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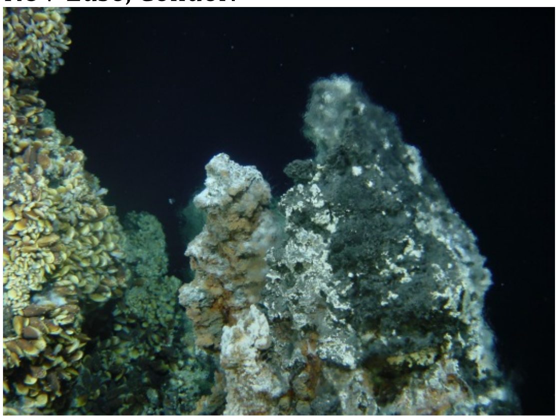

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CONTENTS

Executive Summary

Many of the world's marine ecosystems have undergone significant degradation with negative impacts on not only biological diversity, ecosystem functions and services but also the livelihoods of people that depend on these ecosystems. There is a growing realisation that mankind cannot protect biological diversity and processes, and the services afforded by ecosystems by conservation of habitats alone. Rather, habitats that have been degraded already by human activity need to be restored in order to meet societal aims. Marine ecosystem restoration has been successfully applied in a number of coastal marine habitats worldwide. However, restoration of deep-sea habitats has not yet been attempted. Although remote, these habitats are under increasing pressure and degradation from fishing, mineral, oil and gas exploitation, cables and pipelines, dumping, contamination from shipwrecks, dumping, pollutants and litter.

The need for ecosystem restoration is recognised under different frameworks, conventions and laws as a remedial action for environmental impacts. Whilst the steps required in terrestrial ecosystems are well understood, developments in marine ecosystems are far behind.

The "International Standards for the Practice of Ecological Restoration – including Principles and Key Concepts" produced by the Society for Ecological Restoration (SER), provides documentation to guide practitioners in restoring degraded ecosystems. While the guidelines were developed originally for terrestrial ecosystems they now encompass all geographical terrestrial and aquatic ecosystems. In this work we have evaluated the applicability of the standards to the deep sea, taking each of the six key concepts (definition of reference conditions, key ecosystem attributes, restoration action required (assisting natural recovery), restoration progression, knowledge required and stakeholder involvement) and applying them to four deep-sea case studies.

The case studies were chosen to include a variety of different ecosystems, affected by different levels and kinds of impacts (different activities) in both national and international waters (management, jurisdictions and regulatory frameworks), representing different spatial scales and different types of restoration from natural regeneration to transplantations and deployment of artificial structures. They include cold-water coral ecosystems in the Azores impacted by deep-water fishing (coral transplantation), soft bottom communities in the Mediterranean impacted by scientific rock drilling activities (natural regeneration), abyssal plain communities in nodule-rich areas of the Pacific of interest to deep-sea mining activities (replacement with chemically-conditioned artificial nodules)

and a hydrothermal vent field in the mid-Atlantic that may also be impacted by deep-sea mining at some time in the future (replacement of structures to speed up the development of hydrothermal vent chimneys).

The study involved groups of deep-sea ecosystem experts going through each of the key concepts during a series of MERCES project workshops and compiling advisory information/responses, either literature-supported or as expert opinion, with associated levels of uncertainty. As a desktop exercise and considering the large amount of uncertainty involved in this new area of science, it is cautioned that restoration scenarios included in this document should not be used in any actual risk assessment, management or monitoring plans.

Each of the four case studies includes a detailed description of:

- The reference ecosystem: environmental setting, species composition and diversity, main life-history and other characteristics, structural complexity (habitat forming), vulnerability and fragility/recovery capacity, main ecosystem services.
- Activities, pressures and impacts present at the restoration sites.
- The management landscape: geographic area, jurisdictional framework
- A concise restoration “statement” describing the target objectives
- Existing restoration actions and the potential of applying other techniques.

Key Concept 1: Reference Ecosystem

The selection and description of a reference ecosystem is the first step. This provides a conceptual guide of the desirable local native ecosystem that might be restored. It should not be considered as a static model, but should be inclusive of natural variation of particular ecosystem attributes in time (e.g. in response to climate change). Pre-disturbance sites and analogue sites were available for some case studies. Alongside, each case study was able to identify the information required to describe a reference ecosystem, although dealing with different degrees of knowledge gaps and peculiarities. Therefore, local native reference ecosystems (often near pristine) are still generally available in the deep sea in contrast to most terrestrial and coastal restoration projects. For some deep-sea ecosystems there is a unique opportunity to describe reference ecosystems before impacts occurred, such as from deep-sea mining. However, there is very limited knowledge (and hence great uncertainty) on many aspects of deep-sea ecosystems that may hamper the proper description of reference ecosystems.

Key Concept 2: Key Ecosystem Attributes

An essential part of a restoration project is the definition of a clear target and the specific goals and objectives to reach the target. These are used to monitor the progress of the project over time, applying strategy corrections through adaptive management. For each of the deep-sea case studies, we identified overarching long-term ecological and socio-economic goals, and defined the specific objectives needed to attain these goals. While the goals were broad and similar between case studies, the objectives were specific to the targeted ecosystem. The international standards suggests the description of six categories of ecosystem's key attribute that were considered appropriated to the deep-sea. However, an additional category to describe Ecosystems Goods and Services (EGS) was added to capture the ecological functions and the economic value of these ecosystems which contribute to human well-being. Whilst specific long-term goals and specific objectives could be defined it was evident that there were substantial knowledge gaps in attributes. It was also recognised that the objectives may need to address timescales of decades to centuries and even millennia (in the case of the replacement of polymetallic nodules), so that time steps may not be achievable within timeframes of a human life. Efforts should therefore aim at identifying and reinstating the essential components of an ecosystem that would allow other components of the ecosystem to recover over longer timescales.

Key Concept 3: Assisting Natural Recovery

The ability for natural recovery depends on the initial state of the ecosystem, the level of degradation that has occurred and its restoration potential. If the potential for an ecosystem to recover naturally is low, beyond its natural recovery capacity, physical intervention may be required to reintroduce species or structures. These interventions may also be required if the time frame for natural recovery is very long and there is a desire to speed up recovery processes. This may be particularly important in the deep sea where time frames are expected to be much longer than for terrestrial and shallow water ecosystems. The technical requirements for restoring deep-sea ecosystems will also be much greater owing to difficulties of access and that many operations will need to be carried out in hostile environments with specialised equipment.

Key Concept 4: Restoration Progression

International standards for the practice of Ecological restoration suggest that "restoration projects should adopt the goal of achieving a secure trajectory to full recovery. Due to the specific characteristic of many deep-sea species and ecosystems recovery processes can be slow and take much longer than in terrestrial or shallow water marine ecosystems. In many cases the expected time scales to full recovery may span into time periods where local climate conditions may have changed. Therefore, it is likely that full recovery may not be possible or appropriate everywhere in the deep sea. The five-star recovery system was used to evaluate the likely progress towards full recovery for four deep-sea case studies. This theoretical exercise highlighted the considerable uncertainties, for most sub-attributes of the four the deep-sea case studies, on the likelihood to achieve a certain star level and on the time-scales that will be needed. It therefore also highlighted, that there is limited information to make informed predictions on the trajectories of recovery on deep-sea ecosystems. As described in many sections the expected time scales to full recovery may span into time periods where local climate conditions may have changed, increasing the overall uncertainties on the recovery trajectories. Therefore, achieving a secure trajectory to full recovery seems uncertain for most deep-sea ecosystems; highlighting the need for developing an agenda for continued deep-sea research that could fill most knowledge gaps, reduce uncertainties and better inform how restoration in the deep-sea can be better implemented.

Key Concept 5: Knowledge Required

Successful restoration draws on all relevant knowledge with background knowledge underpinning all phases of restoration including planning, implementation and monitoring. The types of knowledge require a wide range of disciplines, but can be characterised into three groups:

- Ecological knowledge: the natural state of the ecosystem, state and extent of degradation, knowledge on the target species of restoration.
- Technological knowledge: actual techniques for restoration, sourcing material for restoration, industrial solutions for scaling up and monitoring techniques
- Socio-economic knowledge: sector activities, regulatory frameworks, restoration costs, the benefits provided by the restoration and social acceptance

For each case study the major strands of knowledge were identified along with who holds the knowledge (owners). Major knowledge gaps were identified. There was an overall lack of detailed knowledge. What was available was primarily in the hands of the scientists, although fishermen may have local ecological knowledge, and industry may have technological knowledge. There is also a noted lack of knowledge on the ecosystem service benefits that might result from restoration.

Key Concept 6: Stakeholder Engagement

Restoration is a participatory process and should encourage the engagement of a wide variety of stakeholders throughout the project planning stages. Stakeholders may help define the ecological goals, objectives, and methods of implementation. Ongoing stakeholder engagement is also required to ensure social needs continue to be met. The identity of stakeholders concerned with deep-sea restoration may not be obvious because of the remote and inaccessible nature of the deep-seabed compared to many terrestrial or even coastal ecosystems; yet vast areas of the seabed are the Common Heritage of Mankind and so are of importance to all nations. Bearing this in mind potential stakeholders were identified for each case study. Projects closer to shore may involve more local and national stakeholders and may have more public interest or interest from local/national non-governmental organisations (NGOs). With the offshore case studies, the public may be represented by larger world-wide NGOs and other influencers, whilst regulation may still be national within Exclusive Economic Zone (EEZs) or governed by international authorities or conventions in Areas Beyond National Jurisdiction (ABNJs).

Conclusions and Key Considerations

Overall

- The SER framework seems to be generally applicable to deep-sea systems.
- In contrast to terrestrial examples many deep-sea systems are effectively pristine – this allows the restoration agenda to be set in many cases prior to destructive activities taking place.
- We know of no examples of any active restoration activities in the deep sea. Appropriate restoration techniques have not been validated for deep-sea ecosystems.
- Current capacity for deep-sea restoration management is low. This approach requires deep-sea expert knowledge that is in the hands of the few.
- A huge opportunity exists for development of restoration technologies and approaches relevant to the deep sea.

Gaps in the knowledge

- Substantial gaps in the knowledge of biological and ecological attributes for example those related to ecological succession. There is limited information to make informed predictions on the trajectories of recovery on deep-sea ecosystems (high uncertainty).

- It is necessary to identify the key ecosystem features that need to be reinstated that will ensure a successful restoration trajectory.

Time Scales

- Deep-sea systems are slow to respond to changes including management interventions. Timescales may exceed that of multiple human generations.
- Some ecosystems may recover faster than others.

