VanDover CL, Aronson J, Pendleton L, Smith S, Arnaud-Haond S, Moreno-Mateos D, Barbier E, Billett D, Bowers K, Danovaro R, Edwards A, Kellert S, Morato T, Pollard E, Rogers A, Warner R. Ecological restoration in the deep sea: Desiderata. *Marine Policy* 2014, 44, 98-106.

http://dx.doi.org/10.1016/j.marpol.2013.07.006

Marine Policy 44 (2014) 98–106

Contents lists available at ScienceDirect

Marine Policy

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

Ecological restoration in the deep sea: Desiderata ☆

C.L. Van Dover [a,*], J. Aronson [b], L. Pendleton [c], S. Smith [d], S. Arnaud-Haond [e], D. Moreno-Mateos [f], E. Barbier [g], D. Billett [h], K. Bowers [i], R. Danovaro [j], A. Edwards [k], S. Kellert [l], T. Morato [m], E. Pollard [n], A. Rogers [o], R. Warner [p]

[a] Marine Laboratory, Nicholas School of the Environment, Duke University, 135 Marine Lab Road, Beaufort, NC 28516, USA
[b] Centre d'Ecologie Fonctionnelle et Evolutive (CEFE/CNRS-UMR 5175), Montpellier, France
[c] Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC 27708, USA
[d] Nautilus Minerals, 303 Coronation Drive, Milton, Queensland, Australia
[e] Ifremer, Bd Jean Monnet, BP 171, 34203 Sète Cedex, France
[f] Jasper Ridge Biological Preserve, Stanford University, Woodside, CA 94062, USA
[g] Department of Economics and Finance, 1000E University Avenue, Laramie, WY 82071, USA
[h] National Oceanography Centre, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH, UK
[i] Biohabitats, 2120 Noisette Blvd, Suite 106B, North Charleston, SC 29405, USA
[j] Department of Life and Environmental Sciences, Polytechnic University of Marche, Via Brecce Bianche, 601321 Ancona, Italy
[k] School of Biology, Ridley Building, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[l] School of Forestry & Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511, USA
[m] Centre of IMAR, Departamento de Oceanografia e Pescas, Universidade dos Açores and LARSyS Associated Laboratory, 9901-862 Horta, Portugal
[n] The Biodiversity Consultancy, EURC, 72 Trumpington Street, Cambridge, CB2 1RR, UK
[o] Department of Zoology, Tinbergen Building, South Parks Road, Oxford, OX1 3PS, UK
[p] Australian National Centre for Ocean Resources and Security, University of Wollongong, Building 233, Innovation Campus, Squires Way, North Wollongong, New South Wales 2522, Australia

ARTICLE INFO

Article history:
Received 24 March 2013
Received in revised form
13 July 2013
Accepted 17 July 2013
Available online 29 August 2013

Keywords:
Deep-sea resource use
Restoration science
Marine policy
Hydrothermal vents
Cold-water corals

ABSTRACT

An era of expanding deep-ocean industrialization is before us, with policy makers establishing governance frameworks for sustainable management of deep-sea resources while scientists learn more about the ecological structure and functioning of the largest biome on the planet. Missing from discussion of the stewardship of the deep ocean is ecological restoration. If existing activities in the deep sea continue or are expanded and new deep-ocean industries are developed, there is need to consider what is required to minimize or repair resulting damages to the deep-sea environment. In addition, thought should be given as to how any past damage can be rectified. This paper develops the discourse on deep-sea restoration and offers guidance on planning and implementing ecological restoration projects for deep-sea ecosystems that are already, or are at threat of becoming, degraded, damaged or destroyed. Two deep-sea restoration case studies or scenarios are described (deep-sea stony corals on the Darwin Mounds off the west coast of Scotland, deep-sea hydrothermal vents in Manus Basin, Papua New Guinea) and are contrasted with on-going saltmarsh restoration in San Francisco Bay. For these case studies, a set of socio-economic, ecological, and technological decision parameters that might favor (or not) their restoration are examined. Costs for hypothetical restoration scenarios in the deep sea are estimated and first indications suggest they may be two to three orders of magnitude greater per hectare than costs for restoration efforts in shallow-water marine systems.

---

* Corresponding author. Tel.: +1 242 504 7655.
E-mail addresses: clv3@duke.edu (C.L. Van Dover), james.aronson@cefe.cnrs.fr (J. Aronson), linwood.pendleton@duke.edu (L. Pendleton), sls@nautilusminerals.com (S. Smith), sarnaud@ifremer.fr (S. Arnaud-Haond), davidmor@stanford.edu (D. Moreno-Mateos), ebarbier@uwyo.edu (E. Barbier), dsmb@noc.ac.uk (D. Billett), kbowers@biohabitats.com (K. Bowers), r.danovaro@univpm.it (R. Danovaro), alasdair.edwards@newcastle.ac.uk (A. Edwards), stephen.kellert@yale.edu (S. Kellert), telmo@uac.pt (T. Morato), Edward.pollard@thebiodiversityconsultancy.com (E. Pollard), alex.rogers@zoo.ox.ac.uk (A. Rogers), rwarner@uow.edu.au (R. Warner).

0308-597X/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpol.2013.07.006

1. Introduction

The deep-sea—defined here as ocean beyond the shelf break and depths greater than 200 m—is increasingly recognized as a fertile area for offshore industrialization. Current or future activities include fishing, waste disposal, cable lays associated with telecommunications, scientific research, oil and gas development, bioprospecting, mineral extraction, and tourism. Past, on-going, and anticipated human activities and impacts in the deep sea have been increasingly documented since the start of this century [1–12]. In response to these mounting and potentially synergistic impacts, there have been calls for a precautionary approach to continuing and new activities in the deep sea [6], application of spatial and adaptive management tools [7,13,14], development of research programs to quantify goods and services provided by deep-sea ecosystems [7,15] and continuing study of ocean governance and protection of the marine environment beyond national jurisdiction [16]. In addition, there is a consensus on the need to establish environmental baselines [8,17] and to improve tools to predict, manage and mitigate anthropogenic impacts [6,7,18].

Spatial management of the deep sea—including establishment of networks of marine sanctuaries and protected areas—has received considerable attention [3,11]. Area closures and 'move-on' rules for High Seas bottom fisheries have been implemented by Regional Fisheries Management Organizations [13,19,20]. Other conservation and management tools and actions implemented through international treaties, conventions, and agreements include identification and protection of Vulnerable Marine Ecosystems (VMEs; UNGA61/105) [13,20] and Ecologically or Biologically Significant Areas (EBSAs) [21,22], as well as a call for networks of Chemosynthetic Ecosystem Reserves [23] for deep-sea hydrothermal vent and seep ecosystems.

What has been missing to date, however, from the deep-sea conservation, management, and sustainable development discourse is the topic of restoration. Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed; it is an intentional activity that reinitiates ecological processes that were interrupted by human activities [35]. Restoration aims to recover biodiversity and ecosystem functioning, health, and integrity, both for humans and for other living organisms [24]. Ecological restoration is increasingly recognized as a global priority in terrestrial and shallow-water ecosystems [25–27]. In contrast, restoration in the deep sea has yet to receive much attention. At its 11th Conference of the Parties (COP11) in October 2012, the Convention on Biological Diversity (CBD) called on its 173 Contracting Parties to commit to helping identify and restore at least 15% of degraded ecosystems for every ecosystem type on the planet by 2020, including the conservation of at least 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services (CBD COP11 Decision XI/16).

