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Ecological restoration in the deep sea: Desiderata

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Abstract

An era of expanding deep-ocean industrialization is before us,with policy makers establishing governance frameworks for sustainable management of deep-sea resources whiles cientists 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 ared escribed (deep-sea stony corals on the Darwin Mounds of fthe 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.

Keywords

ecological, deep, sea, restoration, desiderata

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Ecological Restoration in the Deep Sea: Desiderata

To be submitted to *Marine Policy*

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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 we choose to continue or expand existing economic activities in the deep sea and develop new deep-ocean industries, then we should 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 ecological damage can be rectified. Here we open the discourse on deep-sea restoration and offer 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. We also consider two deep-sea restoration case studies or scenarios, namely deep-sea stony corals on the Darwin Mounds off the west coast of Scotland and deep-sea hydrothermal vents in Manus Basin (Papua New Guinea) and contrast them with on-going saltmarsh restoration in San Francisco Bay. For these case studies, we examine a set of anthropocentric, eco-centric, and technological decision parameters that might favor (or not) their restoration. Costs for hypothetical restoration scenarios in the deep sea are estimated to be one or more orders of magnitude greater per hectare than costs for restoration efforts in shallow-water marine systems.

Key words: deep-sea resource use, restoration science, restoration policy, hydrothermal vents, cold-water corals

Highlights (mandatory bullet points: max 85 characters; 3-5 bullets; separate file in submission process)

▶ Deep-ocean industries exist and new ones are in development.

▶Restoration can be a component of environmental management in the deep sea.

▶Case studies illustrate motivations for, approaches to, and potential costs of deep-sea restoration.

▶The science, practice, ethics, and economics of deep-sea restoration need to be developed.

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, able communications, scientific research, oil and gas development, bio-prospecting, and mineral extraction. Past, on-going, and anticipated human activities and impacts in the deep sea have been increasingly documented since the start of this century (Hall-Spencer et al. 2002, Glover & Smith 2003, Thiel 2003, Roberts & Hirshfield 2004, Davies et al. 2007, Smith et al. 2008, van den Hove & Moreau 2007, Robison 2009, Benn et al. 2010, Tsounis et al. 2010, Ramirez-Llodra et al. 2011). 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 (Smith et al. 2008), application of spatial and adaptive management tools (van den Hove & Moreau 2007, Ban et al. in press), development of research programs to quantify goods and services provided by deep-sea ecosystems (van den Hove and Moreau 2007, Armstrong et al. 2012) and continuing study of ocean governance and protection of the marine environment beyond national jurisdiction (Gjerde 2012). In addition, there is a consensus on the need to establish environmental baselines (Robison 2009, Collins et al. in press) and to improve tools to predict, manage and mitigate anthropogenic impacts (van den Hove 2007, Danovaro et al. 2008, Smith et al. 2008).

Spatial management of the deep sea—including establishment of networks of marine sanctuaries and protected areas—has received considerable attention (e.g., Thiel 2003, Ramirez-Llodra 2011). Area closures and ‘move-on’ rules for High Seas bottom fisheries have been implemented by Regional Fisheries Management Organizations (e.g., Dinmore et al. 2003, Rogers & Gianni

2010, Durán Muñoz et al. 2012). 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, Rogers & Gianni 2010) and of Ecologically ord Biologically Significant Areas (EBSAs; e.g., Gilman et al. 2011, Weaver and Johnson 2012), as well as a call for networks of Chemosynthetic Ecosystem Reserves (Van Dover et al. 2012) for deep-sea hydrothermal vent and seep ecosystems.

What has been missing 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 (SER 2004). Restoration aims to recover biodiversity and ecosystem functioning, health, and integrity, both for humans and for other living organisms (Clewell & Aronson 2013). Ecological restoration is increasingly recognized as a global priority in terrestrial and shallow-water ecosystems (Hobbs & Harris 2001, Choi et al. 2008, Aronson & Alexander, 2013). 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 called on its 173 Contracting Parties to commit to helping 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; CBD 2012).

A key issue regarding deep-sea restoration focuses on the obligation of responsible parties to undertake steps to repair damages 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 should include assessment of restoration costs in their project plans (e.g., Barbier 2011). The voluntary *Code for Environmental Management of Marine Mining* developed by the International Marine Minerals Society (Verlaan 2011) recommends that plans for mining include at the outset a program to establish 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 (Coffey Natural Systems, 2008). In this case, the company has accepted and embraced the concept of investing in restoration of the deep sea as a corporate responsibility.

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. 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 mining in international waters and of straddling and highly migratory fish stocks (UNGA, 1994, 1995). 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, which are commonly referred to as *ecosystem services* (MA 2005). 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 (Armstrong et al. 2012), including oil, gas, mineral, and living resources; chemical compounds for industrial, biotechnology, and pharmaceutical uses; gas and climate regulation;

waste absorption 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 members of industry, science, intergovernmental panels, NGOs, citizens, etc. 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, etc. 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.

