-the-ground, etc. Third, Armstrong, Foley, Tinch and van den Hove [32] estimate the amount of CO_2 tax money saved by the Norwegian people from injecting CO_2 into a deep sea grit formation in Norwegian waters. The magnitude of the savings provided by the deep sea grit formation depends on Norway's current CO_2 tax-rate, the efficiency of the grit and other economic and engineering aspects – in short, aspects that are not related to the deep sea's ecosystem but to the capacity of human societies. Fourth, Grant, Hill, Trathan and Murphy [38] estimate the market value of the standing stock of krill in the Southern Ocean to be around $ 473 billion (2011 Int. $). However, the *future* market value of the krill stock is heavily influenced by how humans utilize the *current* krill stock in the Southern Ocean. Human intervention has the capacity to decrease or increase the future market value of landings depending on (i) how over-fishing is managed, (ii) whether operation- and capital costs of deep-sea fishing gear decreases or increases, or (iii) whether the demand for krill increases or decreases – higher demand leading to higher market prices. Fifth, the profitability of conducting deep sea mining-activities [2,12,39,40,42] will depend heavily on the sales price of the extracted deep sea minerals, the cost of conducting deep sea mining-activities, the willingness of society to accept ecological restoration costs,[7] etc. Finally, the laws and regulations that apply to human activities in the deep sea also influence the economic value that the deep sea's resources can – and will – provide to human societies. This is evident in the study exploring how changes in EU Regulations on deep sea catches will influence the profit derived from deep sea fishing [45].

4.2. Insights from meta-analysis

The meta-analysis conducted in this paper managed to identify a few factors that influence the economic value derived from the deep sea. These are mainly related to the specific ecosystem services that the deep sea provides to human societies, e.g. provisioning, regulating and cultural services. More importantly, the results indicate that the overall functioning of the deep sea as an ecosystem ("Total ecosystem services") is of high economic importance due to the high coefficient and statistical significance for this variable. Lastly, the results point to a high economic value of the deep sea in comparison with the ecosystem of the open ocean. Nonetheless, it has to be emphasized that the meta-analysis merely investigates which systematic trends may affect the monetary value of the deep sea. Given the limited number of studies, it is by no means conclusive in terms of concluding which factors determine or shape the economic value of the deep sea. The fact that only 25 papers were included in the systematic review and only 15 were included in the meta-analysis may have led to significant bias in the results. However, the study by Ojea and Martin-Ortega [63] also only

[7] Note that 'known' ecological restoration costs here refers to the current knowledge of what it may (hypothetically) cost to restore ecosystems from deep sea mining damage – not necessarily what it will actually cost to do so.

identified 25 studies for their meta-analysis on ecosystem service values of tropical forests in South and Central America. This highlights the tremendous research gap in the literature on ecosystem valuation for specific ecosystems, and the urgent need for future research into ecosystem values.

4.3. Limitations of this study

In spite of the statistically significant results and the lessons drawn from this meta-analysis, a few considerable limitations of this study must be emphasized. First, the lack of studies on the economic value of the deep sea resulted in a low number of observations which leads to the meta-regression suffering from limited degrees of freedom. There is a possibility that the meta-regression may be over-fitted as a consequence. Second, the meta-data may suffer from sample selection bias arising from the literature selection process described in Section 2. This sample selection process ensured that only the most relevant studies were included, in line with standard practice in systematic review methodology, as outlined in previous sections. There remains, however, a risk that the selected sample is not random, and therefore the meta-regression results may be found by chance and do not truly reflect the target population of the full set of valuation studies conducted for the deep sea. Third, the metadata-set contains a few observations with very large values that are likely to have "skewed" the results. Fourth, several of the studies focus on the economic profits or restoration costs associated with DSM activities, while few focus on the economic value of the functioning of the deep sea as an ecosystem, which is also likely to have affected our results. Fifth, the fact that the metadata was categorised into three broad categories of net benefit, exchange value, and replacement costs may have eliminated the possibility of distinguishing the difference between the economic values that, say, DSM and deep-sea fisheries generate. This may have led to misleading results. Taken together, these limitations may have led to errors in the reported statistical and economic significance of the findings. Thus, although regression results enable predictions to be derived for the outcome of a valuation of the deep sea under particular circumstances (following the procedures described by Wooldridge [62]) this paper refrains from doing so because the panel dataset is relatively small, particularly in the 'time' (i.e. number of observations within a primary study) dimension, so predictions would not be consistent [64]. The intention in fitting the meta-regression model to Eq. (1) is to identify the possibility of a systematic relationship between valuation outcomes and moderator variables, as a way of summarising the current state of progress in research on estimating the value of the deep sea. It is not the intention of this study to produce an exact prediction, but rather, to shed some light on likely links between variables of interest, to complement the systematic review component of this study.