A key issue regarding deep-sea restoration focuses on the obligation of responsible parties to undertake steps to repair damage that result from commercial or other activities that affect the environment. Industries that impact terrestrial and coastal systems are liable for injuries to natural resources, must declare the damage they cause, and pay for habitat recovery; as such, industry needs to include an assessment of restoration costs in their project plans [28]. International guidelines for management of deep-sea fisheries indicate that this industry does not yet take responsibility for restoring seabed ecosystems after impacts of trawling activities [29]. In contrast, there is evidence that the seafloor minerals extraction industry does consider environmental impacts and the need for offsets. The voluntary *IMMS Code for Environmental Management of Marine Mining* developed by the International Marine Minerals Society [30] recommends that plans for mining include at the outset procedures that "*aid in the recruitment, re-establishment and migration of biota and to assist in the study of undisturbed, comparable habitats before, during, and after mining operation*", including "*long-term monitoring at suitable spatial and temporal scales and definition of the period necessary to ensure remediation plans are effective*". Such plans are incorporated into the Environmental Impact Statement of the first project to propose mineral extraction at a deep-sea site [31]. In this case, the company involved with the development recognized and embraced the concept of investing in restoration of the deep sea as a corporate responsibility and an important component of a culture of environmental stewardship.

2. Opportunity for restoration in the deep sea

Most of the deep ocean is a huge common space for which all nations share prerogatives and responsibilities. As coastal States claim territorial waters to the limits of continental shelves, they increase their sovereignty over the deep sea and are therefore also key players in deep-sea environmental management and conservation. Governance is limited or underdeveloped regarding most international deep-sea environmental issues and is non-existent for deep-sea restoration, leaving it up to individual entities to decide whether or not restoration should be considered. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) provides a legal order for the seas and oceans that promotes the equitable and efficient utilization of their resources, the conservation of their living resources and the study, protection and preservation of the marine environment. UNCLOS includes the general obligation to protect and preserve the marine environment (Article 192), the duty to protect and preserve rare or fragile ecosystems, and the habitat of depleted, threatened or endangered species and other forms of marine life [Article 194(5)]. Further, States have a duty to cooperate on a global or regional basis in formulating and elaborating international rules, standards and recommended practices and procedures for the protection and preservation of the marine environment (Article 197). These obligations are further specified in the Implementing Agreements for UNCLOS related to the management of seafloor mining in international waters and of straddling and highly migratory fish stocks [32,33]. The opportunity exists to implement guidelines for restoration and rehabilitation as part of a sustainable and ethical environmental management strategy to protect and preserve the marine environment, rare and fragile ecosystems, and vulnerable species, while allowing the responsible use of marine resources.

3. Ecological restoration applied to the deep sea

3.1. Deep-sea ecosystem services and stakeholders

There is increasing recognition that ecosystems should be viewed as economic assets that produce a flow of beneficial goods and services over time, commonly referred to as *ecosystem services* [34]. Such benefits are diverse and wide-ranging, and generally arise through the natural functioning of relatively undisturbed ecosystems. While humans rarely make direct contact with deep-sea ecosystems, they realize direct and indirect benefits from these ecosystems [15], including oil, gas, mineral, and living resources; chemical compounds for industrial, biotechnology, and pharmaceutical uses; gas and climate regulation; waste disposal and detoxification; CO_2 capture and storage; the passage of trans-ocean communication cables; and cultural services such as education and scientific research.

Stakeholders with an interest in the deep sea include national governments, members of industry, science, intergovernmental panels, NGOs, and citizens. These stakeholder groups will likely evolve and expand as human activities increase in the deep sea. The degree of interest and participation in deep-sea restoration will depend upon demand for it by stakeholders and other mechanisms that promote it, e.g., national and international governance frameworks, corporate responsibility. Given that restoration costs in the deep sea will be high (likely orders of magnitude higher) relative to those on land or in shallow water due to the remote and technically challenging aspects of deep-sea manipulations, multi-stakeholder engagement and partnerships could be effective means to share costs and ideas and to maximize benefits of restoration actions and to make collective decisions about whether or not restoration at a particular site is a viable option.

3.2. *Principles and attributes of ecological restoration*

In the last decade, guidance has been created to improve the application of ecological restoration through the development of principles and attributes to help direct conceptualization, planning, and implementation of restoration projects. This guidance has been set out in a Primer on Ecological Restoration published by the Society for Ecological Restoration [35] and follow-on articles e.g., [24] for terrestrial and shallow-water restoration. An overview of how these restoration guidelines could be adapted to the specific conditions of the deep sea is provided here. A more detailed accounting and discussion of applying ecological restoration principles and attributes to the deep sea may be found in Supplementary material (Tables S1 and S2).

Ecological restoration attempts to return a degraded ecosystem to its historical trajectory [35]. For many ecosystems in the deep sea, although the historical trajectory is not always well understood or well documented, it may be inferred from life history and functional attributes of dominant taxa. For some deep-sea ecosystems (e.g., many hydrothermal vent systems), a historical trajectory is understood or can be reasonably established or inferred [36,37]. For others, more research and data would be needed to determine a historical trajectory. This is especially the case where disturbed ecosystems are exceptionally stable, with organisms of centennial or multi-centennial lifespans (e.g., coral reefs) [38] or substrata that grow on millennial time scales (e.g., manganese nodules) [39]. Ensuring that a functional set of flows, interactions, and exchanges with contiguous or interconnected ecosystems occur in restored deep-sea ecosystems requires an understanding of local and regional hydrodynamics as well as interactions among populations and species. For some patchy ecosystems in the deep sea, such as hydrothermal vents, cold seeps, and some seamounts, the understanding of how networks of these ecosystems interact within a bioregion is a fledgling science [40,41]; for apparently vast ecosystems, such as abyssal plains and manganese nodule beds, the spatial scale of ecosystem networks and characteristics of their ecological and genetic connectivity are poorly understood [42].

Restored ecosystems consist of indigenous species to the greatest practicable extent [35], but a number of factors make it challenging to recognize indigenous versus non-indigenous species or taxa: ranges of species and subspecies are often poorly known because pre-disturbance baselines (including successional sequences following natural disturbance) do not exist for most deep-sea ecosystems, taxonomic diversity is very high, and most species have very low abundance in most of the deep sea [43]. While it may be more practical in most deep-sea systems to compare indigenous functional groups (e.g., suspension feeders, deposit feeders, size groups, etc.) rather than attempt to census all indigenous species and taxa, restoration actions based on functional groups could promote a change in community structure and species composition and an over-simplification of structure and diversity [18].