Spatial Scales

- There are issues in scaling up restoration actions in the deep sea to match levels of exploitation and degradation

Restoration Management

- The managers of restoration projects will probably not see results within less than a decade.
- Restoration should only be considered after all avoidance and minimisation efforts have been considered.
- Restoration activities require a mechanism for long-term commitment that exceed typical business and political cycles (financing, managing, regulating, monitoring and enforcement).
- Some short-term objectives are required to allow for measurements in a reasonable time frame to get on the right trajectory that we can check in 5-20 years.
- Restoration costs are anticipated to be very high potentially exceeding the economic benefit of the exploitation. Because restoration costs are high this should not be a reason not to include them through regulation or preclude activities.
- Stakeholders are varied and may be global requiring novel approaches for engagement and enhancing the sharing and capitalisation of existing knowledge

Acronyms Used

AABW	Antarctic Bottom Water
ABNJ	Areas Beyond National Jurisdiction
APEI	Areas of Particular Environmental Interest
AUV	Autonomous underwater vehicle
BACI	Before, After, Control and Impact
BARCI	Before, After, Reference, Control and Impact
BBNJ	Biodiversity Beyond National Jurisdiction
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe – German Federal Institute for Geosciences and Natural Resources
C	Carbon
CCZ	Clarion-Clipperton Zone in the Pacific Ocean
CFP	Common Fisheries Policy
CH4	Methane
CS	Case study
CWC	Cold-water coral
DHNRD	Deepwater Horizon Natural Resource Damage assessment trustees.
DISCOL	DISturbance and re-COLonization experiment
DOSI	Deep-Ocean Stewardship Initiative
EEZ	Exclusive Economic Zone
EGS	Ecosystems Goods and Services
EPR	East Pacific Rise
EU	European Union
FAO	Food and Agriculture Organisation
H2S	Hydrogen sulphide
HD	Habitats Directive
HV	Hydrothermal vent
IMO	International Maritime Organization
ISA	International Seabed Authority
IUCN	International Union for Conservation of Nature
KC	Key Concept
LEK	Local ecological knowledge
LS	Lucky Strike (hydrothermal vent area)
MAR	Mid-Atlantic Ridge
MBARI	Monterey Bay Aquarium Research Institute
MERCES	Marine Ecosystem Restoration in Changing European Seas
MIDAS	Managing Impacts of Deep Sea Resource Exploitation
MOR	Mid-Oceanic Ridges
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MSY	Maximum sustainable yield
NATURA	Coordinated network of European protected areas

NGO	Non-governmental organisation
OCEANA	International advocacy organization focused on ocean conservation
OMA	Local Azorean NGO
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic (Oslo-Paris Convention)
PAP	Porcupine Abyssal Plain
PCB	Polychlorinated biphenyl
POC	Particulate organic carbon
RMFO	Regional Fisheries Management Organisation
ROV	Remotely operated vehicle
RP	Restoration practitioner
SB	Soft bottom (Palinuro seamount case study abbreviation)
SER	Society for Ecological Restoration
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
UNGA	United Nations General Assembly
UNSDG	United Nations Sustainable Development Goals
USD	United States dollars
VME	Vulnerable marine ecosystem
WWF	World Wildlife Fund

1. Introduction

Ecosystem restoration is the "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (SER, 2004) and is a significant component of the Ecosystem Approach "in informing the negotiation of land and marine use options and enhancement of healthy ecosystem networks" (www.iucn.org). Many of the world's marine ecosystems have undergone significant degradation in the historical past with negative impacts, not only on biological diversity, ecosystem functioning and services but also the livelihoods of people that depend on these ecosystems. There is a growing realisation that mankind cannot protect biological diversity and processes, and the services afforded by ecosystems by conservation of habitats alone (www.iucn.org). Therefore, when and where applicable, the restoration of degraded marine ecosystems should be considered and applied in addition to ecosystem conservation measures, such as setting up Marine Protected Areas (MPAs) (Possingham et al., 2015). This is an important aspect of marine ecosystem management and allows coastal and other communities regain the values of biodiversity, ecosystem processes and services from degraded ecosystems. Ecosystem restoration has been successfully applied in a number of marine habitats including coral reefs, seagrass meadows, mangrove forests, salt marshes and oyster reefs worldwide, with reported costs for the restoration of one hectare of coastal marine habitat between 80,000 and 1.6 million USD (Bayraktarov et al., 2016), but with much greater returns in value from ecosystem services such as improved water quality, enhanced fisheries, carbon sequestration and flood protection. Restoration of deep-sea habitats has not been attempted until now but has been suggested as a useful approach for repairing deep-sea habitats that are degraded, damaged or destroyed (Van Dover et al., 2014).

Continued population growth, pollution and the demand for resources are having profound impacts on the open ocean. For instance, the removal of key resources (e.g., fish and other sea-foods) are having profound impacts on deep-sea environments. Pressure from deep-sea fishing has increased since the mid-20th century, particularly on seamounts and along continental margins (Watson and Morato, 2013). There is now strong evidence that many deep-water fish species (e.g., rockfish, Greenland halibut, lings and tusks, orange roughy, sablefish and blue grenadier) have been severely exploited through trawling and longlining, with some species having been fished to commercial extinction (Koslow et al., 2000; McCauley et al., 2015; FAO, 2017). Bailey et al. (2009) documented that overall fish abundances in the NE Atlantic between 800 and 2500 m fell significantly at all depths ranging from 800 to 2500 m between 1977 and 2002, most likely owing to fisheries pressure. Moreover, they showed that the deepest depth affected was considerably deeper than the maximum depth of commercial fishing at the time (approx. 1600 m), suggesting that fishing pressures may be transmitted into deeper waters that are neither routinely monitored nor considered as part of managed fishery areas (Bailey et al., 2009). In terms of trawling, recent studies have shown significant impacts of chronic and persistent bottom trawling on seabed habitats (e.g., habitat heterogeneity, Puig et al., 2012; Daly et al., in press), faunal community composition and food web architecture (Clark et al., 2016), and benthic biodiversity (Koslow et al., 2001; Grehan et al., 2003; Pusceddu et al., 2014). Persistent bottom trawling in the Norwegian Sea has led to cold-water coral reefs (e.g., *Lophelia pertusa*) that act as biodiversity hotspots (Henry and Roberts, 2007; Henry et al., 2013) being heavily damaged; e.g. between 30 and 50% of the reef areas are now damaged or impacted (Fossa et al.; 2002). Looking at the global history of bottom-trawled deep-sea fisheries Victorero et al. (2018) suggest that much more than officially reported biomass of both fish and habitat-forming species has been removed from the deep sea, causing ecosystem changes in ways that are not yet perceived.

At the same time, the deep sea has become a hotspot for the dumping of, and an accumulation site for pollutants including persistent organochlorine pollutants (e.g., PCBs), which may have toxic effects for a variety of fauna at high concentrations (Froescheis et al., 2000; Looser et al., 2000; Ramirez Llodra et al., 2011; Mengerink et al., 2014; Levin and Lebris, 2015). Oil and gas are currently being extracted to depths >3000 m on continental margins. Significant large-scale impacts have occurred due to hydrocarbon leakage and spills, such as the Deepwater Horizon in the Gulf of Mexico (Cordes et al., 2016). The Deepwater Horizon impacted over 2,000 km^2 of benthic habitats including soft bottom communities and cold-water coral gardens (D.H.N.R.D.A.T., 2016; Joye et al., 2016) due to leaked oil and the use of chemical dispersants (De Leo et al., 2016), and significant altered the microbial community structure (Hazen et al., 2010; Yang et al., 2016). The impacted coral communities showed low rates of natural recovery after oil well was sealed (White et al., 2012; Hsing et al., 2013). But the smaller-scale deposition of drill cuttings around platforms can also have significant effects on benthic biodiversity and ecosystem function (Larsson and Purser, 2011; Gates et al., 2012; Jones et al., 2012). In the latter case megafaunal biodiversity and community composition (e.g. sessile to motile fauna abundance ratios) are becoming significantly altered in the immediate vicinity of platforms where disturbances from drill cutting deposition are greatest.

There is now also extensive interest from governments and contractors in mining commercially important minerals from the deep sea, such as copper, lithium, cobalt and nickel. Target mining sites include massive sulphide deposits at hydrothermal vent systems along mid ocean ridges (e.g. in the Mid-Atlantic Ridge within the Portuguese EZZ, the Extended Continental Shelf claim, and in The Area) and back arc basins, cobalt crusts on bathyal and abyssal seamounts, and polymetallic nodules located on abyssal sediments in mesotrophic and oligotrophic equatorial regions (e.g. in the Indian Ocean and the eastern central Pacific), as well as for phosphorites on margins, such as off the coast of Namibia and New Zealand (Mengerink et al., 2014; Thurber et al., 2014; Wedding et al., 2015; Amon et al., 2016; Levin et al., 2016; Vanreusel et al., 2016). Deep-sea mining has not yet occurred on a commercial scale, but is expected to take place within the near future (Wedding et al., 2015). Whilst the theoretical impacts of deep-sea mining have been known for some time (Amos and Roels, 1977), the true nature of impacts are still largely unknown, particularly over the long-term, large-scales and high disturbance intensity (Jones et al., 2017). Nevertheless, deep-sea mining is expected to produce adverse impacts including biodiversity loss, reduction species abundance and ecosystem services (Boschen et al., 2013; Levin et al., 2016a; Van Dover et al, 2017; Niner et al., 2018; Weaver et al., in press).

Exploitation for commercial purposes, and pollution resulting from ineffective management and accidental release are, however, additional to the pervasive effects of increase plastic and microplastics, and climate change in the deep sea (Woodall et al., 2014; Courtene-Jones et al., 2017). Plastic are now reported from within deep-sea fauna (Taylor et al., 2016) and high levels of PCB have been reported in amphipods from the deepest ocean trenches (Jamieson et al., 2017). On the other hand, many observational studies are showing that present-day climate change is impacting deep-sea environments, as exemplified by regional scale deoxygenation (Stramma et al., 2008, 2010, 2012; Keeling et al., 2009; Helm et al., 2011), lowered pH of intermediate deep-waters (Byrne et al., 2010), increased deep-sea temperatures (Purkey and Johnson, 2010), and altered POC flux to the seafloor (Ruhl and Smith, 2004; Smith et al., 2013) with potential severe consequences to the benthic components and ecosystem functioning (Yasuhara et al., 2008; Danovaro et al., 2017; Gambi et al., 2017; Snelgrove et al., 2017). Moreover, climate change models suggest that abyssal ocean temperatures could increase by 1°C over the next 82 years, and that bathyal depths (200–3000 m) worldwide will undergo significant reductions in pH by the year 2100 (0.29 to 0.37 pH units) (Mora et al., 2013; Sweetman et al., 2017). Oxygen concentrations are also predicted to decline in the bathyal deep sea, and the flux of particulate organic matter to the seafloor is likely to decline significantly in most oceans (Jones et al., 2014; Sweetman et al., 2017), most drastically in the abyssal and bathyal Indian Ocean where reductions of 40–55% from present day fluxes are predicted by the end of the century.

Given the multitude and magnitude of stressors that the deep ocean is presently facing, and the dire changes that are predicted, it is imperative to implement ecosystem conservation measures in the deep sea and to evaluate how ecological restoration of degraded deep-sea ecosystems can help achieving ecosystem conservation and the UN Sustainable Development Goals and targets, both in the High Seas and in National jurisdictions. Restoring the deep sea after severe anthropogenic impacts is, however, inherently plagued with added difficulty owing to its isolated nature, greater depth, more limited scientific knowledge, biological connectivity for some fauna, and added effects associated with slow population growth rates (Montero-Serra et al., 2017), and long generation times that characterize the evolution of many deep-sea organisms (including microbes to megafauna). Moreover, the cost of restoring a relatively small area of habitat in the deep sea may be extremely high. Van Dover et al. (2014) estimated that to restore 600 m^2 of stony coral habitat in the Darwin Mounds could cost 4.8 million USD, while restoring 72 m^2 of rare hydrothermal habitat would cost 5.4 million USD. The sheer scale of disturbance that will be inflicted by certain anthropogenic stresses (e.g., polymetallic nodule mining where 200 to 400 km^2 of seafloor will be disturbed per mining operation per year) is likely to impose further constraints on restoration to a greater degree than would be encountered in shallow marine ecosystems.

There's an ongoing debate among different lines of thinking on ecological restoration best practices, namely between a principles-first approach (e.g. Suding et al., 2015; Higgs et al., 2018) and a standards-based approach (SER, 2004; McDonald et al., 2016). It has also been argued that principles and standards should operate together and, generally, principles should precede standards. The SER international standards for the practice of ecological restoration (McDonald et al., 2016) were built upon decades of extensive experience in terrestrial and coastal ecosystem restoration, but did not consider the particular characteristics of deep sea. Therefore, the guidelines, principles, and key concepts of ecological restoration of deep-sea habitats requires additional thinking before restoration of deep-sea ecosystems can be considered as a useful tool to achieve healthy and productive oceans. Here, we built upon Van Dover et al. (2014) contribution to evaluate how principles and key concepts underpinning best practice of ecological restoration (*sensu* McDonald et al., 2016) can be transferred to deep-sea ecosystem and highlight ways forward for restoration of degraded deep-sea ecosystems.