In spite of the aforementioned limitations, this study represents – to the best of our knowledge – the first to attempt to collate and integrate the findings of previous literature on the economic value of the deep sea, through a systematic review and meta-analysis and thus represents a genuine contribution to the literature in this area.

4.4. Future research priorities

This study clearly highlights the need for future research into the economic value of the deep sea. The first point of insight for future research is that the value of the deep sea can be perceived as a flow-value for economies worldwide that increases or decreases depending on the ability of human societies to efficiently utilize and sustain its resources. The deep sea's economic value depends on a multitude of economic aspects not directly related to the deep sea – e.g. tax rates, sales prices, operation costs, equipment, transport efficiency, consumer preferences, etc. In the face of growing pressure on the deep sea, there is an urgent need to revise and optimise policy and legislation related to the extraction and utilisation of deep sea resources in order to facilitate more sustainable and resource-efficient use. The problematic part of this is that too little is known about the ecosystem of the deep sea to determine what is sustainable and resource-efficient, and what is not. For instance, it has previously been impossible to undertake a thorough scientific evaluation of the impacts of DSM projects due to the high number of rare and unknown species that live in and around the deep ocean floor [65].

Therefore, the second point of insight for future research into the economic value of the deep sea is that scientific research into the deep sea's ecosystem inevitably needs to precede further economic valuation, or at the very least be a part of the economic valuation. A better scientific understanding of the deep sea as an ecosystem would be particularly important for determining how changes in the deep sea's ecosystem services may make societies more or less vulnerable [19]. Research in this field is especially urgent as DSM exploration is currently underway, and may lead to large-scale mining in the near future. These insights further emphasize the strong link between the economic value of the deep sea's ecosystems and anthropogenic intervention. Although there is a tendency to avoid the valuation of ecosystems that are difficult to explore or understand [63], a more comprehensive valuation of the deep sea's ecosystem could help form better policies related to its resource use, sustainability – and lastly, its economic value.

5. Conclusion

The systematic review and meta-analysis conducted in this study has allowed the exploration of which factors influence the economic value of the deep sea in monetary terms. The limited number of studies included reveals that knowledge is very limited in this area. The economic value of the deep sea is, by and large, influenced by the scope, value perspective, purpose and methodology of the study in question. More importantly, the results reveal an important connection between anthropogenic intervention and the economic value derived. The variety of studies made it difficult to statistically integrate the findings in the meta-analysis. Nonetheless, the results indicate that particular ecosystem services, deep sea-specific values and the scale of the study are statistically significant in influencing the economic value of the deep sea. The high values reported for total ecosystem services emphasize the need for furthering our understanding of how the deep sea as an ecosystem generates economic value for human societies. In addition, further research is required into (1) different economic value perspectives of the deep sea, and (2) scientific aspects of the deep sea's ecosystem for sustainability and resource-use.

Acknowledgments

Financial support from Griffith University's Ph.D. scholarship programme is gratefully acknowledged. The authors are grateful for the constructive and useful feedback provided by Dr Jim Smart in developing this paper.