Attributes of restored ecosystems also include “connectivity” attributes that describe their relationship to the rest of the world. These include their integration into a larger landscape, their protection from external threats, and the existence of governance in support of restoration. Although all ecosystems are three-dimensional in space, this particular attribute is especially important for the ocean and linkages among its ecosystems. Many fish and invertebrates move freely (actively or passively) in both horizontal and vertical dimensions, during some or all life-history stages. Taxa endemic to some deep-sea ecosystems have patchy distributions and populations (or meta-populations) that may be connected and interdependent among sites at spatial scales relevant to maintenance of populations and gene flow. There are thus spatial and temporal dynamics, often on relatively large scales, that make it challenging to understand how well a particular restoration effort fits into a larger landscape. Similarly, there are external threats to the health and integrity of restored deep-sea ecosystems (e.g., global changes in ocean circulation resulting from a warming climate) that may be impossible to avoid or minimize through restoration efforts, because of the physico-chemical connectivity of deep-sea ecosystems resulting from ocean circulation. Because these ecosystems may be interconnected with other ecosystems [44], we may consistently underestimate the entire suite of extended benefits that results from restoration (or that is lost due to damage). Further, governance of deep-sea ecosystems is an emergent property at both national and international levels. These points should not preclude consideration of deep-sea restoration efforts, but they do highlight some of the challenges that restoration practitioners working in the deep sea will need to take into account.

4. Should we restore deep-sea ecosystems?

A key challenge to promoting ecological restoration is to clarify and prioritize restoration opportunities. The basic decision parameters that determine whether or not to restore fall into at least three broad categories of decision parameters: socio-economic, ecological, and technological, within which there are multiple subcategories (Table 1). Socio-economic factors reflect aspects of restoration that are likely to benefit people, impose costs on them, or are otherwise influenced by societal factors. Ecological factors reflect the ecological contribution of the proposed restoration activities. Technical factors deal with the real world difficulties of conducting restoration and the ultimate likelihood that restoration efforts will be successful. Specific factors and considerations that influence the decision to restore or not to restore ultimately lie with the stakeholders involved.

4.1. *The Sète workshop: case studies and decision parameters*

The authors of this paper—whose expertise spans deep-sea ecology, ecological restoration and restoration practice, economics, ocean governance and policy, environmental management related to seafloor mineral extraction, and human ecology—convened in Sète France (November 2012) and considered how the decision parameters in Table 1 would apply to three specific case studies. As a comparison for deep-sea restoration, we chose one non-deep-sea case study, namely on-going restoration of 160 ha of saltmarsh in San Francisco South Bay that had been lost through coastal development. We also selected two different deep-sea habitats as hypothetical cases for restoration. One is an area of patchy stony coral habitat of the Darwin Mounds (UK) that has been damaged by bottom trawling. The other is a hydrothermal vent site in Papua New Guinea that may be damaged by extraction of seafloor massive sulfide deposits (see Box 1 for brief descriptions of each site). One or more of the authors has direct knowledge of each case-study site.

For San Francisco Bay saltmarsh restoration, all of the socio-economic, ecological, and technological decision parameters listed in

Table 1
Socio-economic, ecological, and technological decision parameters that may contribute to decisions to undertake ecological restoration in the deep sea and elsewhere, and expert opinion of how these factors apply to San Francisco Bay salt marsh (Marsh) restoration and deep-sea Darwin Mounds stony coral (Coral) and Solwara 1 hydrothermal-vent (Vent) restoration case studies (see Box 1). (+): outcome favors restoration effort; (~): outcome may favor restoration effort; (−): outcome does not favor restoration effort; (?): variable or uncertain outcomes with regard to favoring restoration effort.

	Is restoration favored?		
	Marsh	Coral	Vent
Socio-economic decision parameters			
Ecosystem benefits (likelihood) How large and lasting are the human benefits of the restoration effort, including ecosystem goods provided by deep-sea ecosystems? Are these systems of biophilic importance? Because restoration is an inherently human-driven activity, society is more likely to favor restoration when people feel they benefit from restoration, directly or indirectly	+	+	?
Governance Is there an effective civil governance structure that supports or requires restoration? In some cases, laws or contracts may dictate that restoration is a pre-requisite for current or planned activities that may damage the sea floor. In other cases, laws and international treaties and conventions may simply encourage restoration or provide a legal context to increase the likelihood that an area will be restored	+	~	~
Cost What is the cost of restoration? Like any environmental management or intervention decision, it is important that scarce resources be spent wisely. All things being equal, higher costs will make restoration more unlikely	~	−	−
Societal pressure Are there societal pressures to restore? Societal pressure alone may make restoration more likely. Societal pressures include pressure from NGOs, stakeholders, the public, and even corporate culture that seeks to minimize environmental impacts of industrial activities	+	~	?
Financial incentives Are there financial or other incentives/rewards that might encourage restoration? Are there payments or rewards available for the ecosystem services restored or the biodiversity maintained through restoration, whether direct, or indirect (e.g., eco-certification)? Are there penalties for failure to restore, e.g., fines, or customer dissatisfaction?	+	−	−
Wider socio-economic impacts Does the restoration activity itself have wider socio-economic impacts beyond the benefits of a restored ecosystem (e.g., job creation and alleviation of poverty)?	+	−	−
Ecological decision parameters			
Ecological vulnerability Is the ecosystem an Ecologically and Biologically Significant Area (EBSA), for example? EBSAs are marine areas in need of special protection in open-ocean waters on the seabed and are defined by seven criteria adopted by the Conference of the Parties to the Convention on Biodiversity CBD (CBD COP 9, Decision IX/20, 2008): uniqueness or rarity; special importance for life history of species; importance for threatened, endangered or declining species and/or habitats; vulnerability, fragility, sensitivity, slow recovery; biological productivity; biological diversity; naturalness	+	+	~
Wider ecological benefit (likelihood) Does restoration of the ecosystem have a wider ecological benefit? Is the area to be restored a key sources of propagules? Would restoration reintroduce or reinforce populations of critical species?	+	+	?
Natural recovery Is there a high likelihood of natural recovery even in the absence of restoration? Such recovery could be due to the fact that the ecosystem is one already adapted to frequent natural disturbances or is downstream of "sources" of colonizers. Restoration may be less likely to occur if the chance of unassisted recovery is high	+	?	−
Large relative ecological impact Is the impact of the restoration, whether measured in area or another ecological metric, large relative to the whole ecosystem or populations within the ecosystem? Will this restoration activity help to restore a substantial amount of habitat or other measure of the degraded ecosystem? Will it have beneficial impacts on other ecosystems with which it interacts? Restoration with a larger 'ecological footprint' may be more likely for some deep-sea ecosystems	+	+	~
Technological decision parameters			
Success (likelihood) Are the proposed restoration strategies likely to be successful? Restoration success is influenced by factors that could reduce likelihood (e.g., natural catastrophic disturbances, lack of knowledge, human factors) and those that could improve likelihood (e.g., resilience and known capacity for unassisted recovery). Where likelihood of success is low, restoration may be less likely, unless undertaken for research and development purposes	+	~	~
Technically feasible (likelihood) Is the restoration activity, including monitoring and adaptive management, technically difficult? This decision parameter highlights the logistical and technical difficulty of carrying out restoration activities and is closely related to "cost of restoration" and "likelihood of success"	+	~	~
Technological advancement (likelihood) Does the restoration activity increase our technical knowledge and capacity for future restoration? Because we have limited experience restoring many types of ecosystems, restoration activities in the present could provide technical, scientific, and financial lessons that will benefit restoration in the future. Some restoration efforts may be undertaken primarily for the sake of improving knowledge and know-how that could permit scaling up in a cost-effective fashion	~	+	+

Table 1 favor or likely favor the current restoration efforts [45,46]. This observation is borne out by California Law AB 2954, which established the San Francisco Bay Restoration Authority in 2008 with overwhelming public support, despite the $1.43 billion-dollar price tag of restoration (Environmental News Service 28 August 2007 "Cost to restore San Francisco Bay wetlands—$1.43 Billion"). Salt marshes generate ecosystem goods and services that are part of daily life for people living in the San Francisco area including shoreline protection, recreational and commercial opportunities, and wildlife.

