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

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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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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