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 (SER 2004) and follow-on articles (e.g., Clewell & Aronson 2013) for terrestrial and shallow-water restoration. Here we provide an overview of how these restoration guidelines could be adapted to the specific conditions of the deep sea. A more detailed accounting and discussion of applying ecological restoration principles and attributes to the deep sea may be found in Supplementary Materials (Tables S1 and S2).

Ecological restoration attempts to return a degraded ecosystem to its historical trajectory (SER 2004). 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 (e.g., Shank et al. 1998, Govenar et al. 2004). 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 (Roberts et al. 2006)] or substrata that grow on millennial time scales [e.g., manganese nodules (Morgan 2000)]. Ensuring that a functional set of flows, interactions, and exchanges with contiguous or inter-connected 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 (e.g., Vrijenhoek 2010, Moalic et al. 2012); 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 (e.g., Miller et al. 2010).

Restored ecosystems consist of indigenous species to the greatest practicable extent (SER 2004), 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 (e.g., Grassle & Maciolek 1992). 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. Functional groups can be assessed in terms of community structure, biophysical attributes, energy flows and trophic webs, among other things, but the use of functional groups can result in an over simplification of the present assemblage structure and diversity (Danovaro et al. 2008).

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 (e.g., vents, seeps, seamounts) 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 not be possible 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 inter-connected with other ecosystems (Bors et al. 2012), we may consistently underestimate the entire suite of extended benefits that results from restoration (or that are 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 resolve.

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: anthropocentric, eco-centric, and technological, within which there are multiple subcategories (Table 1). Anthropocentric factors reflect aspects of restoration that are likely to benefit people, impose costs on them, or are otherwise influenced by societal factors. Eco-centric 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 marine mineral extraction, and human ecology—convened in Sète France (November 2012) and, in this workshop, we 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 anthropocentric, eco-centric, and technological decision parameters listed in Table 1 favor or likely favor the current restoration efforts (e.g., Grenier & Davis 2010; Callaway et al. 2011). 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 an anthropocentric 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 anthropocentric 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 (Foley et al. 2010). The Solwara 1 hydrothermal vent site (Box 1) and other hydrothermal vents are also generally far removed from public perception, apart from scientific stakeholders, bioprospectors, and documentary film makers, but may offer scientific and societal benefits, including knowledge and education which should be considered (Glowka 1999-2000, Arieta et al. 2010, Godet et al. 2011). 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 have. 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, below) means restoration may not be favorable.

Eco-centric 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 (e.g., Peterson & Lipcius 2003). The Darwin Mounds stony corals stand out as ecologically vulnerable: loss of reef structure by bottom trawling (Wheeler et al. 2005) has resulted in reduction in biodiversity and reproductive success of associated invertebrates and fish (Fosså et al. 2002), and the growth rate of the reef is estimated to be on the order of a millimeter or so per year (Mortensen 2000), or hundreds of years for a colony to reach a diameter of 10-30 m and thousands of years to build a reef structure (Fossa et al. 2002). 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. Hydrothermal vents in general may be considered relatively unusual habitats, but at least in some cases, they are also 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 are likely to have adapted strategies to cope with disturbance. 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 full 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 and the San Francisco Bay salt-marsh restoration project is a work in progress (Callaway et al. 2011). Deep-sea ecosystems may be some of the most technologically difficult ecosystems to restore. However, our developing capacity to undertake complex and costly industrial activities in the deep sea indicates that ecological restoration there is becoming more technologically feasible. Notwithstanding, for Darwin Mounds and Solwara 1, our 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 land-based restoration project or program. In these 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. Deep-sea restoration investments will likely be made preferentially for those opportunities where the benefits are greater than the costs—whether those benefits come from recovery of ecosystem services, corporate culture, or restoration of habitats of particular scientific, cultural, and, in effect, biophilic value (Kellert 2012). As noted, restoration may also be undertaken simply to improve our 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 1 km^2 per day or, over a decade, an area the size of Germany (Thiel 2003). Nodules take millennia to form and the biota associated with manganese nodule beds is relatively obscure, and non-charismatic. How do we begin to contemplate restoration on such a scale of ecosystem degradation? 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, to our knowledge, been calculated for realistic scenarios. To this end, participants at the Sète Workshop also developed estimates of the cost to implement the deep-sea restoration scenarios described above on a per-hectare basis. 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 ((Bett et al. 2001), where bottom trawling has damaged some mounds of stony coral (Wheeler et al. 2005, Huvenne et al. 2011) such that little remains of the original corals but a mobile bed of rubble (Roberts et al. 2006). 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 would 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 distributed over a 10-m x 10-m area of former coral reef, three replicates of each density; i.e., total area under experimental restoration: 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} (Rogers