2. Society for Ecological Restoration: Principles and Key Concepts underpinning best practice in ecological restoration

The Society for Ecological Restoration (SER) International Standards for the Practice of Ecological Restoration – including Principles and Key Concepts (McDonald et al., 2016), provide practitioners with best practices guidelines for the development of successful restoration of degraded ecosystems across all geographical terrestrial and aquatic ecosystems, to improve biodiversity conservation, secure the delivery of ecosystem good and services, ensure restoration projects integrate all relevant socio-cultural components, and also contribute to achieve UN Sustainable Development Goals and targets. The Standards document notes three underpinning principles, that successful ecological restoration practice should be effective, efficient and engaging (Keenleyside et al., 2012):

- **Effective** ecological restoration establishes and maintains an ecosystem's values.
- **Efficient** ecological restoration maximizes beneficial outcomes while minimizing costs in time, resources and effort.
- **Engaging** ecological restoration collaborates with partners and stakeholders, promotes participation and enhances the experience of ecosystems.

The document also highlights six Key Concepts essential for achieving high levels of recovery with a specific procedure for developing targets, evaluating the recovery of key ecosystem attributes and incorporating social engagement. These six key concepts are detailed in the following table together with how they have been applied to the deep-sea case studies used in this report.

Table 1. Key Concepts underpinning best practice in ecological restoration and applications to deep-sea restoration

Key Concept (McDonald et al., 2016)	**Aim and application to deep-sea restoration**
Key concept 1: Ecological restoration practice is based on an appropriate local native reference ecosystem, taking environmental change into account	Defines the reference system (target of the recovery action), characterising the condition of the ecosystem had it not be degraded, taking into account climate change
Key concept 2: Identifying the target ecosystem's key attributes is required prior to developing long-term goals and shorter-term objectives	Defines ecosystem attributes and sub-attributes with measurable indicators that can inform on a restoration project's goals and objectives.
Key concept 3: The most reliable way to achieve recovery is to assist natural recovery processes, supplementing the extent of natural recovery potential where it has been impaired	With respect to the recovery potential of the main ecosystem attributes, this concept informs on the restoration approaches required to restore degraded ecosystems and enhance the rates and processes of natural recovery.

Key Concept (McDonald et al., 2016)	**Aim and application to deep-sea restoration**
Key concept 4: Restoration seeks 'highest and best effort' progression towards full recovery	The time taken for individual ecosystem attributes to reach different defined steps on a 5-Star recovery scale (also incorporating uncertainty), and a graphical representation (recovery wheel) is used to assess the progress of recovery through the status of the attributes at different time intervals.
Key concept 5: Successful restoration draws on all relevant knowledge	Identifies the different types of knowledge, owners of the knowledge for the restoration process, as well as specific knowledge gaps.
Key concept 6: Early, genuine and active engagement with all stakeholders underpins long-term restoration success	Acknowledging social engagement, it identifies the different types of stakeholders that may be required for involvement in the restoration process.

3. Deep-sea restoration case studies considered to evaluate the six Key Concepts

Four case studies (CS) covering a broad range of deep-sea ecosystems, in different ocean and sea basins, of different spatial scales, under different types and levels of human impacts, and under different types of management authorities, were considered to evaluate the six key concepts to achieve ecological restoration (Figure 1). These include 1) cold-water coral ecosystems (CWC CS) impacted by deep-sea fishing, 2) soft bottom communities (SB CS) impacted by scientific rock drilling activities, 3) abyssal plain communities in nodule rich areas (CCZ CS) potentially impacted by deep-sea nodule mining and 4) a hydrothermal vent field (HV CS) potentially impacted by deep-sea seafloor massive sulphides (SMS) mining. Whilst for the first two CSs, the current levels of degradation resulted from existing human activities (fishing and rock drilling), the latter two CSs are hypothetical scenarios of potential future degradation caused by future blue growth activities, such as deep-sea mining.

The case studies also consider different types of management authorities and management regimes, from areas within national jurisdictional waters (e.g. CWC, HV, and SB CSs) that may be managed by national and EU regulatory tools, to areas of the seabed beyond national jurisdiction called "The Area" (CCZ CS) where mining activities are managed, regulated and controlled by a United Nations intergovernmental body; The International Seabed Authority.

For each case study, hypothetical restoration actions were selected according to an existing or assumed level of degradation. The SB was used as an example of small spatial scale and low level of degradation case study, employing 'natural spontaneous regeneration' approaches. The CWC represented a case study of intermediate degradation, where key biotic elements (i.e. gorgonian corals) removed by fishing activities were transplanted to degraded areas, employing 'assisted regeneration with biotic intervention' approaches. For the CCZ and HV CSs, the expected levels of degradation after deep-sea mining is high; with the removal of essential abiotic elements (nodules and vent chimneys) that will take up to millions of years to recover naturally. Recovery of these ecosystems will thus require the reconstruction of abiotic elements through the use of false nodules with appropriate chemical coating in the CCZ and artificial chimney-like structures in the HV case, employing 'assisted regeneration with physical intervention' approaches. However, these two case studies are fundamentally different in terms of the spatial scales to be considered, since the CCZ CS may cover an area of millions of km^2 while the HV CS covers an area of about 200 km^2.

Although in the case of the CWC CS, coral transplantation techniques have been already tested in shallow waters as a potential restoration tool (Linares et al., 2008), transplantation techniques never been tried in the deep sea and therefore have yet to be validated for deep-sea coral gardens. As for the CCZ and HV CSs, the restoration actions discussed in this document are purely theoretical and built upon other theoretical deep-sea restoration scenarios (e.g. Van Dover et al., 2014; MIDAS, 2016). There is, therefore, a great level of uncertainty regarding the potential restoration outcomes of deep-sea restoration projects using artificial structures. For example, it is possible that physical interventions may modify the surrounding environmental conditions through leaching of chemicals or from physical changes to the sediment and may lead to unintended and unexpected negative biological effects. Therefore, the hypothetical **restoration scenarios included in this report should NOT be used for risk assessment or management and monitoring plans**.

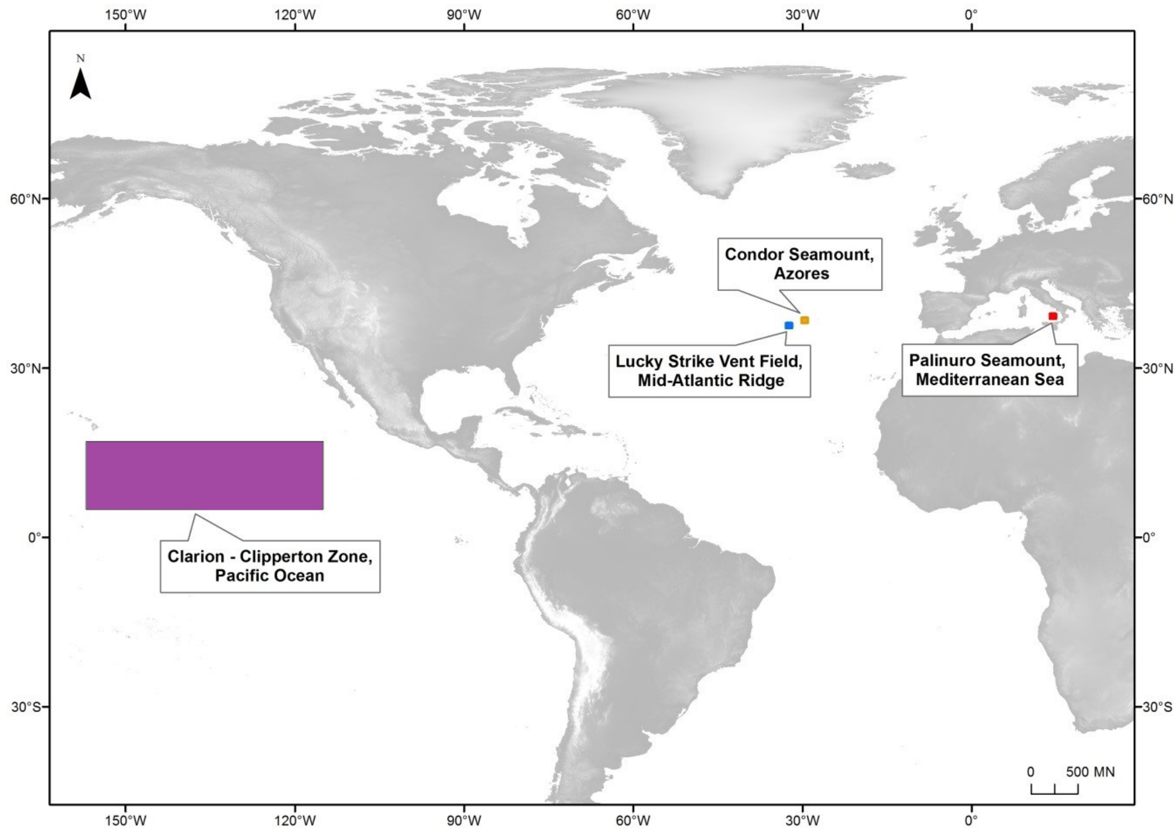

Figure 1. Map showing the locations of the four case studies considered to evaluate the six key concepts to achieve ecological restoration.

3.1. Restoration Project: Cold-water coral gardens in Condor seamount (Azores, Portugal)

3.1.1. *Ecosystem description*

Environmental setting of the ecosystem

The Condor Seamount is an elongated volcanic ridge, rising from 1700 m to a flat summit at ca. 200 m depth (Figure 2). The summit of Condor is characterized by hard substrate, mainly rocky outcrops and boulders, mixed with areas of soft sediments, while the slopes constitute of mostly soft sediments such as gravel, sand and mud. The oceanographic conditions over Condor are different from the surrounding environment, mainly characterized as enclosed circulation around the seamount, pronounced mixing most probably due to semidiurnal tidal effects (Bashmachnikov et al., 2013). This influences the sedimentation processes and organic matter distribution, which appear to follow the seamount model (less organic matter on the seamount than adjacent areas) (Zeppilli et al., 2013). The temperature ranges between 12-16 °C throughout the year, whereas salinity is stable at 36 psu. Such environmental setting supports the existence of rich biological communities found in Condor (Tempera et al., 2012; Braga-Henriques, 2015).

Species composition and diversity

The summit of Condor harbours multi-species aggregations of cold-water corals (CWCs) further referred as coral gardens, where Alcyonacea (gorgonians and soft corals), Pennatulacea (sea pens), Antipatharia (black corals) and Stylasteridae (hydrocorals) are the most conspicuous components (OSPAR 2010). Until now, 61 coral taxa have been described from the Condor seamount and the highest biomass occurs on the summit between 165 to 262 m water depth (Tempera et al., 2012; Braga-Henriques, 2015).

Coral gardens in Condor are found in small and fragmented patches (3.8±3.2 colonies m^{-2}), largely reflecting substrate type and oceanographic conditions (hard substrates where the current flow is accelerated and food input is potentially high). Octocorals *Dentomuricea cf. meteor* and *Viminella flagellum* are the dominant species, with the common presence of large colonies (up to 2 m in height and 1 m in width) of octocorals *Callogorgia verticillata* and *Paracalyptrophora josephinae* and more rarely the black coral *Leiopathes* sp. Other small-sized corals, such as the octocoral *Bebryce mollis* and the soft coral *Schizophytum echinatum* (endemic to the Azores) are also commonly associated with this habitat.

Main life-history and other characteristics

There is currently no information on growth and age of the dominant gorgonian species in Condor. However, studies on deep-sea gorgonians elsewhere show slow growth rates of 0.44–2.32 mm/year, with ages spanning from 30 to more than 400 years (reviewed by Watling et al., 2011). Deep-sea black corals are generally at the end of the spectrum of slow growing organisms with rates of 0.002-0.066 mm/year and estimated ages in the range of nearly hundreds to thousands of years in the Azores and other regions (82–4000 years: Sherwood and Edinger, 2009; Roark et al., 2009; Carreiro-Silva et al., 2013). Knowledge on the reproductive biology of these organisms is also still very limited. Studies on the reproductive biology of black corals and gorgonians in the Azores show that gorgonians have low fecundity (5–10 oocytes per coral polyp) and larvae with potentially low dispersal capabilities (Rakka et al., 2017; Rakka and Carreiro-Silva, unpublished data). Genetic connectivity of coral populations in the Azores has not been studied yet.