Declarations of interest

None.

Appendix A. Studies included in the systematic review

	Reference	Category	Method
1	Aanesen etal., [31]	Cultural	Individual willingness-to-pay (choice experiment)
2	Armstrong etal., [32]	Provisioning, regulating	Benefit or cost
3	Batker and Schmidt [42]	Provisioning	Net Economic Value, Benefit or cost
4	Bertram et al., [12]	Provisioning	Benefit or cost
5	Binney and Fleming [43]	Provisioning	Benefit or cost
6	Cardno [39]	Provisioning	Net Economic Value, Benefit or cost
7	Costanza et al., [25]	Total	Benefit or cost
8	de Groot et al., [26]	Total	Meta-analysis
9	Foley et al., [33]	Provisioning	Sales price
10	Foley et al., [34]	Provisioning	Benefit or cost, sales price
11	Grant et al., [38]	Provisioning	Sales price
12	Hewamanage [20]	Provisioning	Net Economic Value, Benefit or cost
13	Jin et al., [35]	Provisioning	Net Economic Value
14	Jobstvogt et al., [1]	Cultural	Individual willingness-to-pay (choice experiment)
15	Lee and Lee, [37]	Provisioning	Sales price
16	León et al., [30]	Provisioning, cultural	Individual willingness-to-pay (contingent valuation)
17	Li and Fang [27]	Total	Benefit or cost
18	Mangi et al., [45]	Provisioning	Benefit or cost
19	Murillas-Maza et al., [28]	Provisioning, regulating	Benefit or cost
20	Pendleton et al., [36]	Provisioning, cultural, total	Net Economic Value
21	Ressurreição et al., [29]	Cultural	Individual willingness-to-pay (contingent valuation)
22	Seidel and Lal [40].	Provisioning	Benefit or cost
23	Sumaila et al., [6]	Provisioning	Benefit or cost
24	Van Dover et al., [2]	Provisioning	Benefit or cost
25	Vendeville et al., [44]	Provisioning	Benefit or cost