1999), although growth in the field is much lower (3.8 mm yr^{-1}; Brooke & Young 2009)] 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 academic research proposals (D'Angelo & Wiedenamnn 2012) and include salaries for a Project Manager (1 month per year) and technician (full time), 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 full-time 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 academic research vessels. Most of the direct costs (80%) of the restoration effort are associated with shiptime, including 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 ~0.1 km^2 (10 ha) of seafloor. Commercial mineral extraction to recover copper-, gold-, and silver-rich seafloor massive sulfides will remove some actively venting and inactive substrata and their associated organisms; the extraction plan leaves some patches of vent habitat intact within the Solwara 1 field. The expectation is that the fauna at active vents will likely recover passively within a decade through natural processes of colonization (Van Dover 2010), but a restoration project is envisioned to facilitate this recovery process. A restoration project is proposed with the goal of reestablishment of 3-dimensional conical edifices (~0.5-m radius, 2 m height = ~4 m^2 surface area) after mineral extraction is completed that support fauna associated with actively venting (e.g., holobiont provannid snails) and inactive sulfide deposits (e.g., bamboo corals). 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. Measures of success wouldinclude 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, but with the addition of funds to cover cost of construction of substrata and additional ship time to accommodate deployment of these substrata. The full-time 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 5.4M, 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 ~\$75M ha^{-1} while the Solwara 1 scenario is estimated to be ~\$740M ha^{-1}. To place these values in context, restoration costs for the 160 ha in San Francisco Bay range from \$103,740 ha^{-1} to \$222,300 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} (Edwards et al. 2010), although costs of restoring coral reefs badly damaged during ship-groundings have ranged from \$5.5M ha^{-1} (M/V *Elpis*) to >\$100M ha^{-1} 1 (R/V *Columbus Iselin*: \$3.76M in natural resource damages applied primarily to restoration in response to destruction of 345 m^2 reef; Spurgeon & Lindahl 2000).

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 thus be considered *a priori* when planning extraction activities 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 might be reduced through economies of scale and through development of specialized underwater tools, including task-optimized Remotely Operated Vehicles (ROV) that can operate off smaller, less costly vessels, a relatively low-cost, Autonomous Underwater Vehicle (AUV) specialized for monitoring activities, and, possibly, cabled observatories.

5. Conclusions: A Way Forward

Principles and attributes of ecological restoration, originally formulated for terrestrial and coastal ecosystems (SER 2004) 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 anthropocentric, eco-centric, and technological factors. There has already been large-scale negative impact to some deep-sea ecosystems (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 (McKenny & Kiesecker 2010) wherein restoration is financed and undertaken, but occurs only after all effort has been made to avoid and minimize impacts. For restoration to have a sustained effect, governance and finances should be in place to protect restored areas against new damage. Furthermore, the multiple benefits of restoration should be considered in valuation and financing schemes; where restoration is prohibitively expensive or technically unfeasible, then offsetting should be considered. Neither restoration nor rehabilitation objectives (or commitments) should be taken as a ‘license to trash’. 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’, low-cost restoration approach.

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 (Turner 2005) and misconceptions about what can be achieved (Hilderbrand et al. 2005). The results of even the best-planned ecosystem restoration projects can still be highly uncertain (Suding 2011, Moreno Mateos et al. 2012). 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 our 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.

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REFERENCES

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

Aronson J, Clewell AF, Blignaut JN, Milton SJ. Ecological restoration: A new frontier for both nature conservation and economics. J Nat Conserv 2006; 14: 135–139.

Aronson J, Milton SJ, Blignaut JN. (2007). Definitions and Rationale**.** In: Aronson J, Milton SJ, Blignaut JN, editors. Restoring natural capital: Science, business and practice. Washington DC: Island Press; 2007. P. 3–8.

Aronson J, Alexander S. Ecosystem restoration is now a global priority: Time to roll up our sleeves. Restor Ecol 2013 (in press).

Arrieta JM, Arnaud-Haond S, Duarte CM. What lies underneath: Conserving the oceans' genetic resources. P Natl Acad Sci USA 2010; 107: 18318–2.

Ban NC, Bax NJ, Gjerde KM, Deviller R, Dunn DC, Dunstan PK, Hobday AJ, Maxwell S, Kaplan DM, Pressey RL, Ardron JA, Game ET, Halpin PN. Systematic conservation planning: A better recipe for managing the high seas for biodiversity conservation and sustainable use. Conservation Letters in press doi: 10.1111/conl.12010.

Barbier EB. Coastal wetland restoration and the Deepwater Horizon oil spill. Vanderbilt Law Rev 2011; 62: 1821–1849.

Benn AR, Weaver PPE, Billett DSM, van den Hove S, Murdock AP, Doneghan GB, Le Bas T. Human activities on the deep seafloor in the North East Atlantic: An assessment of spatial extent. PLoS One 2010; 5: e12730.

Bett BJ. UK Atlantic margin environmental survey: introduction and overview of bathyal benthic ecology. Cont Shelf Res 2001; 21: 917–956.

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.

Brooke S, Young CM. *In situ* measurement of survival and growth of *Lophelia pertusa* in the northern Gulf of Mexico. Mar Ecol-Prog Ser 2009; 397: 153–161.

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.

Choi Y, Temperton V, Allen E, Grootjans A, Halassy M, Hobbs R, Naeth M, Torok K. Ecological restoration for future sustainability. Ecoscience 2008; 15: 53–64.

Clewell AF, Aronson J. Motivations for the restoration of ecosystems. Conserv Biol 2006; 20: 420–428.