Structural complexity (habitat forming)

Coral gardens, especially if built by tall and arborescent gorgonian and black coral colonies, form tri-dimensional complex habitats and add functional capacity to the surrounding deep-sea environment. A high number of associated sessile (e.g. zoantharians, anemones, hydroids) and vagile (e.g. polychaetes, echinoderms, crustaceans, fish) species use coral gardens as refuge, source of food, spawning and nursery areas (Braga-Henriques, 2015; Pham et al., 2015). Several commercial fish species inhabit the seamount, including *Helicolenus dactylopterus, Polyprion americanus,* and *Pagellus bogaraveo*, among others. However, how fish species use the seamount and the coral gardens (migrations between habitats) is still uncertain. The food web in Condor is complex with mesopelagic organisms having an important role in the transfer of energy between the epipelagic environment and the deeper-living benthic and benthopelagic organisms (Colaço et al., 2013). Finally, the associated microbial communities are a major knowledge gap.

Vulnerability and fragility / recovery capacity

Because of CWC life history characteristics (i.e. slow growth, high longevity, low reproductive potential) and fragmented habitat, CWC are perceived as very vulnerable to damage by fisheries or other human activities, with recovery of individual coral colonies and communities requiring decades to centuries. These characteristics have resulted in coral gardens' being listed as vulnerable marine ecosystems (VMEs) (UNGA, 2007; OSPAR, 2010).

Main ecosystem services

In addition to their bioengineering role, coral gardens provide important provisioning services such as fisheries resources and pharmaceutical compounds, regulation services such as carbon storage and nutrient remineralization, and cultural services for aesthetical, educational and scientific purposes (Thurber et al., 2014).

3.1.2. *Activities, pressures and impacts*

Current human activities on Condor seamount include scientific research, tourism (e.g. shark diving and big-game fishing), shipping, and pelagic fishing for tuna. However, only scientific research may currently be considered a pressure on the benthic ecosystems due to the impacts from destructive sampling. Since the 1990s the Condor Seamount has been targeted by local demersal fisheries. Fishing activities comprised mainly of bottom longline and handline fishing down to depths of ca. 600 m. Longline fisheries can impact coral gardens through the accidental capture (bycatch) of corals during fishing activities or by mechanically damaging corals that remain on the seafloor (e.g. breakage, displacement, tissue abrasion) (Sampaio et al., 2012; Mytilineou et al., 2014; Pham et al., 2014). Moreover, longline fishing impacts mostly organisms with complex 3D morphologies, which may eventually threaten their population health since growth and recruitment may be outbalanced by the amount removed making population resilience low and recovery highly unlikely. This in turn will reduce the habitat for associated species, resulting in overall loss of biodiversity and the ecosystem services they provide. Because of the "selective" impact of fisheries on larger coral colonies, information on the maximum size that corals can attain is uncertain. Therefore it may be necessary to use historical records of coral maximum size from early century oceanographic campaigns in the Azores, such as Prince Albert I of Monaco expeditions (Sampaio et al., subm).

3.1.3. *Management landscape*

The Condor Seamount is located southwest of Faial Island within the Azores EEZ. An area of 242 km2 surrounding the seamount has been closed since 2010 to fisheries for research purposes (Morato et al., 2010). The area has been included in the Azores Marine Park since 2016.

3.1.4. *Restoration "statement"*

Restoring cold-water coral gardens impacted by deep-water fishing using assisted restoration of three gorgonian species with transplantation.

3.1.5. *Existing restoration actions and potential future techniques*

No restoration techniques have yet been validated for deep-sea coral gardens. Restoration actions and techniques are currently being tested for deep-sea coral gardens in European Seas within MERCES and in the Pacific Ocean by the Monterey Bay Aquarium Research Institute (MBARI). Knowledge gaps, restoration techniques and management issue are being evaluated for cold water coral communities impacted by the Deepwater Horizon blowout in the Gulf of Mexico (D.H.N.R.D.A.T., 2016).

Restoration protocols being tested in the Azores are based on techniques developed for tropical coral reefs and Mediterranean continental shelf gorgonians (Project ShelfReCover www.shelfrecover.com) and red coral populations, whereby transplants of small to medium size coral fragments from adult donor specimens are transplanted to impacted areas (Rinkevich, 1995; Linares et al., 2008). Because CWCs are highly vulnerable to human pressure, restoration actions should act in concert with protection measures that remove as many pressures as possible from the area to be restored (e.g. closures to fishing activities). Moreover, because of the patchy or fragmented nature of deep-sea coral gardens, a combination of restoration approaches will likely be necessary, with natural spontaneous regeneration (through fisheries closures, MPAs) at large scales, and assisted regeneration and reconstruction at smaller scales.

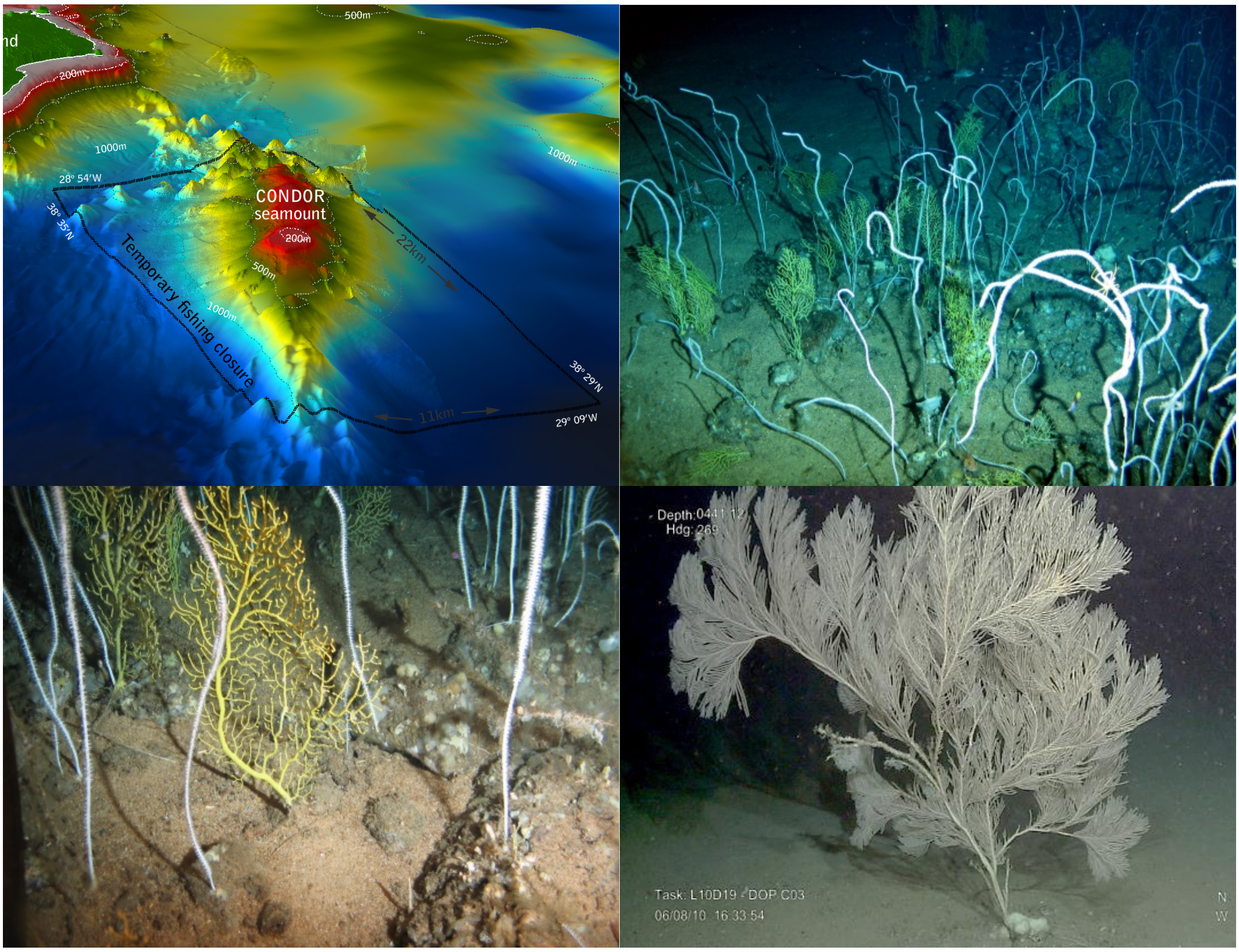

Figure 2. Cold-water coral gardens in Condor seamount (Azores, Portugal). (top left) Map of the Condor Seamount showing the boundaries of the fishing closure; (top right and bottom left) typical coral communities at the seamount summit composed by the octocorals *Dentomuricea* cf. *meteor* (yellow) and *Viminella flagellum* (white); (bottom right) large colony of the octocoral *Callogorgia verticillata*. Map graphics: F. Tempera ©ImagDOP. Bathymetry data credits: EMEPC, DOP-UAz, Project STRIPAREA/J. Luís/UAlg-CIMA, Lourenço et al., 1998. Photo credits: (b-c) Gavin Newman ©Greenpeace; (d) EMEPC, ROV Luso, Condor (EEA Financial Mechanism (PT0040/2008), CORALFISH (FP7 ENV/2007/1/21314 4).

3.2. Restoration Project: Abyssal plain communities in nodule rich areas in the CCZ (Pacific Ocean)

3.2.1. *Ecosystem description*

Environmental setting of the ecosystem

The Clarion Clipperton Zone (CCZ) is an approximately 6 million km^2 area in the central northern Pacific bounded by the Clarion Fracture Zone to the north and the Clipperton Fracture Zone to the south (Figure 3). There is a gradual increase in water depth from east (4000 m) to west (5000 m) owing to the sinking of older and cooler oceanic crust towards the west (Pushcharovsky, 2006). However, slight variations in spreading rate have led to a series of bathymetric highs and lows with a characteristic spacing of 1 to 10 km, elongated perpendicular to fracture zones (Mammerickx and Klitgord, 1982; Olive et al., 2015). These horst and graben structures shape the CCZ seafloor as a succession of crenulated ridges, low profile valleys, and flat zones, which are characteristic of most abyssal landscapes worldwide (Harris et al., 2014). Chains of seamounts orientated east-west are common throughout the area, reaching altitudes of over 1000 m above the average depth. Very low influx of terrigenous sedimentation ensures these geomorphologies are unobscured by the blanketing of sediments at the CCZ, in contrast to abyssal plains closer to continental margins (Smith and Demopoulos, 2003).

Seabed sediments in the CCZ consist of fine-grained nannofossil muds (Mewes et al., 2014). The carbonate compensation depth in the area is located between 4200 and 4500 m water depth (Johnson, 1972). The background sedimentation is around 2 $mm \cdot kyr^{-1}$, however, in sediment-trapping locations sedimentation rates can be up to 18 $mm \cdot kyr^{-1}$ (Riech and von Rad, 2013). The major characteristic of the area is the presence of polymetallic nodule deposits. The nodules occur at abundances frequently exceeding 10 $kg \cdot m^{-2}$ and are mostly exposed on the sediment surface (Radziejewska, 2014).

Bottom waters in the CCZ consist mainly of Antarctic Bottom Water (AABW). Moderate current speeds in the order of 1-10 $cm \cdot s^{-1}$ were measured by Hayes (1979), although peak velocities of up to 25 $cm \cdot s^{-1}$ have been registered in the wider area (Amos and Roels, 1977). Seabed temperatures are around 1.5 °C. Oxygen concentration is around 130 micromole of oxygen. The oxygen minimum zone in the CCZ is very pronounced and occurs generally within 100-1000 m water depth (Hannides and Smith, 2003) and does not extend to the seafloor. Particulate Organic Carbon (POC) flux at the CCZ ranges between 0.4 – 2.2 g $C \cdot m^{-2} \cdot yr^{-1}$ with higher fluxes to the east and towards the equator (Lutz et al., 2007).