The remoteness of the deep sea and the general lack of awareness on the part of the public about the deep sea suggest that a socio-economic case for restoration may not be as easy to make for deep-sea restoration as for coastal restoration (Table 1). Within the deep sea, the link between socio-economic pressures to restore (e.g., benefits from restored goods and services, regulatory requirements, societal pressure) depends on the circumstance. For example, stony corals from the Darwin Mounds (Box 1) are beyond the experience of most people, but they do provide habitat for commercially important fish and may offer future opportunities for pharmaceutical and materials research [47]. The Solwara 1 hydrothermal vent site (Box 1) and other hydrothermal vents are also generally far removed from public perception, apart from scientific stakeholders,

Box 1–San Francisco Bay Salt Pond and Wetlands Restoration

By the 1960s, more than 70% of the tidal wetlands of San Francisco Bay had been destroyed due to diking and filling for agriculture, hunting, salt pond construction, and urban and industrial development [46]. The lost wetlands included a combination of tidal salt, brackish, and freshwater marshes. Associated with loss of wetlands and with coastal development were loss of biodiversity, water quality, fisheries, shoreline protection, bird habitat, recreational opportunities and other ecosystem goods and services [69].

Darwin Mounds coral reef restoration

The Darwin Mounds comprise hundreds of small (100 m diameter, 5 m relief) mounds in the NE Rockall Trough (900–1100 m water depth off the west coast of Scotland) colonized by cold-water corals (*Lophelia pertusa* and other species) that create habitat for fish and invertebrates [70]. The corals feed on zooplankton and reproduce vegetatively as well as by sexual reproduction through broadcast spawning. They are sensitive to water quality (temperature, water flow, pH), and have an associated fauna of diverse invertebrate taxa. Characteristics of a healthy reef include on-going accretion and self-recruitment, high biodiversity of associated fauna, and good coverage by live coral.

Bottom trawling at the Darwin Mounds was known to have taken place between 2000 and 2003; temporary emergency closure was put in place in 2003, followed by permanent closure to bottom trawling in 2004 [71]. Longevity of *Lophelia pertusa* colonies is estimated to be several decades to 100 yr [72]; the age of the Darwin Mounds is likely to be on the order of 10,000 yr by comparison with coral mounds of nearby Rockall Bank [73]. There is evidence that there are benefits of deep-sea corals perceived and appreciated by society, based on choice experiments showing a willingness-to-pay value for coral protection (1 per annum tax) [74] and benefits are realized through fishing [4]. Fragments of broken corallites of *L. pertusa* show rapid regeneration potential in the laboratory [75], suggesting that laboratory propagation may be feasible in support of subsequent restoration efforts.

Solwara 1 hydrothermal vent restoration

Solwara 1 is a weakly active seafloor hydrothermal vent field comprising inactive and actively venting areas at 1500 m in Manus Basin, Papua New Guinea. The site has a deposit of commercial-grade seafloor massive sulfide (SMS) rich in copper, gold, and silver [76]. Locally dense populations of snails that host chemoautotrophic bacterial endosymbionts and associated fauna live where warm water flows through the sulfide mounds [77] and for which a number of pre-disturbance baseline studies have been undertaken as part of the Environmental Impact Assessment process e.g., [31,78,79]. The snails present (*Alviniconcha* spp. and *Ifremeria nautilei*) are endemic to hydrothermal vent ecosystems and are found at other vent fields in Manus Basin and elsewhere in the South Pacific region. The natural disturbance regime is considered to be relatively intense at Solwara 1, with the warm water flows on which the snail holobionts depend subject to clogging, sealing, or other disruptions on annual or sub-annual timescales. The faunal assemblage associated with these hydrothermal vents is thought to be relatively resilient, with species having life history characteristics that allow for rapid colonization of suitable habitat and subsequent rapid growth and reproduction [61].

bioprospectors, and documentary film makers, but may offer scientific and societal benefits, including knowledge and education [48–50]. Restoration of the Darwin Mounds corals or the Solwara 1 hydrothermal vent site will not have wider socio-economic impact (e.g., job creation) in the way that restoration of the San Francisco Bay wetlands will. More difficult to quantify, but extremely important, are existence values of deep-sea ecosystems, which contribute to perceived ecosystem benefits and may favor decisions to restore. There can also be societal pressures that favor restoration, such as a corporate culture of environmental responsibility. There are no financial or other incentives in place that might favor a decision to restore either deep-sea ecosystem; the high cost of deep-sea restoration (developed in Section 4.2) does not favor restoration.

Ecological decision parameters favor restoration in San Francisco Bay wetlands, Darwin Mounds stony corals, and Solwara 1 hydrothermal vents in different ways. San Francisco Bay wetlands restoration will have large relative ecological impact by providing, for example, nursery habitat for fish and crustaceans and habitat for marsh birds, as well as wider ecological benefit such as subsidy to detrital food chains of estuaries and enhanced productivity of estuarine organisms [51]. The Darwin Mounds stony corals stand out as ecologically vulnerable: loss of reef structure by bottom trawling [52] has resulted in reduction in biodiversity and reproductive success of associated invertebrates and fish [53]. Growth rate of a reef coral is estimated to be on the order of a millimeter or so per year [54]; it takes hundreds of years for a colony to reach a diameter of 10–30 m and thousands of years to build a reef patch [53]. Once restored and protected from further impact, these coral systems are likely to persist and deliver natural goods and services for a very long time [55]. Hydrothermal vents are considered to have a high likelihood of unassisted recovery and furthermore, are likely to undergo natural catastrophic destruction through tectonic or volcanic activity, meaning vent taxa have adaptive strategies to cope with disturbance and thus may be resilient to it. Because the ecological benefits of restoration in the deep sea are unknown, a prudent approach might be to undertake targeted restoration and monitor its impacts to get a better understanding of the benefits of doing so.

Restoration practices for San Francisco Bay marshes are technologically better understood than those of any deep-sea environment, though success of restoration efforts even in a coastal system is varied [46]. Deep-sea ecosystems may be some of the most technologically difficult ecosystems to restore, but the developing capacity to undertake complex and costly industrial activities in the deep sea indicates that ecological restoration is also technologically feasible. Notwithstanding, for Darwin Mounds and Solwara 1, the ability to implement a restoration project with even modest goals is unknown. At the outset, restoration efforts might be more in the realm of a scientific and technological experiment and learning, than actual restoration practice that could be scrutinized as rigorously as a contemporary land-based restoration project or program. In these deep-sea cases, opportunity for technological and scientific advancement may be one of the strongest decision parameters favoring investment in restoration efforts.