References

[1] N. Jobstvogt, N. Hanley, S. Hynes, J. Kenter, U. Witte, Twenty thousand sterling under the sea: estimating the value of protecting deep-sea biodiversity, Ecol. Econ. 97 (1) (2014) 10–19.
[2] C. Van Dover, J. Aronson, L. Pendleton, S. Smith, S. Arnaud-Haond, D. Moreno-Mateos, E. Barbier, D. Billett, K. Bowers, R. Danovaro, Ecological restoration in the deep sea: desiderata, Mar. Policy 44 (1) (2014) 98–106.
[3] S. Arico, C. Salpin, Bioprospecting of Genetic Resources in the Deep Seabed: Scientific, Legal and Policy Aspects, Institute for the Advanced Study of Sustainability, Tokyo, Japan, 2005.
[4] A. Davies, J. Roberts, J. Hall-Spencer, Preserving deep-sea natural heritage: emerging issues in offshore conservation and management, Biol. Conserv. 138 (3) (2007) 299–312.
[5] S. Yooseph, G. Sutton, D. Rusch, A. Halpern, S. Williamson, K. Remington, J. Eisen, K. Heidelberg, G. Manning, W. Li, The sorcerer II global ocean sampling expedition: expanding the universe of protein families, PLoS Biol. 5 (3) (2007) e16.
[6] U. Sumaila, A. Cisneros-Montemayor, A. Dyck, L. Huang, W. Cheung, J. Jacquet, K. Kleisner, V. Lam, A. McCrea-Strub, W. Swartz, R. Watson, Impact of the Deepwater Horizon well blowout on the economics of US Gulf fisheries, Can. J. Fish. Aquat. Sci. 69 (3) (2012) 499–510.
[7] A. Ahnert, C. Borowski, Environmental risk assessment of anthropogenic activity in the deep-sea, J. Aquat. Ecosyst. Stress Recovery 7 (4) (2000) 299–315.
[8] P. Hoagland, S. Beaulieu, M. Tivey, R. Eggert, C. German, L. Glowka, J. Lin, Deep-sea mining of seafloor massive sulfides, Mar. Policy 34 (3) (2010) 728–732.
[9] T. Yamazaki, Impacts of upcoming deep-sea mining, in: S. Brunn (Ed.), Engineering Earth: The Impacts of Megaengineering Projects, Springer Science & Business Media, Netherlands, 2011, pp. 275–295.
[10] The World Bank, Precautionary management of deep sea mining potential in Pacific island countries. 〈http://pubdocs.worldbank.org/en/125321460949939983/Pacific-Possible-Deep-Sea-Mining.pdf〉. (Accessed 12 March 2017).
[11] Nautilus Minerals, Seafloor Gold & Copper Exploration. 〈http://www.nautilusminerals.com/s/Home.asp〉. (accessed 22 June 2015).
[12] C. Bertram, A. Krätschell, K. O'Brien, W. Brückmann, A. Proelss, K. Rehdanz, Metalliferous sediments in the Atlantis II Deep—Assessing the geological and economic resource potential and legal constraints, Resour. Policy 36 (4) (2011) 315–329.
[13] C. Van Dover, Tighten regulations on deep-sea mining, Nature 470 (7332) (2011) 31.
[14] International Seabed Authority, A Geological Model of Polymetallic Nodule Deposits in the Clarion Clipperton Fracture Zone, Technical Study No. 6, Kingston, Jamaica, 2010.
[15] Earthworks, Seabed mining, 〈https://www.earthworksaction.org/issues/detail/seabed_mining#.WOGkQ2-GNtQ〉. (Accessed 17 February 2017), 2017.