Clewell AF, Aronson J. Ecological Restoration: Principles, values, and structure of an emerging profession. 2nd edition. Washington DC: Island Press; 2013.

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 2 February 2013.

Collins P, Kennedy R, Van Dover C. A biological survey method applied to seafloor massive sulfides (SMS) with contagiously distributed hydrothermal-vent fauna. Mar Ecol-Prog Ser 2012; 452: 89–107.

Collins P, Kennedy R, Copley J, Boschen R, Fleming N, Forde J, Ju S, Lindsay D, Marsh L, Nye V, Patterson A, Watanabe H, Yamamoto H, Carlsson J, Thaler AD. VentBase: Developing a consensus among stakeholders in the deep sea regarding environmental impact assessment for deep-sea mining. Mar Policy in press.

Convention on Biological Diversity (CBD) COP 110 Decision X1/162. Strategic Plan for Biodiversity 2011-2020. Nagoya, Aichi Prefecture, Japan. Ecosystem Restoration. 2010. http://www.cbd.int/cop/cop-11/doc/2012-10-24-advanced-unedited-cop-11-decisions-en.pdf. P 88–90; accessed 26 January 2013.

Convention on Biological Diversity (CBD) CBD COP11 Decision XI/16. 2012 http://www.cbd.int/cop/cop-11/doc/2012-10-24-advanced-unedited-cop-11-decisions-en.pdf; accessed on 26 January 2013.

D’Angelo C, Wiedenmann J. An experimental mesocosm for long-term studies of coral reefs. J Mar Biol Assoc UK 2012; 92: 769–775.

Danovaro R, Gambi C, Dell'Anno A, Corinaldesi C, Fraschetti S, Vanreusel A, Vincx M, Gooday AJ. Exponential decline of deep-sea ecosystem functioning linked to benthic biodiversity loss. Curr Biol 2008; 18: 1–8.

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 J Mar Sci 2003; 3139: 371-380.

Davies AJ, Roberts JM, Hall-Spencer J. Preserving deep-sea natural heritage: Emerging issues in offshore conservation and management. Biol Conserv 2007; 138: 299–312.

DeSanto EM, Jones PJS. The Darwin Mounds□: From undiscovered coral to the development of an offshore marine protected area regime. Bull Mar Sci; 2007, 81(Supplement): 147–156.

Durán Muñoz P, Sayago-Gil M, Murillo FJ, Del Río JL, López-Abellán LJ, Sacau M, Sarralde, R. Actions taken by fishing Nations towards identification and protection of vulnerable marine ecosystems in the high seas: The Spanish case (Atlantic Ocean). Mar Policy 2012; 36: 536–543.

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. 129–136.

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

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

Frank N, Ricard E, Lutringer-Paquet A, van der Land C, Colin C, Blamart D, Foubert A, van Rooij D, Henriet J-P, de Haas H, van Weering T. The Holocene occurrence of cold water corals in the NE Atlantic: Implications for coral carbonate mound evolution. Mar Geol 2009; 266: 129–142.

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

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. Biodivers Conserv 2011; 20: 3363–3383.

Gjerde KM. Challenges to protecting the marine environment beyond national jurisdiction. Int J Mar Coastal Law 2012; *27*: 839–847.

Glover AG, Smith CR. The deep-sea floor ecosystem: Current status and prospects of anthropogenic change by the year 2025. Environ Conserv 2003 30: 219–241.

Glowka L. Bioprospecting, alien invasive species, and hydrothermal vents: Three emerging legal issues in the conservation and sustainable use of biodiversity. Tulane Environ Law J 1999-2000; 329: 329–360.

Godet L, Zelnio KA, Van Dover CL. Scientists as stakeholders in conservation of hydrothermal vents. Conserv Biol 2011; 25: 214–22.

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. Biol Bull 2004; 207: 177–82.

Grassle JF, Maciolek NJ. Deep-sea species richness: Regional and local diversity estimates from quantitative bottom samples. Am Nat 1992; 139: 313–341.

Grenier JL, Davis JA. Water quality in San Francisco Bay, California: Current condition and potential issues for the South Bay salt pond restoration project. Rev Environ Contam T 2010; 206: 115-147.

Hall-Spencer J, Allain V, Fosså JH. Trawling damage to Northeast Atlantic ancient coral reefs. P Roy Soc Lond B Bio 2002; 269: 507–11.

Hilderbrand RH, Watts AC, Randle AM. The myths of restoration ecology. Ecol Soc 2005; 10: article19.

Hoagland P, Beaulieu S, Tivey MA, Eggert RG, GermanC, Glowka L, Lin J. Deep-sea mining of seafloor massive sulfides. Mar Policy 2010; 34*:* 728–732.

Hobbs RJ, Harris JA. Restoration ecology: Repairing the Earth’s ecosystems in the new millennium. Restor Ecol 2001; 9: 239–246.