Species composition and diversity

Over 170 morphotypes of megafauna have been found with the UK-1 contract area (International Seabed Authority - ISA - contract) but this is likely under-represented owing to the low sampling effort made to date (Amon et al., 2016). Around half of megafauna species found on nodules are obligate nodule dwellers (Amon et al., 2016). Megafauna abundance averaged 1.48 ind·m^{-2} (Amon et al., 2016). Megafauna protists (xenophyophores) are the most abundant megafauna taxon (Amon et al., 2016) and consist of around 29 morphospecies of which 28 are new to science. This represents 30% of known global species richness of xenophyophores (Gooday et al., 2015). A total of 20 mobile scavenging species were found in UK-1 (Leitner et al., 2017).

Macrofauna across the CCZ range in abundance between 36-268 ind·m^{-2} and a total of 381 species have been found (Hecker and Paul, 1979), most of which are undescribed (Glover et al., 2016). Sediment-dwelling macrofauna are primarily polychaetes. Macrofauna living on nodules have received limited assessment. Meiofauna in the CCZ are primarily nematodes and harpacticoid copepods (Radziejewska, 2014). In the GSR contract area of the CCZ (ISA contract area), 14 meiofauna taxa, 28 nematode families and 80 nematode genera have been identified (Pape et al., 2017). Nematodes at the GSR area reached densities of around 80,000 – 150,000 ind·m^{-2} (Pape et al., 2017). Bacterial biomass in the GSR area was 237-416 mgC·m^{-2} (Pape et al., 2017). A total 113,000 prokaryotic operational taxonomic units have been found within UK-1 claim area (Shulse et al., 2017) of which 97,000 only occur in sediments with nodules, 94% of these have not been recorded previously.

Main life-history and other characteristics

Growth rates of CCZ fauna are very slow with long generation times (McClain et al., 2012). Preliminary results suggest that connectivity (based on gene flow) in common species is relatively high (100s of km), although there is a strong turnover of species (and limited connectivity) with increasing depth (Glover et al., 2016). Dispersal ability of individual adults, juveniles and propagules is not known beyond inferences from genetics.

Food webs in the CCZ are driven largely by POC flux. There are around four trophic levels (Drazen et al., 2008). Microbes rely on both *in situ* chemoautotrophy (e.g. nitrification Molari et al., 2013) or on dissolved organic matter (Sweetman et al., in revision). The majority of metazoans feed upon POC that reaches the sediment surface. There is little evidence to suggest that benthic scavengers consume benthic prey (Bailey et al., 2006). In the Pacific Ocean many of the scavenging fauna are eating nekton carrion that has fallen from surface waters (Drazen et al., 2008). Most of this respiration is from bacteria. Inorganic carbon fixation seems to be important in supplying carbon to benthic ecosystems.

Structural complexity (habitat forming)

The nodules on the seafloor surface provide high structural complexity with apparently high diversity of microhabitats (Gooday et al., 2015). There are some large nodule-dwelling fauna, for example hexactinellid sponges, that provide habitat for other fauna (e.g. Purser et al., 2016). There is also structure within the sediment itself, associated with buried nodules. There are strong gradients of sediment shear strength with increasing depth in the sediment.

Although at present there has been little research and therefore some uncertainty, it is likely that ecological interactions are important for maintaining ecosystem structure and functioning. It may be that particular species have critical, but currently unknown, functions in maintaining ecosystem structure. It is highly likely that some roles carried out by the microbiome are important (e.g. carbon fixation). Bioturbation by larger animals (megafauna and macrofauna) also appear important for maintaining and regenerating sediment structure and functioning after disturbance. Conversely, it is possible that some species may have negative effects by repressing or disrupting successional dynamics. Further research is required including experimental approaches.

The spatial and temporal mosaic of seafloor habitats and species may be important in maintaining ecosystem structure and functioning (e.g. as a mechanism for maintaining diversity Huston, 1979). This may be disrupted by disturbance either by fragmentation or homogenization. At a broader scale, the variety of habitats on the seafloor of the CCZ, including flat areas with nodules, horst and graben structures, seamounts, will lead to higher overall regional diversities and potentially maintenance of important local patterns. There may be supply of propagules from other environments, for example bathyal source populations (Rex et al., 2004).

Vulnerability and fragility / recovery capacity

The ecosystems of the CCZ are both vulnerable and fragile. They are vulnerable to disturbance as many of the species are sessile suspension feeders. Furthermore, many individuals live on nodules, which are the target of mining activities. The recovery capacity of the ecosystems is likely to be low, or at least recovery is likely to take a long time. Nodules grow only very slowly (ca. 1 mm each ky) and so once removed result in total removal on ecological timescales. Results from disturbance experiments in the CCZ suggest limited recovery of sediment-dwelling communities even after decades, particularly in sessile and larger fauna (Jones et al., 2017). A recent re-evaluation of recovery at the an abyssal site off Peru, known as the DISCOL site, by the JPI-Oceans project suggests that ecosystem functioning, microbial communities, and the community structure of all size classes of metazoan fauna show very little sign of recovery in areas disturbed previously even after the 26-years (Martinez-Arbizu, pers. comm.).

Main ecosystem services

The main ecosystem services can be classified into regulating, provisioning and cultural services, following Thurber et al. (2014). The primary regulating services provided by the CCZ are nutrient cycling and carbon sequestration. Both processes are globally important but happen over millennial time periods. The provisioning services provided by the CCZ will be primarily the minerals on the seafloor targeted by seabed mining, but also include surface fisheries (mostly for tuna) and the potential for supply of novel marine biochemicals or marine genetic resources, which may be targeted by bioprospectors. The deep sea in general and the CCZ in particular provides cultural services through the aesthetic and existence values of the environment and the species that live there. The value of these ecosystem services are increasing with the improved public awareness of these environments and their fauna, driven primarily through media coverage arising from scientific expeditions to the area.

3.2.2. *Activities, pressures and impacts*

The primary anthropogenic activities affecting the CCZ at present are shipping, pelagic fishing in surface waters, cable laying on the seabed and the exploration for mineral resources. Deep-sea mining has the potential to increase the intensity of anthropogenic activity. Climate change and pollution are also important drivers influencing the CCZ. Shipping primarily leads to impacts from both atmospheric and water-column pollution (e.g. from oil/emissions) and eutrophication (from discharged sewerage). It may also increase the likelihood of both macro- and micro- plastic pollution, as well as other anthropogenic litter being introduced into the environment. The main impacts from fishing are removal of fish biomass from near-surface waters that may alter the trophic dynamics of the pelagic ecosystem by removal of top predators. This may affect benthic ecosystems by reducing food supply for scavenging communities and potentially altering the quality and quantity of carbon flux to the seafloor. Cable laying may lead to some disturbance on the seafloor, but these impacts are likely to be minimal.

Mining has not yet occurred on a commercial scale at the CCZ, but the impacts are predictable. It will lead to widespread physical damage to the seafloor and the creation of sediment-laden plumes, which may also lead to some negative chemical impacts, as well as physical impacts associated with increased turbidity or smothering. Mining will lead to physical changes on the seabed by removal of nodules, exposure of subsurface layers, and change in grain size, porosity and sediment structure. It will change sediment, pore water and water column biogeochemistry, including concentration of organic material, nutrients and metals. These impacts may all lead to secondary biological effects, which may further change the seabed environment. Mining may lead to changes in the morphology of the seafloor. There will be additional impacts, such as sound and light that may impact mobile animals. The mining equipment and associated shipping may also introduce additional pollutants into the environment.

Climate change will impact the deep waters of the CCZ from both deoxygenation in intermediate waters and particularly reduction in POC flux. The reduction in POC flux is likely to lead to notable changes to the benthos of the CCZ (Jones et al., 2014).

3.2.3. *Management landscape*

The CCZ is entirely within "the Area", the seabed beyond national jurisdiction and is bordered by the Mexican EEZ to the east and Kiribati to the west. All the mineral-related activities in the Area are managed, regulated and controlled by ISA. The ISA formed regulations for the prospecting and exploration of polymetallic nodules in 2000. The ISA is currently discussing draft regulations for the exploitation of all deep-sea minerals, including nodules. Under the exploration regulations, the ISA has entered into contracts with sixteen contractors (one contractor has contracts for two separate areas) for exploration for polymetallic nodules in the CCZ. Each contractor gains the exclusive use of one or more exploration areas of up to 75,000 km^2. Seven contractors have completed their initial contract period of 15 years and have been granted an extension of a further 5 years. The CCZ was the first (and currently only) area to have a regional management plan developed by the ISA and includes a network of protected areas called Areas of Particular Environmental Interest (APEI).

Restoration activities would come under the exploitation regulations, but is uncertain whether they will be included in the developing legal environment and whether restoration will be explicitly included in the Regulations or only in subsequent Recommendations and Guidelines.

3.2.4. *Restoration "statement"*

Restoring abyssal plain benthic communities in nodule rich areas in the CCZ impacted by deep-sea mining using assisted regeneration with physical interventions, namely the replacement of nodules lost to mining with false nodules (with a coating of similar chemical composition to natural nodules).

3.2.5. *Existing restoration actions and potential future techniques*

Introducing artificial substrata is likely to be the most realistic restoration strategy for abyssal nodule systems. Nodules will be removed by mining and will take millions of years to recover naturally. Many species live only on nodules. Restoration activities that replace the hard substratum provided by nodules, may encourage much more rapid recolonization of nodule-dwelling fauna. No information exists as to whether this is an effective technique. There are some examples of abyssal organisms recolonizing artificial substrata, such as xenophyophores growing on release weights after 26-years at the DISCOL site (Martinez-Arbizu, pers. comm.). The type of material used for the artificial nodules may be an important factor, with the choice of materials affecting potential geochemical changes and settlement efficacy. It may be necessary for the chemical nature of the nodules to be retained to attract species and this, may include some of the metals of economic interest.

Transplanting fauna from undisturbed areas to impacted areas is a common restoration activity in other environments. This is likely to be technically challenging in the abyss. It is also uncertain the type of fauna that would be best to concentrate on for transplantation as we do not know the species that are important for maintaining ecosystem structure or function. It may also be possible to introduce larvae or juveniles to the environment to speed up recovery. We currently do not have the ability to mass-produce viable propagules for deep-sea organisms or to release them in a way that would stimulate natural recovery processes.

Introducing new sediment, potentially including sediment enriched in organic material, provides a mechanism to restore ecosystems affected by sediment compaction and removal of the more organic-rich sediment surface layers. It may also help to restore areas with elevated levels of metals in surface layers from mining activities. There are many challenges and uncertainties in this approach, for example the technical challenges in creating and deploying sediment and the potential for unintended biogeochemical changes that may exacerbate impacts or lead to unintended consequences.

Redistributing sediment may restore sediments that have been compacted or otherwise altered by the action of the mining collector. Redistribution may be achieved mechanically or hydraulically. This is more likely to be effective when done at the same time as the nodule collection (e.g. with a rake at the back of the nodule collector), which would make it more of a minimization strategy, rather than true restoration. There is a clear need for greater experimentation on methods that might be used to speed up natural recolonisation processes in the deep sea. Such research is likely to require a concerted research programme over a long period using current sediment disturbance experiments being undertaken by ISA contractors.