[16] International Seabed Authority, Exporation areas. 〈https://www.isa.org.jm/contractors/exploration-areas〉. (Accessed 17 February 2017), 2017.
[17] J. Higgins, S. Green, Cochrane Handbook for Systematic Reviews of Interventions, Wiley-Blackwell, Chichester, UK, 2008.
[18] G. Glass, Primary, secondary, and meta-analysis of research, Educ. Res. 5 (10) (1976) 3–8.
[19] P. Sierra-Correa, J. Kintz, Ecosystem-based adaptation for improving coastal planning for sea-level rise: a systematic review for mangrove coasts, Mar. Policy 51 (1) (2015) 385–393.
[20] L. Hewamanage, Economic efficiency of the deep sea fishing fleet of Sri Lanka. 〈http://www.unuftp.is/static/fellows/document/lalith09prf.pdf〉 (Accessed 12 February 2017).
[21] P. Erwin, S. López-Legentil, P. Schuhmann, The pharmaceutical value of marine biodiversity for anti-cancer drug discovery, Ecol. Econ. 70 (2) (2010) 445–451.
[22] N. Beaumont, M. Austen, S. Mangi, M. Townsend, Economic valuation for the conservation of marine biodiversity, Mar. Pollut. Bull. 56 (3) (2008) 386–396.
[23] B. Wiegmans, S. Dekker, Benchmarking deep-sea port performance in the Hamburg-Le Havre range, Benchmark. Int. J. 23 (1) (2016) 96–112.
[24] Millennium Ecosystem Assessment, Ecosystems and Human Well-being: current State and Trends, Island Press, Washington DC, USA, 2005.
[25] R. Costanza, R. de Groot, P. Sutton, S. van der Ploeg, S. Anderson, I. Kubiszewski, S. Farber, R. Turner, Changes in the global value of ecosystem services, Glob. Environ. Change 26 (1) (2014) 152–158.
[26] R. de Groot, L. Brander, S. van der Ploega, R. Costanza, F. Bernardd, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, S. Hussain, P. Kumar, A. McVittie, R. Portela, L. Rodriguez, P. ten Brink, P. van Beukering, Global estimates of the value of ecosystems and their services in monetary units, Ecosyst. Serv. 1 (1) (2012) 50–61.
[27] G. Li, C. Fang, Global mapping and estimation of ecosystem services values and gross domestic product: a spatially explicit integration of national 'green GDP'accounting, Ecol. Indic. 46 (1) (2014) 293–314.
[28] A. Murillas-Maza, J. Virto, M. Gallastegui, P. González, J. Fernández-Macho, The value of open ocean ecosystems: a case study for the Spanish exclusive economic zone, Nat. Resour. Forum 35 (2) (2011) 122–133.
[29] A. Ressurreição, J. Gibbons, T. Dentinho, M. Kaiser, R. Santos, G. Edwards-Jones, Economic valuation of species loss in the open sea, Ecol. Econ. 70 (4) (2011) 729–739.
[30] C. León, J. Araña, A. Melián, Tourist use and preservation benefits from big-game fishing in the Canary Islands, Tour. Econ. 9 (1) (2003) 53–65.
[31] M. Aanesen, C. Armstrong, M. Czajkowski, J. Falk-Petersen, N. Hanley, S. Navrud, Willingness to pay for unfamiliar public goods: preserving cold-water coral in Norway, Ecol. Econ. 112 (1) (2015) 53–67.
[32] C. Armstrong, N. Foley, R. Tinch, S. van den Hove, Ecosystem goods and services of