The decision parameters listed in Table 1 reveal the complexity of decision-making when contemplating whether or not to restore areas of the deep sea. Some opportunities will likely be considerably costlier than others. Restoration investments will likely be made preferentially for those opportunities where benefits are greater, likelihood of success are higher, and costs are lower. Benefits include recovery of ecosystem services, contribution to corporate culture, or restoration of habitats of particular scientific, cultural, and, in effect, biophilic value [56]. As noted, restoration may also be undertaken simply to improve knowledge of potential restoration methods. Not all deep-sea restoration opportunities will generate large ecological or human benefits in the short-term.

The Darwin Mounds and Solwara 1 habitats cover relatively small areal extents but support communities of organisms that garner attention and make them good case studies for thinking about the potential for ecological restoration. On a very different scale are manganese nodule beds, which cover huge expanses of the seafloor. Early estimates suggested a single commercial mining effort might plow up to1 km^2 per day or, over a decade, an area the size of Germany [3]; more recent estimates suggest a rate sixty times slower than this (Parianos, pers. comm., Nautilus Minerals). Nodules take millennia to form and the biota associated with manganese nodule beds is relatively obscure and non-charismatic, but their contribution to biotic diversity is very high. How do we begin to contemplate restoration of nodule beds, bearing in mind factors such as these? In such a case, restoration simply may not be the optimal goal or tool for environmental management.

4.2. *The Sète workshop: the cost of deep-sea restoration*

Costs of deep-sea restoration are expected to be high, but the magnitude in difference between costs of shallow-water vs. deep-sea restoration projects has not been calculated for realistic scenarios. To this end, participants at the Sète Workshop also developed estimates of the cost per hectare to implement experimental deep-sea restoration in the scenarios described above. These costs are then compared to those of saltmarsh and shallow-water coral restoration projects.

4.2.1. *Darwin Mounds scenario*

The Darwin Mounds are located off the coast of Scotland [57], where bottom trawling has damaged some mounds of stony coral [52,58] such that little remains of the original corals but mobile beds of rubble [4]. A hypothetical pilot restoration project is described here with the goal of reestablishing the destroyed reef structure. It does not take into account major geoengineering of the seabed that might be required to reconstruct the elevated sandbanks upon which the corals occurred originally. The project would use a laboratory propagation-and-transplant protocol within an adaptive management framework to test the efficacy of coral transplants at two densities (10 and 20 1-m^2 patches of corallites distributed over a 10-m × 10-m area of former coral reef, three replicates of each density; i.e., total area under experimental restoration would be 600 m^2 or 0.06 ha). Corallite fragments of *Lophelia pertusa* have a relatively fast growth rate in the laboratory (up to 2.5 cm yr^{-1}) [59], although growth in the field is much lower (3.8 mm yr^{-1}) [60] and would be attached to substrata using inserts at 15-cm spacing. Coral fragments would be harvested sustainably by collecting short fragments of coral tips. These fragments would be propagated in the laboratory, attached to anchor substrata, positioned on the seafloor, and monitored for coral growth and biodiversity of associated fauna. Three adjacent coral rubble patches would serve as reference areas. Measures of success would include demonstration that transplanted corals grow and propagate through sexual and asexual reproduction and an increase in associated biodiversity.

Costs for this hypothetical restoration effort (Table 2a) are estimated using standard practices for proposals from academic research institutions [e.g., Grant Proposal Guide for the National Science Foundation USA or the Research Grants Handbook for the Natural Environment Research Council UK] and include salaries for a Project Manager and technician, monitoring equipment and miscellaneous supplies for corallite grow-out in a shore-based facility, field sampling of coral and corallite deployment, and post-deployment monitoring cruises. The technician would be responsible for corallite culture and construction of deployment arrays as well as for maintenance of monitoring equipment and data analysis post-deployment. The amount of shiptime required is based on expert knowledge of workshop participants who routinely work in the deep sea using research vessels. Most of the direct costs (80%) of the restoration effort are associated with this shiptime, and include use of remotely operated and autonomous underwater vehicles.

4.2.2. *Solwara 1 scenario*

Solwara 1 is a hydrothermal vent site located off the coast of Papua New Guinea and covers an area of $\sim$0.1 km^2 (10 ha) of seafloor. Commercial mineral extraction to recover a copper-, gold-, and silver-rich seafloor massive sulfide deposit will remove some actively venting and inactive substrata and their associated organisms; the extraction plan leaves some patches of vent habitat intact

Table 2
Hypothetical project costs (direct costs only) for 5-yr deep-sea restoration efforts at Darwin Mounds and Solwara 1. Costs are in 2013 US dollars. Salaries are based on current competitive salaries in a university setting. Costs for research vessels are based on 2012 day rates (rounded) for R/V *Knorr* ($43K), ROV *Jason* ($22K), and AUV *Sentry* ($15K) provided by the operator (Woods Hole Oceanographic Institution; E. Benway, pers. comm.). Indirect costs can be ≥50% of direct costs, depending on institutional policies.

2a. Darwin Mounds stony corals (600 m^2 or 0.06 ha)[a]	**Direct costs**
Project manager (technical staff; 1 month per year, 5 yr @$12K per month)	$60,000
Lab grow-out technician (12 months per year @$6.5K per month × 5 yr)	$390,000
Miscellaneous supplies ($4K per year)	$20,000
Time-lapse cameras (9 × $50K each)	$450,000
Sampling cruise (ROV; 7 d @$65K per day)	$455,000
Corallite and camera deployment cruise (ROV; 27 d @ $65K per day)	$1,755,000
Camera maintenance and survey cruises (AUV, ROV; 7 d @ $80K per day × 3 yr)	$1,680,000
Total direct costs	**$4,810,000**

2b. Solwara 1 hydrothermal vent (72 m^2 or 0.007 ha)[b]	**Direct costs**
Project manager (technical staff; 1 month per year, 5 yr @$12K per month)	$60,000
Lab technician (12 months per year @$6.5K per month × 5 yr)	$390,000
3-D Substrata ($2K per edifice, 18 edifices)	$36,000
Miscellaneous supplies ($4K per year)	$20,000
Time-lapse cameras (9 × $50K each)	$450,000
Substratum deployment cruise (ROV; 15 d @ $65K per day)	$975,000
Transplant and camera deployment cruise (ROV; 27 d @ $65K per day)	$1,755,000
Camera maintenance and survey cruises[c] (AUV, ROV; 7 d @ $80K per day × 3 visits)	$1,680,000
Total direct costs	**$5,366,000**

[a] A project manager is employed for 1 month per year for 5 yr; a full-time technician is employed in year 1 to propagate the corals and to engage in daily needs for mission planning and data analysis for 5 yr. Salaries include fringe benefits. Supplies for propagation and miscellaneous laboratory and shipboard expenses are budgeted. A ship and a remotely operated vehicle (ROV) are required to collect corallites and then to deploy coral substrata and imaging systems; additional cruises are required to maintain imaging systems (ROV) and survey with an autonomous underwater vehicle (AUV).

[b] A project manager is employed for 1 month per year for 5 yr; a lab technician constructs edifices and engages in daily needs for mission planning, data analysis and reporting. Salaries include fringe benefits. Supplies for construction of edifices are budgeted, with additional funds budgeted for miscellaneous laboratory and shipboard expenses. A ship and a remotely operated vehicle (ROV) are required to deploy edifices and then to transplant organisms and deploy imaging systems; additional cruises are required to maintain imaging systems (ROV) and survey with an autonomous underwater vehicle (AUV).