Huvenne VAI and cruise participants. RRS James Cook Cruise 60, 09 May-12 Jun 2011: Benthic habitats and the impact of human activities in Rockall Trough, on Rockall Bank and in Hatton Basin. (National Oceanography Centre Cruise Report, No. 04) Southampton, UK: National Oceanography Centre, Southampton; 2011.

Kellert S. Birthright: People and nature in the modern world. New Haven: Yale University Press; 2012.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 2006; 312: 1806–9.

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. Mar Geology 2003; 194: 159–180.

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

MA (Millennium Ecosystem Assessment). Ecosystems and human well-being: Synthesis. Washington DC: Island Press; 2005.

McKenney BA, Keisecker JM. Policy development for biodiversity offsets: A review of offset frameworks. Environ Manage 2010; 45: 165–176.

Miller K, Williams A, Rowden AA, Knowles C, Dunshea G. Conflicting estimates of connectivity among deep-sea coral populations. Mar Ecol 2010; 31: 144–157.

Mikkelsen N, Erlenkeuser H, Killingley JS, Berger WH. Norwegian corals: radiocarbon and stable isotopes in *Lophelia pertusa*. Boreas 1982; 11: 163–171.

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 Biol 2012; 61: 127–137.

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

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. 145–170.

Mortensen PB. *Lophelia pertusa* (Scleractinia) in Norwegian waters. Distribution, growth, and associated fauna. Univ. Bergen: Dr. scient. Thesis; 2000.

Peterson C, Lipcius R, Powers S. Conceptual progress towards predicting quantitative ecosystem benefits of ecological restorations. Mar Ecol-Prog Ser 2003; 264: 297–307.

Ramirez-Llodra E, Brandt A, Danovaro R, De Mol B, Escobar E, German CR, Levin LA, Martinez Arbizu P, Menot L, Buhl-Mortensen P, Narayanaswamy BE, Smith CR, Tittensor DP, Tyler PA, Vanreusel A, Vecchione M. Deep, diverse and definitely different: Unique attributes of the world's largest ecosystem. Biogeosciences 2010; 7: 2851–2899.

Ramirez-Llodra E, Tyler PA, Baker MC, Bergstad OA, Clark MR, Escobar E, Levin LA, Menot Rowden AA, Smith CR, Van Dover CL. Man and the last great wilderness: Human impact on the deep sea. PloS One 2011; 6: e22588.

Roberts S, Hirshfield M. Deep-sea corals: out of sight, but no longer out of mind. Front Ecol Environ 2004; 2: 123–130.

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

Rogers AD. The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activities. Int Rev Hydrobiol 1999; 84:315–406.

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. Report prepared for the Deep-Sea Conservation Coalition. London, United Kingdom: International Programme on State of the Ocean; 2010.

Robison BH. Conservation of deep pelagic biodiversity. Conserv Biol 2009; 23: 847–85858.

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 Res Pt II 1998; 45: 465–515.

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. 334–349.

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

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. 125–136.

Suding KN 2011. Toward an era of restoration in ecology: Successes, failures, and opportunities ahead. Annu Rev Ecol Evol S 2011; 42: 465–487.

Thaler AD, Zelnio K, Saleu W, Schultz TF, Carlsson J, Cunningham C, Vrijenhoek, RC, Van Dover, CL. The spatial scale of genetic subdivision in populations of *Ifremeria nautilei*, a hydrothermal-vent gastropod from the southwest Pacific. BMC Evol Biol 2011; 11: 372.

Thiel H. Anthropogenic impacts on the deep sea. In: Tyler P, editor. Ecosystems of the deep ocean. Amsterdam: Elsevier Science; 2003. p. 427–471.

Tsounis G, Rossi S, Grigg R, Santangelo G, Bramanti L, Gili J. The exploitation and conservation of precious corals. Oceanogr Mar Biol 2010; 48: 161–212.

Turner R. On the cusp of restoration: Science and society. Restor Ecol 2005; 13: 163–173.

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 August 1994, United Nations General Assembly; 1994.

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

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.

Van Dover CL. Mining seafloor massive sulphides and biodiversity: What is at risk? ICES J Mar Sci 2010; 68: 341–348.

Van Dover CL, Smith CR, Ardron J, Dunn D, Gjerde K, Levin L, Smith S. Designating networks of chemosynthetic ecosystem reserves in the deep sea. Mar Pol 2012; 36: 378–381.

Verlaan P. The International Marine Mineral Society’s Code for Environmental Management of Marine Mining. Proceedings of the Offshore Technology Conference, 2011.

Vrijenhoek RC. Genetic diversity and connectivity of deep-sea hydrothermal vent metapopulations. Mol Ecol 2010; 19: 4391–411.

Warner R, Marsden S, editors. Transboundary environmental governance: inland, coastal and marine perspectives. Farnham Surrey, UK: Ashgate Publishing; 2012. p. 297–321.

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. Fish Res 2011; 107: 59–67.

Weaver P, Johnson D. Biodiversity: Think big for marine conservation. Nature 2012; 483: 399.

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. 807–817.

Table 1. Anthropocentric, eco-centric, 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). GREEN (+): outcome favors restoration effort; YELLOW (~): outcome may favor restoration effort; RED (–): outcome does not favor restoration effort; WHITE (?): variable or uncertain outcomes with regard to restoration effort.