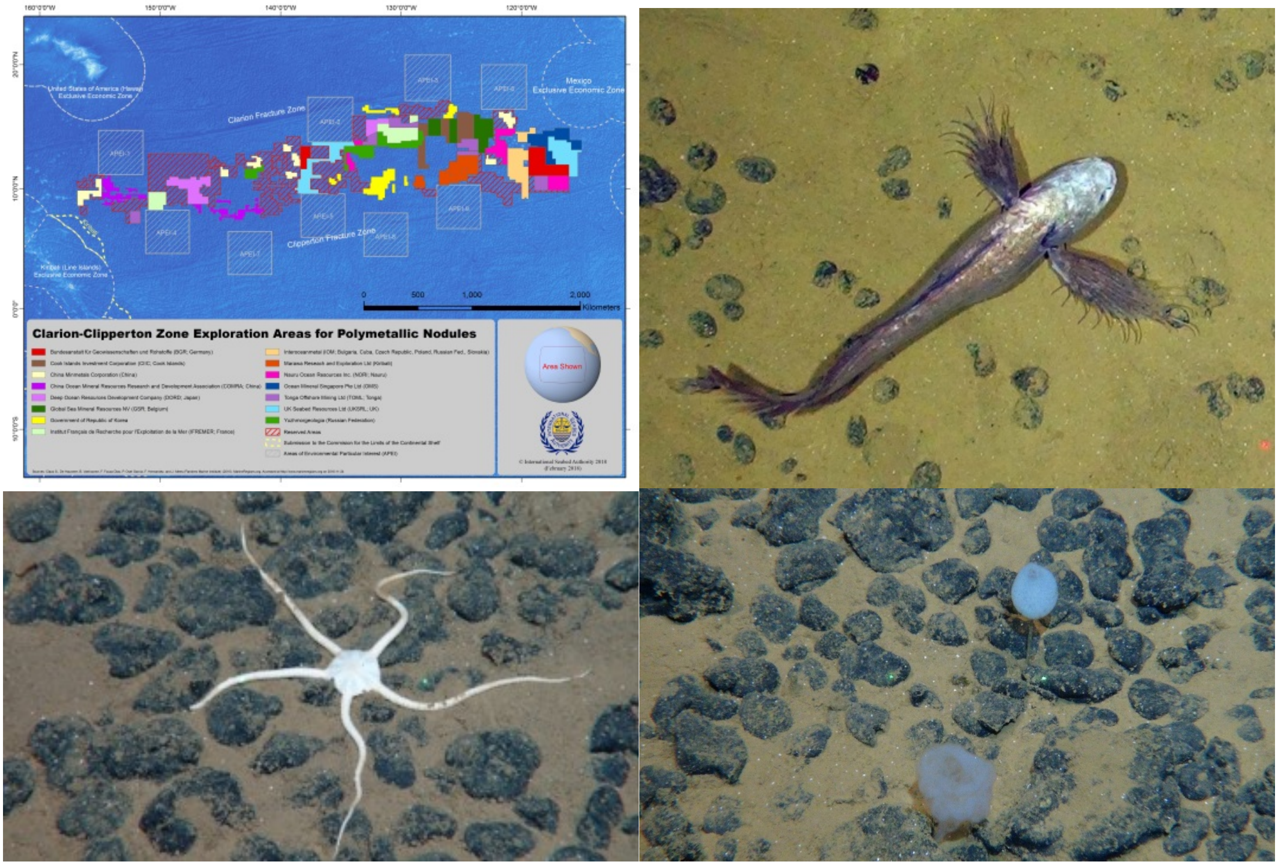

Figure 3. Abyssal plain communities in nodule rich areas in the Clarion Clipperton Zone (CCZ, Pacific Ocean). (top left) Map of the CCZ showing exploration areas for polymetallic nodules for different contractors. (top right) seabed image showing nodules and Ophidiid fish, (bottom left) unidentified ophiuroid echinoderm; (bottom right) unidentified Porifera from the northeastern area of particular environmental interest in the CCZ. Map credits: International Seabed Authority; Photo credits: (top left) National Oceanography Centre, Southampton, UK, RRS James Cook Cruise JC120; (bottom) GEOMAR Helmholtz Centre for Ocean Research Kiel, cruise SO239, ROV Kiel 6000.

3.3. Restoration Project: Hydrothermal vent communities in the Lucky Strike field (Mid-Atlantic Ridge, Atlantic Ocean)

3.3.1. *Ecosystem description*

Environmental setting of the ecosystem

The following terminology is often used (based on Chevaldonné et al., 1997): A "vent field" (e.g. Lucky Strike) is a cluster of several vent sites located a few hundred meters apart. A "vent site" is a spatially continuous area of venting, constituted of several emission types only a few meters apart, emerging from a common network of fissures. Vent sites are often referred as edifices (e.g. Eiffel Tower edifice) or as sulphide structures. Each vent site (edifice, structure) usually comprises several emission types including black smokers, flanges and diffusion zones (Fustec, 1985; Jollivet, 1993). The Lucky Strike (LS) is the third segment of the Mid Atlantic Ridge south of the Azores platform (Figure 4). It is approximately 65 km long, with depths ranging between 1550 and 3000 m. LS is a basalt hosted vent field (Langmuir et al., 1997; Fouquet et al., 1998; Desbruyères et al., 2000). It is rectangular in shape, with 11 km wide rift valley (Langmuir et al, 1997). In the central part of this valley lies a 13 km long, 7km wide, and 430 m high composite volcano. This volcano is divided in two parts separated by a N-S valley. The western part is an elongated narrow ridge, while the eastern part is semi-circular in shape with three volcanic cones on its summit. The central depression in the middle of those cones forms a 300 m diameter and 6 m deep circular lava lake, and is situated between 1730 and 1736 m depth. The currents in the LS are mostly controlled by the topography of the sites (Khripounoff et al., 2001; Khripounoff et al., 2008) and is directed SE with an average of 2.8 cm s^{-1}. Particle fluxes were measured near Sintra vent site in 1994 (25 days) and 2001 (360 days), reaching values of 264 mg $m^{-2}d^{-1}$ and 131mg $m^{-2}d^{-1}$, respectively. The temperature of the sea water in LS oscillates between 4.3 and 5.1°C (Khripounoff et al., 2001).

The hydrothermal activity featured at LS consists of black smokers (up to 324°C), active flanges rich in barite, iron and zinc sulphides (170°C) and low temperature diffuse zones with deposition of amorphous silica (Fouquet et al, 1994; Langmuir et al., 1997; Sarradin et al., 1999; Charlou et al., 2000). Over 20 active sulphide edifices surround the LS lava lake, with the most active ones situated on the western side (Fouquet et al, 1994). These edifices can reach several meters in height and exhibit complex 3D relief with several emission zones. The fluids are depleted in sulphides and metals but are enriched in gas, with important amounts of CH_4. The pH varies between 3.8 and 4.5. The vent sites grow mostly through a hydrothermally cemented volcanic breccia, referred to as "slab", while the surrounding seafloor is sedimented and cut by a dense network of fissures and scarps (Ondréas et al., 1997, 2009) from which vent fluids originate (Langmuir et al., 1997; Ondréas et al., 1997). A subsurface circulation of hydrothermal fluids occurs underneath the slabs, allowing a subsurface microbial production.

Based on analyses of the trace element (Cs, Rb, Sr, Br and Li) and chlorine concentrations (which is the main anion in the fluids and therefore controls cation abundance) the whole LS field appears to be fed on a unique fluid source, strongly affected by phase separation processes (Leleu, 2017). Due to the depth and the temperature of the system, Lucky Strike has metal depleted - gas enriched fluids except for H_2S and He_3 (Wilson et al., 1996; Charlou et al., 2000). The north-western and north-eastern vents (White Castle, Helene, Bairro Alto, Elisabeth, Y3, Statue of Liberty and Sintra) differ from those in the south-east (i.e. Isabel, Eiffel Tower and Montsegur,) (Langmuir et al., 1997; Von Damm et al., 1998; Charlou et al., 2000; Humphris et al., 2002). The south-eastern vents show the lowest chlorine concentrations (~420 mM) and is mainly controlled by vapor-dominated phases (Von Damm et al., 1998; Charlou et al., 2000; Leleu, 2017).

Species composition and diversity

Hydrothermal vent edifices are inhabited by faunal assemblages that form mosaics linked with the underlying hydrothermal conditions (Sarrazin et al., 1997, 1999; Cuvelier et al., 2009, 2011a, 2011b). The sulphide structures of LS are dominated visually by *Bathymodiolus azoricus* mytilids (Van Dover, 1995; Colaço et al., 1998; Desbruyères et al., 2001), alvinocaridid shrimp and more marginally by small gastropod assemblages (Sarrazin et al., 2015, unpublished data for gastropods). Mussels are considered as engineering species as they offer secondary surfaces for other invertebrates to colonize. *Bathymodiolus azoricus* mussels harbour both thiotrophic and methanotrophic symbionts within their gills (Duperron et al., 2006).

The best known hydrothermal site at LS is the Eiffel Tower edifice where a total of 79 vent taxa have been sampled over the years (Husson et al., 2017). Studies of macro-and meio-faunal community structure have distinguished three faunal assemblages associated with three different types of microhabitats: (1) cold microhabitats characterized by low temperatures, high concentrations of dissolved Cu, high pH and low dissolved sulphide concentrations dominated by small mussels; (2) warm microhabitats characterized by higher temperatures, low pH and high total iron and sulphide concentrations dominated by the alvinocarid shrimp *Mirocaris fortunata*; and (3) microhabitats characterized by intermediate abiotic conditions and dominated by large mussels (Sarrazin et al., 2015). The warm microhabitats had lower macro-and meio-faunal densities, and lower species richness and diversity than the cold and intermediate microhabitats. Six macrofaunal species (*Branchipolynoe seepensis, Amathys lutzi, Bathymodiolus azoricus, Lepetodrilus fucensis, Protolira valvatoides, Chorocaris chacei*) and three meiofaunal taxa (*Paracanthonchus* sp., *Cephalochaetosoma* sp., *Microlaimus* sp.) were identified as being significant indicator species/taxa of particular microhabitats. Moreover, mussel assemblages exhibit a spatial segregation by size, with the larger individuals living in the warmer areas (Comtet and Desbruyères, 1998; Cuvelier et al., 2009, 2011; Sarrazin et al., 2015; Husson et al., 2017). Shrimp assemblages are present in fissures and around black smoker chimneys and are indicative of nearby hydrothermal fluid emissions (Cuvelier et al., 2009). Contrary to what was expected, at Eiffel tower, the highest beta diversity was not associated with a particular microhabitat type on the edifice, but rather with particular locations. A link with hydrodynamic conditions may be present, as seen on other hydrothermal edifice. Recent unpublished results from other structures in the vent field (Sarrazin et al., in preparation) show that faunal samples from the same edifice at LS share more similarities in species composition and diversity within a single edifice than between edifices (Sarrazin et al., unpublished data). However, although they are gregarious (Matabos et al., 2015), *Mirocaris fortunata* shrimp never attain the swarms observed for *Rimicaris exoculata* on the southern vent fields (TAG, Snake Pit). Contrary to what was expected, the highest beta diversity was not associated with a particular microhabitat type on the edifice, but rather with particular locations. A link with hydrodynamic conditions may be present, as seen on other hydrothermal edifice. Recent unpublished results from other structures in the vent field (Sarrazin et al., in preparation) show that faunal samples from the same edifice at LS share more similarities in species composition and diversity within a single edifice than between edifices (Sarrazin et al., unpublished data). Fifteen taxa were shared between the 4 edifices studied (Eiffel Tower 2011, 2013, Montsegur, Y3, Cypress), seventeen taxa were shared between two or more edifices, and four were observed on only one edifice: Hesionidae was found only on Cypress, Thalycrocuma sarradini was found only on Montsegur and Sipuncula and Desmosponge were found only on Eiffel Tower in 2011 (Sarrazin et al., unpublished data). Although the diversity is not yet well described at LS, some patterns have been observed. Therefore, Montsegur shows the highest richness and evenness values, followed by Eiffel Tower samples from 2013 and Cypress. Y3 and Eiffel Tower 2011 samples display the lower expected richness (Sarrazin et al., unpublished data). The *Bathymodiolus azoricus* assemblages at LS can be considered a climax-community as its dominance is undisputed over several decades (Cuvelier et al., 2014).