[c] This figure does not include vessel and ROV mobilization and demobilization costs, which depend on ship locations and availability.

within the Solwara 1 field. The expectation is that the fauna at active vents will likely recover passively and relatively quickly (within a decade) through natural processes of colonization [61]. Despite this likely resilience, a restoration project is envisioned to facilitate this recovery process. The restoration objective is reestablishment of 3-dimensional conical edifices (~0.5-m radius, 2 m height=~4 m^2 surface area) after mineral extraction is completed within an area, to support fauna associated with actively venting (e.g., holobiont provannid snails) and inactive sulfide deposits (e.g., stalked barnacles). The edifices would be deployed on active fluid flows to mimic active sulfide deposits and over areas without fluid flow to mimic inactive vents. Animals would be transplanted from the area in front of the extraction tools to the appropriate (active or inactive) edifice structures deployed in the area behind the extraction tools. The experimental restoration design would include 2 states (active and inactive), 3 conditions (high, medium, low density transplants), and 3 replicates per condition. Three adjacent untreated active and inactive sites would serve as reference areas, thus allowing a comparison between assisted and unassisted recovery. Measures of success would include demonstration that transplanted invertebrates survive and evidence of growth and recruitment.

We use a cost model for Solwara 1 (Table 2b) similar to that used for the Darwin Mounds scenario, i.e., as an academic activity, with the addition of funds to cover cost of construction of substrata and ship time to accommodate deployment of these substrata. The technician would be responsible for construction of substrata as well as for maintenance of monitoring equipment and data analysis post-deployment. As with the Darwin Mounds scenario, most of the direct costs (80%) for the Solwara 1 restoration scenario are associated with ship use, including use of remotely operated and autonomous underwater vehicles.

4.2.3. Deep-sea restoration costs and context

Both the Darwin Mounds and Solwara 1 restoration scenarios described above are estimated to cost between $4.8 and 5.4 M, but because the area under restoration differs between scenarios (Darwin Mounds: 0.06 ha; Solwara 1: 0.007 ha), the total direct cost of the Darwin Mounds restoration scenario is estimated to be about ~$75 M ha^{-1}, while the Solwara 1 scenario is estimated to be an order of magnitude higher at ~$740 M ha^{-1}. To place these values in context, restoration costs for the 160 ha in San Francisco Bay range from $0.1M ha^{-1} to $0.2 M ha^{-1} (Biohabitats, 2008, unpublished). The lower cost range includes breaching existing levees, allowing natural sediment transport and erosion processes to self-form tidal flat elevations and channels, and natural colonization of vegetation species. In addition to breaching existing levees, the higher cost range includes actively filling, grading and excavating tidal channels within the site to achieve a predetermined marsh morphology, and actively planting the marsh to achieve predetermined vegetation communities. The median cost for 11 case studies of shallow-water coral reef rehabilitation was just under $500,000 ha^{-1} [62], although costs of restoring coral reefs badly damaged during ship-groundings have ranged from $5.5 M ha^{-1} (M/V *Elpis*) to > $100 M ha^{-1} (R/V *Columbus Iselin*: $3.76 M in natural resource damages applied primarily to restoration in response to destruction of 345 m^2 reef) [63].

Deep-sea restoration will be expensive, likely two to three orders of magnitude more expensive than restoration undertaken in shallow-water ecosystems. Restoration costs should be considered a priori when planning activities that impact ecosystems in the deep sea. Partnerships and collaborations with industries that operate ships and underwater assets in the area might contribute to some of the at-sea costs. The cost of deep-sea restoration will also be reduced through economies of scale (e.g., by increasing the area restored) and through development of specialized underwater tools, including task-optimized Remotely Operated Vehicles (ROV) that can operate off smaller, less costly vessels and a relatively low-cost, Autonomous Underwater Vehicle (AUV) specialized for monitoring activities, and, possibly, through use of cabled observatories. Costs may also be reduced through development plans that incorporate restoration activities occurring concurrent with the activity. This would work particularly well where similar assets are required for both activities (e.g. vessels, ROVs, AUVs, etc.).

5. Conclusions: a way forward

Principles and attributes of ecological restoration, originally formulated for terrestrial and coastal ecosystems [35] can be applied to the deep sea. While there are no human populations associated with the deep-sea environment, scientists, industry, NGOs, and citizens are among the stakeholders who value the deep sea in many different ways, and decisions to undertake deep-sea restoration programs will result from a mix of socioeconomic, ecological, and technological factors. There has already been large-scale negative impact to some deep-sea ecosystems (e.g., deep-water corals, seamounts) with unknown effects on ecosystem resilience and delivery of ecosystem services. Where deleterious human impacts are extant or expected, restoration should be considered as part of an impact mitigation hierarchy [64] wherein restoration is financed and undertaken after all effort has been made to avoid and minimize impacts. The scope for unassisted restoration—sometimes called passive restoration—should be assessed for each type of deep-sea ecosystem; practices can be developed to facilitate this 'natural', relatively low-cost restoration approach. For restoration to have a sustained effect, governance should be in place to protect restored areas against new damage.

Deep-sea restoration will be expensive, but cost alone should not be a reason for inaction. The multiple benefits of restoration should be considered in valuation and financing schemes and where restoration is prohibitively expensive or technically unfeasible, other actions such as offsetting can be considered. Neither restoration nor rehabilitation objectives (or commitments) should be taken as a 'license to trash'.

Restoration is often a long-term investment undertaken in the context of societal priorities, and requires many resources from a diverse portfolio of investors and participants. These resources include funds, time, and a willingness to tackle scientific and technological challenges. Realistic expectations should be set for deep-sea restoration goals. Thirty years after the emergence of ecological restoration as a scientific discipline and a realm of professional practice, there remain many obstacles [65] and misconceptions about what can be achieved [66]. The results of even the best-planned ecosystem restoration projects can still be highly uncertain [67,68]. There is a clear need for continued advances in restoration science, technology, and practice, from genes to whole landscapes—and seascapes. Such efforts will improve the ability to identify worthwhile restoration activities to protect deep-sea biodiversity and ecosystem functioning and integrity, while enabling delivery of ecosystem services to human society.

Acknowledgments

This workshop was inspired by discussions about the need to consider restoration in the deep-sea that arose through an industry-academic collaboration between Nautilus Minerals and Duke University. This paper is a product of the Sète Workshop on Deep-Sea Restoration, brought about by continuing collaboration between Nautilus Minerals and the Nicholas School of the Environment at Duke University. While Nautilus Minerals and Duke University provided funding for the workshop, the views and recommendations expressed in this paper are solely those of the authors. We are grateful to Ms. Kristen Maize for her pre-workshop interviews of participants and to the Fall 2011 Duke deep-sea restoration discussion group (Dr. Rebecca Vidra, Danielle Boudreau, Melissa Kemm, Kaitlin Kovacs).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2013.07.006.

References

[1] Hall-Spencer J, Allain V, Fosså JH. Trawling damage to Northeast Atlantic ancient coral reefs. Proceedings of the Royal Society London, Series B, Biology 2002;269:507–11.

[2] Glover AG, Smith CR. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environmental Conservation 2003;30:219–41.

[3] Thiel H. Anthropogenic impacts on the deep sea. In: Tyler P, editor. Ecosystems of the deep ocean. Amsterdam: Elsevier Science; 2003. p. 427–71.