	IS RESTORATION FAVORED?		
	Marsh	Coral	Vent
Anthropocentric 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)?			
Eco-centric 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 CBD (CBD COP 9): 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 2. Hypothetical project costs for 5-yr deep-sea restoration efforts at Darwin Mounds and Solwara 1. Costs are in 2012 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).

2a. Darwin Mounds Stony Corals (600 m^2 or 0.06 ha)[1]	**Direct Costs**
Project Manager (technical staff; 1 mo per year, 5 yrs @$12K per mo)	$60,000
Lab grow-out technician (12 months per year @$6.5K per mo x 5 yrs)	$390,000
Miscellaneous Supplies ($4K per yr)	$20,000
Time-lapse cameras (9 x $50K each)	$450,000
Sampling cruise (ROV; 7 d @$65K per d)	$455,000
Corallite and camera deployment cruise (ROV; 27 d @ $65K per d)	$1,755,000
Camera maintenance and survey cruises (AUV, ROV; 7 d @ $80K per d x 3 years)	$1,680,000
TOTAL DIRECT COSTS	**$4,810,000**

[1] A project manager is employed for 1 month per year for five years; 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 years. 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).

2b. Solwara 1 Hydrothermal Vent (72 m^2 or 0.007 ha)[2]	**Direct Costs**
Project Manager (technical staff; 1 mo per year, 5 yrs @$12K per mo)	$60,000
Lab Technician (12 months per year @$6.5K per mo x 5 yrs)	$390,000
3-D Substrata ($2K per edifice, 18 edifices)	$36,000
Miscellaneous Supplies ($4K per yr)	$20,000
Time-lapse cameras (9 x $50K each)	$450,000
Substratum deployment cruise (ROV; 15 d @ $65K per d)	$975,000
Transplant and camera deployment cruise (ROV; 27 d @ $65K per d)	$1,755,000
Camera maintenance and survey cruises (AUV, ROV; 7 d @ $80K per d x 3 years)	$1,680,000
TOTAL DIRECT COSTS	**$5,366,000**

[2] A project manager is employed for 1 month per year for five years; a lab technician is employed in year 1 to construct edifices and engage in daily needs for mission planning and data analysis. 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).

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 (Callaway et al. 2011). 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 (e.g., Lotze et al. 2006).

Darwin Mounds Coral Reef Restoration

The Darwin Mounds comprise several hundred 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 (Masson et al. 2003). The corals feed on zooplankton and reproduce vegetatively as well as 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.

The Darwin Mounds were subjected to demersal trawling (Roberts et al. 2006) and comprise the first offshore, protected area established in the UK (De Santo & Jones 2007). Longevity of *Lophelia pertusa* colonies is estimated to be several decades to ~100 years (Mikkelsen et al. 1982); the Darwin Mounds themselves are likely to be on the order of 10,000 years by comparison with coral mounds of nearby Rockall Bank (Frank et al. 2009). 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; Wattage et al. 2011) and the fact that fishers choose coral-rich areas for deep-sea fishing (Roberts & Hirshfield 2004). Fragments of broken corallites of *L. pertusa* show rapid regeneration potential in the laboratory (Maier 2008), suggesting that laboratory propagation may be feasible in support of subsequent restoration efforts.

Solwara 1 Hydrothermal Vent Restoration

Solwara 1 is an active seafloor hydrothermal vent field at ~1500 m in Manus Basin, Papua New Guinea. The site has a deposit of commercial-grade seafloor massive sulfide (SMS) rich in copper (Hoagland et al. 2010). Locally dense populations of snails that host chemoautotrophic bacterial endosymbionts and associated fauna live where warm water flows through the sulfide mounds (Galkin 1997) and for which a number of pre-disturbance baseline studies have been undertaken as part of the Environmental Impact Assessment process (e.g., Thaler et al. 2011, Collins et al. 2012). 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 (Van Dover 2010).

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Table S1. Principles of ecological restoration and notes on their application to deep-sea ecosystems.