Like all the active edifices at hydrothermal vents, the sulphide deposits at LS are colonized by a diversity of Archaea and Bacteria that utilize the chemical energy available in the hydrothermal fluid, including reduced sulphides, methane and hydrogen. Archeal communities are composed of thermophilic lineages that belong to different families (e.g. Desulfurococcaceae, Thermococcaceae, Thermofilaceae, the mixotrophic Archaeoglobaceae). Bacterial communities are dominated by Epsilon- and Gamma-proteobacteria and Thiotrichales that play a significant role in carbon and sulphur cycling. At LS bacterial diversity was shown to be higher than archeal diversity (Flores et al., 2011). While previous studies have reported the absence of known methanogens at the LS vent field, probably in relation to the H2-depleted fluid characteristics of LS (Flores et al., 2011), more recent analyses have shown their presence in active chimneys, as well as a strong coupling between geological, geochemical and microbiological processes (Flores et al., 2011). From this knowledge, it is expected that there will be a succession and adaptation of microbial communities to changes in environmental conditions, and consequently on the course of the growth and maturation of vent chimneys. Microbial mats covering *B. azoricus* have low archeal diversity restricted to the *Thaumarchaeota* group, balanced by a high bacterial diversity composed of *Proteobacteria* and *Bacteroidetes* (Crépeau et al., 2010). The Proteobacteria include genera within the epsilon- and gamma- proteobacteria that are involved in sulphur and methane oxidation. It was suggested that symbiont transmission to the mussel *B. azoricus* might be facilitated by these bacterial mats (Crépeau et al., 2010). As for chimney habitats, there are no data available on the early colonisation and succession of the microbial community associated with *B. azoricus* mussel assemblages. Finally, microbial communities in the surrounding hydrothermal sediments are enriched in anaerobic methanogens and *Proteobacteria* similar to vent microbial communities rather than pelagic microbial taxa (Cerqueira et al., 2017).

Main life-history and other characteristics

More than one hundred metazoan species have been described at the LS active vent sites, but only a few species have been well studied in terms of life history. Knowledge on the reproductive biology of the LS vent organisms is still very limited. Studies on the reproductive biology of mussels in the vent fields south of the Azores indicate that *B. azoricus* spawns annually in January releasing eggs between 70-80 µm in diameter (Colaço et al., 2006; Dixon et al., 2006). Gametogenesis in *Bathymodiolus* is typical of mytilids (Tyler and Young, 1999). Larvae of two size groups, approximately 300 µm and 500 µm in length were found among mussel clumps. Genetic connectivity of mussel populations inside the LS vent field is a work in progress (Ribeiro et al., subm.). Previous genetic studies on a segment of the Mid Atlantic Ridge between 37°50'N to 14°N have revealed the presence of two species of *B. azoricus* in the north and *B. puteoserpentis* in the south, with the potential to hybridize at the Broken Spur hydrothermal vent area (29°12N, 43°11W). This indicates extensive connectivity for the species over scales of thousands of kilometres (Breusing et al., 2016; O'Mullan et al., 2001). However, physical models of larval drift do not support this scale of connectivity, and it is expected that additional intermediate stepping stones habitats occur to maintain this level of connectivity (Breusing et al., 2016). Studies of the vent shrimp *Mirocaris fortunata* from LS suggest continuous reproduction with egg sizes ranging between 320-500 µm which are likely to lead to planktotrophic larvae (Ramirez-Llodra et al., 2000).

Structural diversity and complexity (habitat forming and trophic levels)

Faunal assemblages at hydrothermal vents form repeating mosaics relating to the changing physico-chemical conditions (Sarrazin et al., 1997, 1999; Cuvelier et al., 2009, 2011a, 2011b). Large sessile organisms, such as mussels, tend to provide a secondary surface for other organisms to occupy and could enhance faunal settlement, increased biodiversity and greater survival of the associated fauna (Menge and Sutherland, 1976; Van Dover and Trask, 2000).

The hydrothermal vent mussel, *Bathymodiolus azoricus*, obtains its nutrition from a variety of sources including a dual endosymbiosis with both sulphur-oxidising and methylotrophic bacteria (Fiala Medioni et al., 2002), from particulate feeding and use of dissolved organic carbon (Colaço et al., 2009; Riou et al., 2010). The contribution of methanotrophic versus autotrophic sources varies according to the concentrations of the reduced compounds (e.g. CH4, H2S) (Halary et al., 2008).

At the community level, detritivores and bacterivorous specialists are the dominant feeding behaviours, while predator abundances are low. Most of the few predators appear to be generalist feeders rather than specialists (Portail et al., 2017).

Vulnerability and fragility / recovery capacity

The close relationship of hydrothermal vent activity with spreading centres, is why they are known as ephemeral or transient habitats. Despite this, decadal-scale constancy is observed at Lucky Strike (Cuvelier et al., 2011). Hence, only partial knowledge of the natural succession patterns occurring at these vents is available, and no knowledge is available on nascent hydrothermal vent sites in the wider Mid-Atlantic region.

Mid-Oceanic Ridges (MOR) are underwater mountain ranges that are located on the boundaries between the tectonic plates and what differentiates one from another is their spreading rate, going from ultra-slow to fast-spreading ridges. The hydrothermal vents are situated on the ridges and due to tectonic movement they are prone to occasional perturbations. LS is situated along the slow-spreading Mid-Atlantic Ridge (MAR) and is estimated to be 45,000 years old (Humphris et al., 2002). The hydrothermal vents are characterised by episodic activity (Lalou et al., 1993) and the current phase of activity at LS approximates to a period of several hundreds of years (Humphris et al., 2002), which seems to be much longer compared with active vents on fast-spreading ridges.

Even though overall decadal stability in faunal coverage is observed, significant changes occur on shorter time-scales of 1 to 4 years (Cuvelier et al., 2011). The rate of change over periods of 1- to 3-year periods at the Eiffel Tower edifice in the LS vent field is about 15% slower than that observed on sulphide edifices from faster-spreading ridges in the North-East Pacific (Cuvelier et al., 2011).

Main ecosystem services

Hydrothermal vents provide different type of ecosystem services relating to the different functions that occur in hydrothermal ecosystems. Supporting services relate to the *in situ* chemosynthetic microbial primary production and its effects on subsequent secondary production in the deep sea; regulating services (i.e. reducing geological and biological methane release, promoting carbonate precipitation and providing habitat) have indirect benefits to human populations. Hydrothermal vents also represent important sources of energy (heat) and minerals (massive polymetallic sulphides). The unique organisms that occur at hydrothermal vents also harbour molecules of biotechnological and medical interest. In addition, they provide cultural services for aesthetical, educational and scientific purposes (Thurber et al., 2014).

3.3.2. *Activities, pressures and impacts*

Since the 1993, when the LS vent field was discovered, only scientific cruises have taken place, and no commercial activity is currently taking place. LS is considered one of the largest vent fields in the North Atlantic. It hosts a deep-sea scientific observatory which is maintained and updated with new technologies on a yearly base. There are no plans for deep-sea mining in the Lucky Strike, but since more discussion is needed on the matter of restoration of hydrothermal vents, this hypothetical exercise is considering deep sea mining as a future potential activity in the LS.

3.3.3. *Management landscape*

This hydrothermal field is about 180 nautical miles southeast of Faial at a depth of 1700 meters within the Portuguese/Azores EEZ with an area of 192 km^2 created in 2002 (OSPAR; NATURA2000) that increased to 301 km^2 in 2012.The LS hydrothermal vent field falls within the designated Azores Marine Park and therefore is theoretically protected, including the segment and transform fault.

3.3.4. *Restoration "statement"*

Restoring hydrothermal vent communities impacted by deep-sea mining using assisted regeneration with physical interventions, namely the construction of appropriately shaped artificial structures mimicking hydrothermal chimneys which might be lost owing to deep-sea mining.

3.3.5. *Existing restoration actions and potential future techniques*

There are no direct studies which have reported the environmental impacts that might be caused by mining of polymetallic sulphides on mid-ocean ridges. To date only one mining operation has successfully extracted minerals from the hydrothermal vents, off the coast of Okinawa, Japan (Japan Times, 2017). In addition, Nautilus Minerals set up a recolonisation experiment using artificial chimney structures off Papua New Guinea about 6 years ago, but due to lack of funding the site has not been revisited since it was set up (Dr Sam Smith, pers. comm.).

Natural marine eruptions occurring at deep-sea hydrothermal vents may mimic some impacts associated with mining disturbance, but these have never been observed on slower-spreading ridges such as the MAR. No restoration actions have been tried at LS. Cuvelier et al. (subm.) described a range of possible mitigation and restoration actions for hydrothermal vents, amongst other deep-sea ecosystems, but overall predictability for the vast majority of the proposed actions is low due to the lack of knowledge.

Mining of sulphide deposits at LS implies toppling edifices and thus eliminating suitable habitats and associated fauna. Actions to help restore the sulphide substrata include artificially recreating hydrothermal vents (e.g. by drilling) or aiding precipitation and subsequent consolidation through the use of 3D tower structures (Cuvelier et al., subm.). Providing artificial substrata, may help faunal colonisation through natural spontaneous regeneration processes. Besides this, the possibility of transplanting fauna, larval showering, seeding and adding in organic material have been suggested in order to accelerate rates of recovery of biodiversity and functioning (Cuvelier et al., subm.). Most proposed actions still require further evidence to confirm their efficacy. None of them have been tested in a mining context.

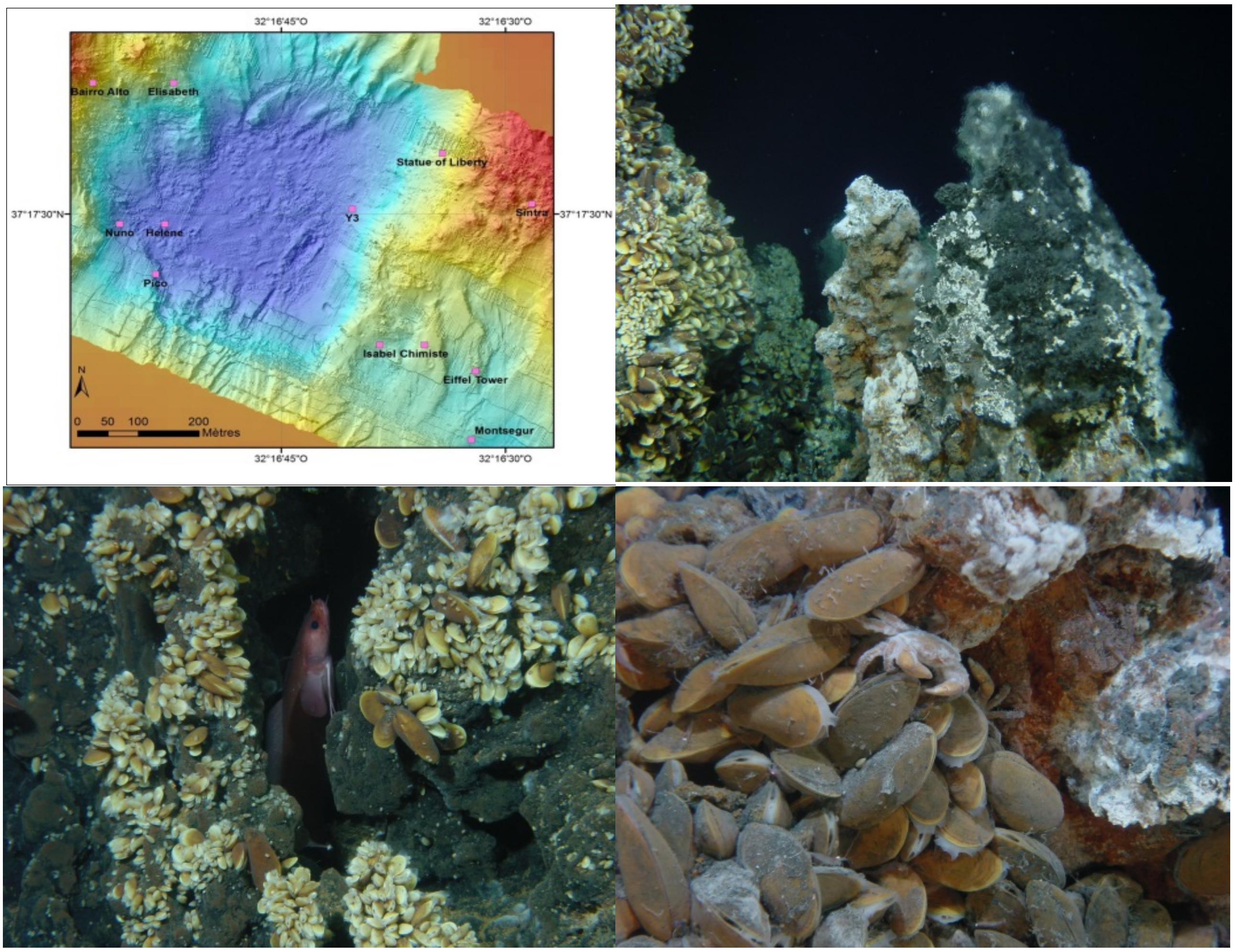

Figure 4. Hydrothermal vent communities in the Lucky Strike field (Mid-Atlantic Ridge, Atlantic Ocean). (top left) Map of the field showing the different vent edifices; (top right) vent chimney; (bottom) typical vent community dominated by the mussel *Bathymodiolus azoricus*. Photo credits: © MISSAO SEHAMA, 2002 (funded by FCT, PDCTM 1999/MAR/15281).