[4] Roberts S, Hirshfield M. Deep-sea corals: out of sight, but no longer out of mind. Frontiers in Ecology and the Environment 2004;2:123–30.

[5] Davies AJ, Roberts JM, Hall-Spencer J. Preserving deep-sea natural heritage: emerging issues in offshore conservation and management. Biological Conservation 2007;138:299–312.

[6] Smith CR, Levin LA, Koslow A, Tyler PA, Glover AG. The near future of the deep seafloor ecosystems. In: Polunin N, editor. Aquatic ecosystems: trends and global prospects. Cambridge: Cambridge University Press; 2008. p. 334–49.

[7] van den Hove S, Moreau V. Deep-sea biodiversity and ecosystems: a scoping report on their socio-economy, management and governance.Cambridge, UK: UNEP World Conservation Monitoring Centre; 2007.

[8] Robison BH. Conservation of deep pelagic biodiversity. Conservation Biology 2009;23:847–85858.

[9] Benn AR, Weaver PPE, Billett DSM, van den Hove S, Murdock AP, Doneghan GB, et al. Human activities on the deep seafloor in the North East Atlantic: an assessment of spatial extent. PLoS One 2010;5:e12730.

[10] Tsounis G, Rossi S, Grigg R, Santangelo G, Bramanti L, Gili J. The exploitation and conservation of precious corals. Oceanography and Marine Biology: An Annual Review 2010;48:161–212.

[11] Ramirez-Llodra E, Tyler PA, Baker MC, Bergstad OA, Clark MR, Escobar E, et al. Man and the last great wilderness: human impact on the deep sea. PloS One 2011;6:e22588.

[12] Watson R, Morato T. Fishing down the deep: accounting for within-species changes in depth of fishing—a second look. Fisheries Research 2013;140:63–5.

[13] Taranto GH, Kvile KØ, Pitcher TJ, Morato T. An ecosystem evaluation framework for global seamount conservation and management. PLoS One 2012;7:e42950.

[14] Ban NC, Bax NJ, Gjerde KM, Deviller R, Dunn DC, Dunstan PK, et al. Systematic conservation planning: a better recipe for managing the high seas for biodiversity conservation and sustainable use. Conservation Letters 2013; XX:1–14.

[15] Armstrong CW, Foley NS, Tinch R, van den Hove S. Services from the deep: steps towards valuation of deep-sea goods and services. Ecosystem Services 2012;2:2–13.

[16] Gjerde KM. Challenges to protecting the marine environment beyond national jurisdiction. International Journal of Marine and Coastal Law 2012;27:839–47.

[17] Collins P, Kennedy R, Copley J, Boschen R, Fleming N, Forde J, et al. VentBase: developing a consensus among stakeholders in the deep sea regarding environmental impact assessment for deep-sea mining. Marine Policy 2013;42:334–6.

[18] Danovaro R, Gambi C, Dell′Anno A, Corinaldesi C, Fraschetti S, Vanreusel A, et al. Exponential decline of deep-sea ecosystem functioning linked to benthic biodiversity loss. Current Biology 2008;18:1–8.

[19] Dinmore TA, Duplisea DE, Rackham BD, Maxwell DL, Jennings S. Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. ICES Journal of Marine Science 2003;3139:371–80.

[20] Rogers AD, Gianni M. The implementation of UNGA resolutions 61/105 and 64/72 in the management of deep-sea fisheries on the High Seas.London, United Kingdom: International Programme on State of the Ocean; 2010 ([report prepared for the Deep-Sea Conservation Coalition]).

[21] Gilman E, Dunn D, Read A, Hyrenbach KD, Warner R. Designing criteria suites to identify discrete and networked sites of high value across manifestations of biodiversity. Biodiversity and Conservation 2011;20:3363–83.

[22] Weaver P, Johnson D. Biodiversity: think big for marine conservation. Nature 2012;483:399.

[23] Van Dover CL, Smith CR, Ardron J, Dunn D, Gjerde K, Levin L, et al. Designating networks of chemosynthetic ecosystem reserves in the deep sea. Marine Policy 2012;36:378–81.

[24] Clewell AF, Aronson J. Ecological restoration: principles, values, and structure of an emerging profession. 2nd edWashington DC: Island Press; 2013.

[25] Hobbs RJ, Harris JA. Restoration ecology: repairing the Earth's ecosystems in the new millennium. Restoration Ecology 2001;9:239–46.

[26] Choi Y, Temperton V, Allen E, Grootjans A, Halassy M, Hobbs R, et al. Ecological restoration for future sustainability. Ecoscience 2008;15:53–64.

[27] Aronson J, Alexander S. Ecosystem restoration is now a global priority: time to roll up our sleeves. Restoration Ecology 2013;21:293–6.

[28] Barbier EB. Coastal wetland restoration and the deepwater horizon oil spill. Vanderbilt Law Review 2011;62:1821–49.

[29] FAO. International guidelines for the management of deep-sea fisheries in the high seas.Rome, Italy: FAO; 2009.

[30] Verlaan P. The International Marine Mineral Society's code for environmental management of marine mining. In: Proceedings of the offshore technology conference; 2011.

[31] Coffey Natural Systems. Environmental impact statement for the Nautilus Minerals Solwara 1 Project in Papua New Guinea; 2008. ⟨http://www.cares.nautilusminerals.com/EIA2.aspx?npath=1,4,5,13⟩ [accessed 02.02.13].

[32] UNGA. Resolution 48/263 agreement relating to the implementation of part XI of the United Nations convention on the law of the sea of 10th December 1982. Document A/RES/48/26317. United Nations General Assembly; August 1994.

[33] UNGA. Agreement for the implementation of the provisions of the United Nations Convention on the law of the sea of 10th December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks. Document A/CONF.164/37. United Nations General Assembly; 8 September 1995.

[34] Millenium Ecosystem Assessment. Washington DC: Island Press; 2005.

[35] Society for Ecological Restoration (SER). The SER primer on ecological restoration.Washington DC: Society for Ecological Restoration International, Science and Policy Working Group; 2004.

[36] Shank TM, Fornari DJ, Von Damm KL, Lilley MD, Haymon RM, Lutz RA. Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents (9°50′N, East Pacific Rise). Deep-Sea Research Part II 1998;45:465–515.

[37] Govenar B, Freeman M, Bergquist DC, Johnson GA, Fisher CR. Composition of a one-year-old *Riftia pachyptila* community following a clearance experiment: insight to succession patterns at deep-sea hydrothermal vents. Biological Bulletin 2004;207:177–82.

[38] Roberts JM, Wheeler AJ, Freiwald A. Reefs of the deep: the biology and geology of cold-water coral ecosystems. Science 2006;312:543–7.

[39] Morgan CL. Resource estimates of the Clarion–Clipperton manganese nodule deposits. In: Cronan DS, editor. Handbook of marine mineral deposits. Boca Raton, USA: CRC Press; 2000. p. 145–70.

[40] Vrijenhoek RC. Genetic diversity and connectivity of deep-sea hydrothermal vent metapopulations. Molecular Ecology 2010;19:4391–411.

[41] Moalic Y, Desbruyères D, Duarte CM, Rozenfeld AF, Bachraty C, Arnaud-Haond S. Biogeography revisited with network theory: retracing the history of hydrothermal vent communities. Systematic Biology 2012;61:127–37.