the deep sea, Deliverable D6 2 (1) (2010) 68.
[33] N. Foley, T. van Rensburg, C. Armstrong, The ecological and economic value of cold-water coral ecosystems, Ocean Coast. Manag. 53 (7) (2010) 313–326.
[34] N. Foley, T. van Rensburg, C. Armstrong, The rise and fall of the Irish orange roughy fishery: an economic analysis, Mar. Policy 35 (6) (2011) 756–763.
[35] D. Jin, P. Hoagland, B. Wikgren, An empirical analysis of the economic value of ocean space associated with commercial fishing, Mar. Policy 42 (1) (2013) 74–84.
[36] L. Pendleton, F. Krowicki, P. Strosser, J. Hallett-Murdoch, Assessing the Value of Marine and Coastal Ecosystem Services in the Sargasso Sea, Duke Environmental and Energy Economics Working Paper Series EE 14-05, Duke University, Durham, North Carolina, 2014.
[37] K. Lee, T. Lee, Opportunities and issues in the health tourism industry: deep sea water development in Taiwan, Tour. Anal. 20 (4) (2015) 419–424.
[38] S. Grant, S. Hill, P. Trathan, E. Murphy, Ecosystem services of the Southern Ocean: trade-offs in decision-making, Antarct. Sci. 25 (5) (2013) 603–617.
[39] Cardno, An Assessment of the Costs and Benefits of Mining Deep-sea Minerals in the Pacific Island Region: Deep-sea Mining Cost-Benefit Analysis, Suva, Fiji, 2016.
[40] H. Seidel, P. Lal, Economic Value of the Pacific Ocean to the Pacific Island Countries and Territories, IUCN, Gland, Switzerland, 2010, pp. 1–74.
[41] C. Armstrong, N. Foley, R. Tinch, S. van den Hove, Services from the deep: steps towards valuation of deep sea goods and services, Ecosyst. Serv. 2 (1) (2012) 2–13.
[42] D. Batker, R. Schmidt, Environmental and Social Benchmarking Analysis of Nautilus Minerals Inc., Solwara 1 Project, Earth Economics, 2015.
[43] J. Binney, C. Fleming, Counting the Potential Cost of Deep Sea-bed Mining to Fiji, A Report for WWF International, Mainstream Economics and Policy, Brisbane, Australia, 2016.
[44] P. Vendeville, H. Fadhel, A. Magraoui, J. Sacchi, Restoring the ecosystem creates wealth. The case of the Northern coast of Tunisia's deep-water rose shrimp trawl fishery, Fish. Res. 183 (1) (2016) 55–73.
[45] S. Mangi, A. Kenny, L. Readdy, P. Posen, A. Ribeiro-Santos, F. Neat, F. Burns, The economic implications of changing regulations for deep sea fishing under the European Common Fisheries Policy: uk case study, Sci. Total Environ. 562 (1) (2016) 260–269.
[46] J. Luick, Physical Oceanographic Assessment of the Nautilus EIS for the Solwara 1 Project, Prepared for the Deep Sea Mining Campaign, Austides Consulting, Adelaide, Australia, 2012.
[47] H. Oebius, H. Becker, S. Rolinski, J. Jankowski, Parametrization and evaluation of marine environmental impacts produced by deep-sea manganese nodule mining, Deep Sea Res. Part II: Top. Stud. Oceanogr. 48 (17) (2001) 3453–3467.
[48] J. Roberts, A. Wheeler, A. Freiwald, Reefs of the deep: the biology and geology of cold-water coral ecosystems, Science 312 (5773) (2006) 543–547.
[49] I. Bateman, G. Mace, C. Fezzi, G. Atkinson, K. Turner, Economic analysis for ecosystem service assessments, Environ. Resour. Econ. 48 (2) (2011) 177–218.
[50] A. Freeman, The Measurement of Environmental and Resource Values: Theory and Methods, 2nd ed, Resources for the Future, Washington DC, 2003.
[51] G. Ellis, A. Fisher, Valuing the environment as input, J. Environ. Manag. 25 (1) (1987) 149–156.
[52] E. Barbier, Valuing ecosystem services as productive inputs, Econ. Policy 22 (1) (2007) 177–229.
[53] B. Day, An Overview of Valuation Techniques for Ecosystem Accounting, University of East Anglia, Norwich, United Kingdom, 2013 (Working Paper).
[54] R. Brouwer, L. Brander, O. Kuik, E. Papyrakis, I. Bateman, A synthesis of approaches to assess and value ecosystem services in the EU in the context of TEEB, Amsterdam, 2013.
[55] J. Nelson, P. Kennedy, The use (and abuse) of meta-analysis in environmental and natural resource economics: an assessment, Environ. Resour. Econ. 42 (3) (2009) 345–377.
[56] L. Londoño, R. Johnston, Enhancing the reliability of benefit transfer over heterogeneous sites: a meta-analysis of international coral reef values, Ecol. Econ. 78 (1) (2012) 80–89.
[57] A. Ghermandi, P. Nunes, A global map of coastal recreation values: results from a spatially explicit meta-analysis, Ecol. Econ. 86 (1) (2013) 1–15.
[58] R. Woodward, Y.-S. Wui, The economic value of wetland services: a meta-analysis, Ecol. Econ. 37 (2) (2001) 257–270.
[59] A. Reynaud, D. Lanzanova, A global meta-analysis of the value of ecosystem services provided by lakes, Ecol. Econ. 137 (1) (2017) 184–194.
[60] The World Bank, World Bank Development Indicators. ⟨http://wdi.worldbank.org/table/4.16⟩. (Accessed 19 December 2017).
[61] International Monetary Fund, EconStats. ⟨www.econstats.com.weo⟩. (Accessed 19 December 2017).
[62] J. Wooldridge, Introductory Econometrics: A Modern Approach, 3rd ed, Thomson South-Western, USA, 2006.
[63] E. Ojea, J. Martin-Ortega, Understanding the economic value of water ecosystem services from tropical forests: a systematic review for South and Central America, J. For. Econ. 21 (2) (2015) 97–106.
[64] A. Cameron, P. Trivedi, Microeconometrics Using Stata, Stata Press, College Station, Texas, 2010.
[65] H. Thiel, G. Schriever, E. Foell, Polymetallic nodule mining, waste disposal, and species extinction at the abyssal seafloor, Mar. Georesources Geotechnol. 23 (3) (2005) 209–220.