	Principle	**Application to deep-sea ecosystems**
1	Ecological restoration attempts to return a degraded ecosystem to its historical trajectory (SER 2004).	For many ecosystems in the deep sea, the historical trajectory is not always well understood or well documented, though it may be inferred from life history and functional attributes of the dominant taxa in some systems.
2	Ecological restoration aims to initiate or facilitate resumption of those processes that will return the ecosystem to its intended trajectory; historical trajectories or reference conditions require baseline understanding of ecological structure, functions and dynamics and predictive models (SER 2004).	For some deep-sea ecosystems (e.g., many hydrothermal vent systems), "intended trajectories" [*sensu* SER (2004)] are understood or can be reasonably inferred. For other ecosystems in the deep sea, more research and data are needed before it is possible to achieve this principle of restoration [e.g., in the case of disturbed ecosystems that are very stable, with organisms of centennial or multi-centennial lifespans (e.g., coral reefs and coral gardens) or specialized substrata that grow on millennial time scales (e.g., manganese nodules)]. Structure is currently better understood than function and dynamics in most deep-sea ecosystems.
3	Ecological restoration should be approached with a spatially explicit landscape perspective to ensure suitability of flows, interactions and exchanges with contiguous systems (SER 2004).	Landscape perspectives in the deep sea can be locally obtained through seabed mapping with high resolution. For example, a 500 m x 500 m box of flat bottom can be mapped with high-resolution (10-cm) multi-beam sonar and photo-documented within a 24-h seabed mission by an autonomous underwater vehicle. Ensuring that flows, interactions, and exchanges with contiguous or inter-connected ecosystems occur requires an understanding of local and regional hydrodynamics and interactions and exchanges as well as seabed characteristics. Direct measurements of currents are possible. Multi-dimensional ocean circulation models can be developed from ground-truthed physical properties (temperature, density) of seawater, and from these predictive modeling of larval dispersal is possible. Some of these flows, interactions, and exchanges can also be estimated indirectly, using, for example, molecular tools to estimate gene flow and

		directionality of exchange or isotopic markers to estimate export of chemosynthetic carbon to the surrounding benthic and pelagic ecosystems.
4	Ecological restoration is undertaken within the context of a network of ecosystems; ecosystems are part of a bioregion (Clewell & Aronson, 2013).	For some patchy ecosystems in the deep sea, such as hydrothermal vents and cold seeps, the understanding of how networks of these ecosystems interact within a bioregion is a fledgling science; 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 even less well understood. Interactions between seabed and water column ecosystems are tied through bentho-pelagic food webs and through dependence of most benthic species on a pelagic life history phase lasting weeks to months or more.
5	Ecological restoration should be informed by a reference system that serves as a model for planning and for evaluation of the restoration project; a reference system may be a specified site, a written description, or a combination of both. No restored ecosystem can ever be identical to a single reference (SER 2004).	Simple reference systems *sensu* SER (2004) should be possible to identify in deep-sea systems using best available knowledge and strategic mapping efforts. Published descriptions of microhabitats, species composition, and community structure within their geological, geochemical, and geographical contexts are nearly universal elements of “discovery papers” that report on explorations in the deep sea. Even assembly of a composite reference based on multiple sites to capture potential states of an ecosystem, as advocated by SER (2004), is possible, and even simple to accomplish with access to state-of-the-art deep-sea mapping technologies.
6	Ecological restoration encourages and may indeed be dependent upon long-term participation of local people (SER 2004).	“Local people” *sensu* SER (2004) are not associated with deep-sea ecosystems. This means that something other than local community advocacy and support will be required for restoration to proceed. Global participation may include actions by national and international governance frameworks, calls for restoration from global ocean-citizen networks, etc. The SER Primer (SER 2004) notes that

		"*perhaps all natural ecosystems are culturally influenced in at least some small manner, and this reality merits acknowledgement in the conduct of restoration*." The deep sea as a natural system seems the exception, though the history of exploration and discovery in the deep sea has resulted in cultural icons such as the Yeti crab, the submersible *Alvin*, as well as theories about the origin of life on Earth and in the universe.
7	Ecological restoration may accept and even encourage new culturally appropriate and sustainable practices that take into account contemporary conditions and constraints (SER 2004).	This principle of embracing new restoration practices is motivated by the global change in cultural conditions of traditional cultures. While the deep sea is largely outside the sphere of traditional cultures, a parallel to this principle is that in consideration of a new sphere for restoration action, *to wit,* the deep sea, innovation in ecological restoration practices should be accepted and encouraged.
8	Ecological restoration results in a restored ecosystem that is no different from an undamaged ecosystem of the same kind, and both are likely to require some level of ecosystem management (SER 2004).	This principle of the need for environmental management is true for restored and undamaged deep-sea ecosystems as well.
9	Ecological restoration requires thoughtful deliberation among stakeholders (ecological, socio-economic, political, cultural); collective decisions are more likely to be honored and implemented than are those that are made unilaterally (SER 2004, Clewell & Aronson 2013).	Stakeholders of the deep sea include industry, science, intergovernmental panels, NGOs, citizens, etc. Given that restoration costs in the deep sea will be high (orders of magnitude higher) relative to those on land or in shallow water, stakeholder engagement and partnerships may be an effective means to share costs and maximize benefits.
10	Ecological restoration should be integrated into strategies for conservation management and sustainable use of resources (Aronson et al., 2007; Clewell & Aronson, 2013)	Strategic plans for conservation management and in the deep sea are needed from all sectors, and best practices should be shared freely. Stakeholder groups are likely to evolve and expand as more and more human activities are undertaken in the deep sea.
11	Ecological restoration may be site and context-specific; cultural and social traditions influence restoration approaches and values (SER 2004).	In the deep sea, ecological restoration is also likely to be site and context specific, as, for example in the case of restoration projects that engage with maritime industries with a long history of resource extraction in the deep sea or historical use of the deep sea as a dump.