[42] Miller K, Williams A, Rowden AA, Knowles C, Dunshea G. Conflicting estimates of connectivity among deep-sea coral populations. Marine Ecology 2010;31:144–57.

[43] Grassle JF, Maciolek NJ. Deep-sea species richness: regional and local diversity estimates from quantitative bottom samples. American Naturalist 1992;139:313–41.

[44] Bors EK, Rowden AA, Maas EW, Clark MR, Shank TM. Patterns of deep-sea genetic connectivity in the New Zealand region: implications for management of benthic ecosystems. PLoS One 2012;7:e49474.

[45] Grenier JL, Davis JA. Water quality in San Francisco Bay, California: current condition and potential issues for the South Bay salt pond restoration project. Reviews of Environmental Contamination and Toxicology 2010;206:115–47.

[46] Callaway J, Parker V, Vasey M, Schile L, Herbert E. Tidal wetland restoration in San Francisco Bay: history and current issues. San Francisco Estuary and Watershed Science 2011;9:1–12.

[47] Foley N, van Rensburg TN, Armstrong CW. The ecological and economic value of cold-water coral ecosystems. Ocean and Coastal Management 2010;53:1–39.

[48] Glowka L. Bioprospecting, alien invasive species, and hydrothermal vents: three emerging legal issues in the conservation and sustainable use of biodiversity. Tulane Environmental Law Journal 2000;329:330–1.

[49] Arrieta JM, Arnaud-Haond S, Duarte CM. What lies underneath: conserving the oceans' genetic resources. Proceedings of the National Academy of Science, USA 2010;107:18318–24.

[50] Godet L, Zelnio KA, Van Dover CL. Scientists as stakeholders in conservation of hydrothermal vents. Conservation Biology 2011;25:214–22.

[51] Peterson C, Lipcius R, Powers S. Conceptual progress towards predicting quantitative ecosystem benefits of ecological restorations. Marine Ecology Progress Series 2003;264:297–307.

[52] Wheeler AJ, Bett BJ, Billett DSM, Masson DG, Mayor D. The impact of demersal trawling on NE Atlantic deep-water coral habitats: the case of the Darwin Mounds, U.K. In: Barnes PW, Thomas JP, editors. Benthic habitats and the effects of fishing. Bethesda, Maryland: American Fisheries Society; 2005. p. 807–17.

[53] Fosså JH, Mortensen PB, Furevik DM. The deep-water coral *Lophelia pertusa* in Norwegian waters: distribution and fishery impacts. Hydrobiologia 2002;471:1–12.

[54] Mortensen, P. B. *Lophelia pertusa* (Scleractinia) in Norwegian waters; distribution, growth, and associated fauna. Dr scient. Diss. thesis. Department of Fisheries and Marine Biology, University of Bergen, 2000.

[55] Baillon S, Hamel J-F, Wareham VE, Mercier A. Deep cold-water corals as nurseries for fish larvae. Frontiers in Ecology and the Environment 2012;10:351–6.

[56] Kellert S. Birthright: people and nature in the modern world.New Haven: Yale University Press; 2012.

[57] Bett BJ. UK Atlantic margin environmental survey: introduction and overview of bathyal benthic ecology. Continental Shelf Research 2001;21:917–56.

[58] Huvenne VAI and cruise participants. Benthic habitats and the impact of human activities in Rockall Trough, on Rockall Bank and in Hatton Basin. Southampton, UK: National Oceanography Centre; 2011 ([RRS James Cook Cruise 60, 09 May–12 June 2011 National Oceanography Centre Cruise report, no. 04]).

[59] Rogers AD. The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activities. International Review of Hydrobiology 1999;84:315–406.

[60] Brooke S, Young CM. In situ measurement of survival and growth of *Lophelia pertusa* in the northern Gulf of Mexico. Marine Ecology Progress Series 2009;397:153–61.

[61] Van Dover CL. Mining seafloor massive sulphides and biodiversity: what is at risk? ICES Journal of Marine Science 2010;68:341–8.

[62] Edwards AJ, Job S, Wells S. Learning lessons from past reef-rehabilitation projects. In: Edwards AJ, editor. Reef rehabilitation manual. St. Lucia, Australia: Coral Reef Targeted Research & Capacity Building for Management Program; 2010. p. 129–36.

[63] Spurgeon JPG, Lindahl U. Economics of coral reef restoration. In: Cesar HSJ, editor. Collected essays on the economics of coral reefs. Sweden: CORDIO; 2000. p. 125–36.

[64] McKenney BA, Keisecker JM. Policy development for biodiversity offsets: a review of offset frameworks. Environmental Management 2010;45:165–76.

[65] Turner R. On the cusp of restoration: science and society. Restoration Ecology 2005;13:163–73.

[66] Hilderbrand RH, Watts AC, Randle AM. The myths of restoration ecology. Ecological Society 2005;10:19–29.

[67] Suding KN. Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution and Systematics 2011;42:465–87.

[68] Moreno Mateos D, Power ME, Comin FA, Yockteng R. Structural and functional loss of restored wetland ecosystems. PLoS Biology 2012;10:1–8.

[69] Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, et al. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 2006;312:1806–9.

[70] Masson D, Bett B, Billett DS, Jacobs C, Wheeler A, Wynn R. The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. Marine Geology 2003;194:159–80.

[71] DeSanto EM, Jones PJS. Offshore marine conservation policies in the North East Atlantic: emerging tensions and opportunities. Marine Policy 2007;31:336–47.

[72] Mikkelsen N, Erlenkeuser H, Killingley JS, Berger WH. Norwegian corals: radiocarbon and stable isotopes in *Lophelia pertusa*. Boreas 1982;11:163–71.

[73] Frank N, Ricard E, Lutringer-Paquet A, van der Land C, Colin C, Blamart D, et al. The Holocene occurrence of cold water corals in the NE Atlantic: implications for coral carbonate mound evolution. Marine Geology 2009;266:129–42.

[74] Wattage P, Glenn H, Mardle S, Van Rensburg T, Grehan A, Foley N. Economic value of conserving deep-sea corals in Irish waters: a choice experiment study on marine protected areas. Fisheries Research 2011;107:59–67.

[75] Maier C. High recovery potential of the cold-water coral *Lophelia pertusa*. Coral Reefs 2008;27:821.

[76] Hoagland P, Beaulieu S, Tivey MA, Eggert RG, German C, Glowka L, et al. Deep-sea mining of seafloor massive sulfides. Marine Policy 2010;34:728–32.

[77] Galkin SV. Megafauna associated with hydrothermal vents in the Manus Back-Arc Basin (Bismarck Sea). Marine Geology 1997;142:197–206.

[78] Thaler AD, Zelnio K, Saleu W, Schultz TF, Carlsson J, Cunningham C, et al. The spatial scale of genetic subdivision in populations of *Ifremeria nautilei*, a hydrothermal-vent gastropod from the southwest Pacific. BMC Evoloutionary Biology 2011;11:372.

[79] Collins P, Kennedy R, Van Dover C. A biological survey method applied to seafloor massive sulfides (SMS) with contagiously distributed hydrothermal-vent fauna. Marine Ecology Progress Series 2012;452:89–107.