12	Ecological restoration results in restored ecosystems that are healthy, i.e., that function normally relative to a reference ecosystem, or to an appropriate set of restored ecosystem attributes (SER 2004).	Suitable methods for assessing the health of deep-sea ecosystems are readily available, including measures of taxonomic composition, abundance, biomass, community structure, genetic diversity, community respiration, etc.
13	Ecological restoration requires planning, monitoring, and setting of success criteria (SER 2004).	This principle applies to ecological restoration in the deep sea.

Table S2. Selected state, temporal, and connectivity attributes of restored ecosystems [based primarily on SER (2004) and Clewell & Aronson (2013)] and their application to the deep sea. *Note: These attributes are ecological; they do not include socio-economic or cultural principles.*

	Attributes of Restored Ecosystems:	**Application to the Deep-Sea:**
State Attributes (including composition, structure, functions)		
1	Restored ecosystems contain a characteristic assemblage of the species that occur in the reference ecosystem and that provide appropriate community structure (SER 2004).	Finding an appropriate reference system may not be possible for some deep-sea ecosystems.
2	Restored ecosystems consist of indigenous species to the greatest practicable extent (SER 2004).	Neither exhaustive samplings of species, nor pre-disturbance baselines (including successional sequences following natural disturbance) exist for most deep-sea ecosystems, making it challenging to recognize indigenous versus non-indigenous species at present.
3	All functional groups necessary for the continued development and/or stability of the restored ecosystem are represented or, if they are not, the missing groups have the potential to colonize by natural means (SER 2004).	Functional groups may be difficult to determine in the deep sea; they are often defined for convenience by size groups and by inference. Potential for functional groups to colonize is also largely unknown, although can be estimated for some species.
4	Restored ecosystems apparently functions normally for its ecological stage of development, and signs of dysfunction are absent (SER 2004).	Some functions are relatively well understood (e.g., respiration in sediments, organic carbon flux from the photic zone), whereas what constitutes "normal" function is not well known for most ecosystems; some estimates of function may be measured through proxy indicators (e.g., relative biomass pre- and post-disturbance).
5	Restored ecosystems exhibit 3-D structure, function, dynamics (this paper).	Applies particularly to deep-sea ecosystems.
Temporal Attributes (including dynamics and resilience)		
6	Restored ecosystems are self-sustaining to the same degree as their reference ecosystems, and have the potential to persist indefinitely under existing environmental conditions (SER 2004).	Some habitats naturally cease and locally shift in time and space (vents, seeps); other habitats are long-lived (e.g., abyssal plains, nodules, coral reefs and gardens, some seamounts). The ability for an ecosystem to persist needs to take into account effects of cumulative impacts.
7	Restored ecosystems are sufficiently resilient to endure the normal periodic stress events in	Resilience may be difficult to assess for some deep-sea ecosystems given the

	the local environment that serve to maintain the integrity of the ecosystem (SER 2004).	slow rate of many deep-sea processes, but perhaps not for others (e.g., hydrothermal vents).
8	Physical environments of restored ecosystems are capable of sustaining reproducing populations of the species necessary for its continued stability or development along the desired trajectory (SER 2004).	The physical environment for some systems (e.g., nodule beds) may not recover without assisted regeneration (engineering) or may not recover at all (e.g., seeps). For some systems, we don't know what the essential part of a physical environment may be.
9	Restored ecosystems exhibit historical continuity with the pre-disturbance reference system (Clewell & Aronson 2013).	For some deep-sea ecosystems, there is historical knowledge of ecological attributes, but for most ecosystems this temporal attribute is not well documented or is unknown.
10	Restored ecosystems develop complex ecological structures that facilitate niche differentiation and habitat diversity (Clewell & Aronson 2013).	For some ecosystems (e.g., sediments) niches are not well understood at the species level, but may be possible to infer at the level of functional groups.
Connectivity Attributes (relationship to the rest of the world)		
11	Restored ecosystems are integrated into a larger ecological matrix or landscape, with which it interacts through abiotic and biotic flows and exchanges (SER 2004).	Seascape structure and dynamics are not well understood for most deep-sea ecosystems; connectivity between and among ecosystems is likely to be as important as or even more important than in many terrestrial ecosystems due to the multi-dimensional nature of the environment and ocean circulation. Some ecosystems (vents and seeps) have a patchy distribution and while they seem connected locally and regionally, there are biogeographic filters and barriers that may vary among taxa.
12	Potential threats from the surrounding landscape to the health and integrity of the restored ecosystems have been eliminated or reduced as much as possible (SER 2004).	May be more difficult to achieve in some ecosystems due to the inferred great connectivity of deep-sea ecosystems by virtue of ocean circulation.
13	National and international governance must support ecological restoration (this paper).	Governance is limited or underdeveloped regarding deep-sea conservation issues, and non-existent for deep-sea restoration. There is great likelihood of a need for trans-boundary jurisdictional regulations. What exists: within Exclusive Economic Zones (EEZ): national laws and CBD; outside EEZ: UN regulations, International Seabed Authority for

	environmental issues associated to mineral exploitation in areas beyond national jurisdiction, Regional Fishery Management Organizations.