3.4. Restoration Project: Resilience of the Palinuro Seamount ecosystem (Mediterranean Sea)

3.4.1. *Ecosystem description*

Environmental setting of the ecosystem

The Palinuro volcanic complex is located at the north-eastern end of the chain of Aeolian volcanoes in the Tyrrhenian Sea. The first exploration of the seamount started in 1970s, but recently it has received more attention in the geomorphological context (Milano et al., 2012; Petersen et al., 2014). It comprises several coalesced volcanic centres that extend for about 55 km from east to west (Monecke et al., 2009; Passaro et al., 2010), likely along a major lithospheric fault system that extends seaward off the northern limit of Calabria (Rosenbaum and Lister, 2004). The maximum base width of the Palinuro volcanic complex is approximately 25 km (Monecke et al., 2009; Passaro et al., 2010) and is located at ca. 3500m-depth. Seafloor sulphides were first discovered at the Palinuro volcanic complex on the westernmost summit of the western sector at ca 600-650m-depth (Minniti and Bonavia, 1984). Previous investigations revealed that the seafloor of the top of the Palinuro seamount is largely covered by unconsolidated fine-grained sediments (Petersen et al., 2014). These sediments host meio- and macro-faunal assemblages. The small scale habitat heterogeneity along with the quality and quantity of organic matter influence the spatial distribution of benthic fauna (Gambi et al., 2014, 2017). The temperature of the sediments on the summit of the Palinuro seamount is ca. 12°C (Yasuhara and Danovaro 2016). The water column characteristics above the top of Palinuro seamount have not been investigated yet.

Species composition and diversity

The benthic fauna associated to the Palinuro seamount has been investigated to only a limited degree to date (Pusceddu et al., 2009; Danovaro et al., 2009). Meiofauna (20-500 µm) and macrofauna (>0.5 mm), the main biological components of the soft bottom communities on the top of the Palinuro seamount, have been studied in the top 10 cm of the sediment at ca. 650 m on the summit of the Palinuro seamount. Meiofaunal assemblages are dominated by nematodes, followed by copepods and tardigrades. Other rare taxa such as amphipods, isopods, kinorhynchs, ostracods, polychaetes, and tanaidaceans represent <1% of the community. More than 170 species of nematodes have been found on Palinuro seamount. Macrofaunal assemblages are characterized by the presence of amphipods, decapods, echinoderms, nemerteans, oligochaetes and polychaetes. A major knowledge gap for this ecosystem concerns native microbiota and rare/endemic species.

Main life-history and other characteristics

The knowledge on the longevity and reproductive aspects of the different species/taxa of meio- and macrofauna is scant due to the limitations of investigations conducted in deep-sea ecosystems. Meiofauna have faster growth rates than macrofauna (Giere, 2009; van der Grient et al., 2015), and their life cycles are generally limited from a few months up to a few years. The connectivity of soft bottom communities has not been investigated yet in the Palinuro seamount both for meio- and macro-fauna. Ecosystem functioning has been investigated as i) benthic prokaryotic (heterotrophic) production, ii) meio and macro-faunal biomass and iii) the rates at which organic matter is remineralised. These are key indicators of deep-sea ecosystem functioning because they regulate i) the ecosystem's ability to transfer energy to higher trophic levels, through heterotrophic production, ii) the conversion of organic detritus into benthic biomass and iii) the recycling of organic material, which reflects the ability of ecosystems to sustain their functions over time (Danovaro et al., 2008).

Structural complexity (habitat forming)

The concept of habitat forming species is not applicable for soft bottom communities. However, previous investigations carried out in other deep-sea habitats have revealed that the presence of habitat-forming species (i.e. cold-water corals and gold corals) increases meiofaunal biodiversity in adjacent sediments (Bongiorni et al., 2010; Cerrano et al., 2010). Unfortunately, there is only scarce information on the presence of habitat forming species on the top of the Palinuro seamount (Friewald et al., 2011). Living vestimentiferan tube worm colonies have been discovered as well as temperatures of up to 60°C in sediment cores recovered from the western sector confirming active hydrothermal venting (Petersen et al., 2008; Monecke et al., 2009), but probably not on the restoration site. Nematode trophic structure shows the presence of four trophic groups (selective and non-selective deposit feeders, epistrate feeders and few predators) at all the sites which have been investigated. No information is available on the overall trophic structure of macrofaunal assemblages, nor on connectivity and migration patterns.

Vulnerability and fragility / recovery capacity

Soft-bottom communities are generally influenced by sediment/substrate removal and re-deposition (i.e. from bottom trawling activities, mining tests; Miljutin et al., 2011; Pusceddu et al., 2014; Vanreusel et al., 2016; Jones et al., 2017; Van Dover et al., 2017). The benthic response in terms of recovery capacity is different when different groups (meiofauna, macrofauna and megafauna) are considered according to the different turnover rates, life cycles and reproduction (Gollner et al., 2017) but also depending on the type of mechanical impacts (Jones et al., 2017). The ecosystem resilience of soft bottom communities has been estimated using the percentage of the ratio impacted vs reference sites (Gollner et al., 2017) for all the investigated attributes of the Palinuro seamount ecosystem.

Main ecosystem services

Soft bottom communities provide important provisioning services such as fisheries resources and new pharmaceutical compounds, regulation services such as carbon storage and nutrient remineralization, and cultural services for educational and scientific purposes (Thurber et al., 2014). In this particular case study, we consider only aspects of nutrient remineralization because this is a proxy indicated in common to the other case studies (Thurber et al., 2014).

3.4.2. *Activities, pressures and impacts*

In August 2007 the British Geological Survey conducted a scientific expedition in order to inspect the subseafloor barite and sulfide occurrence of the Palinuro volcanic complex (Petersen et al., 2014). Eleven successful holes were drilled in the small depression located at a water depth of approximately 610 to 650 m on the top of the Palinuro seamount (Petersen et al., 2014). In general, rock-drilling activities provoke a substrate removal/abrasion with potential consequences for meiofaunal and macrofaunal abundance, diversity and community composition. Effects of these activities could be relevant also for the ecosystem functioning (i.e., biomass production, organic C degradation rates, prokaryotic C production). Soft bottom communities could be also impacted by trawling activities, but the information of potential fishing in the investigated area is based on the presence of lost fishing gear found on the summit of Palinuro seamount (Freiwald et al., 2011).

3.4.3. *Management landscape*

The Palinuro seamount is located in the Tyrrhenian Sea, in the Italian territorial waters of the Mediterranean and it is not subject to a specific management plan.

3.4.4. *Restoration "statement"*

Restring the soft bottom communities of the Palinuro seamount impacted by experimental rock-drilling activities using spontaneous natural regeneration.

3.4.5. *Existing restoration actions and potential future techniques*

No restoration activities have been carried out yet for deep-sea soft bottom communities. The case study of the Palinuro seamount offers the first attempt to test natural regeneration capacity of the soft bottom communities using the After – Multi Controls – Multi Impacts sampling design. The site was chosen on the same seamount because soft bottom communities tend to differ among seamounts, different topographic structures within the same seamount, deep-sea habitats and depths (Bianchelli et al., 2010; Danovaro et al., 2010; Vanreusel et al., 2010; Zeppilli et al., 2013, 2016).

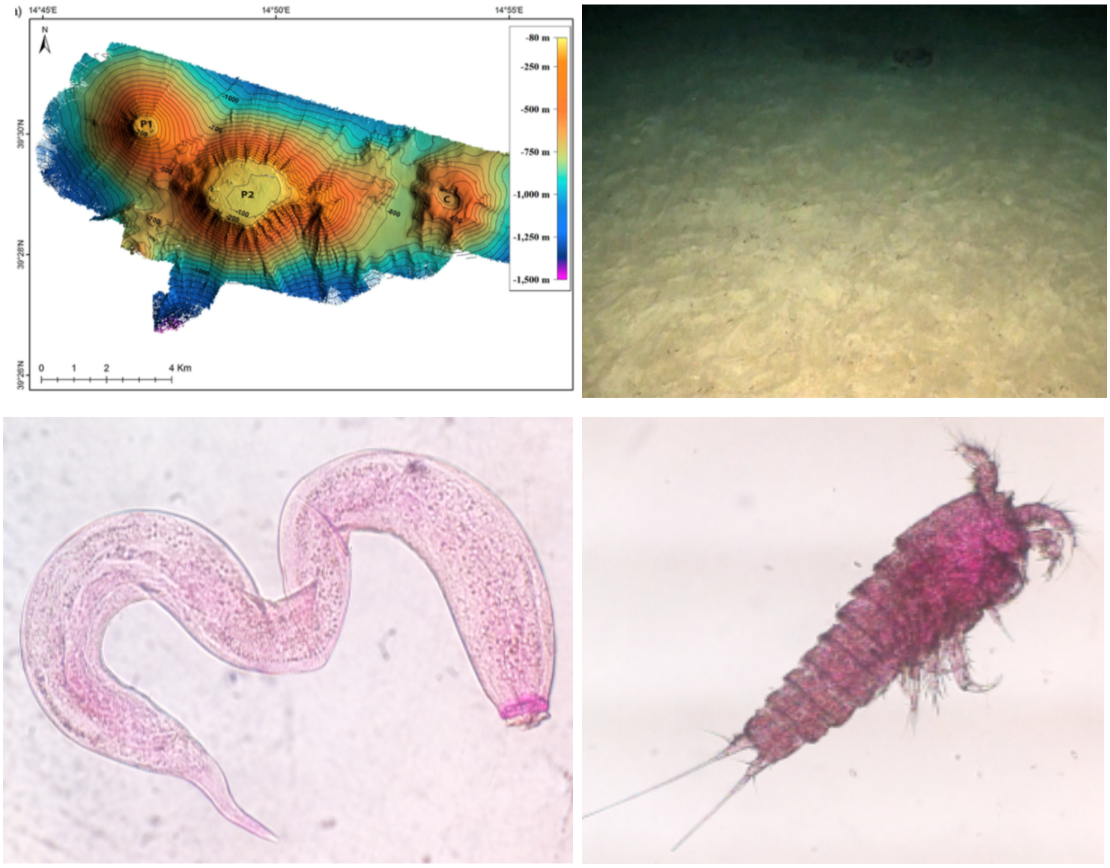

Figure 5. Soft bottom communities at Palinuro seamount, Mediterranean Sea. (top left) Map of the Palinuro seamount; (top right) seabed image of soft bottoms in the seamount; dominant infauna (bottom left) nematodes and (bottom right) harpacticoid copepods. Map credits: Innangi et al (2016), (top left) C. Smith, HCMR (bottom) Cristina Gambi, UNIVPM.

4. Society for Ecological Restoration Key Concepts underpinning best ecological restoration practice

The Society of Ecological Restoration has recently updated the international standards for the practice of ecological restoration, including six key concepts (McDonald et al., 2016). These key concepts aim to provide a framework to guide activities and measure outcomes of ecological restoration practices. However, KC were built mainly upon examples in terrestrial and coastal ecosystems and do not considered the particular characteristics of deep-sea ecosystems. In this section, we built upon Van Dover et al. (2014) contribution to evaluate how the six Key Concepts (KC) defined by the international Society for Ecological Restoration (SER) and described in section 2 of this report can be transferred to deep-sea ecosystem.

4.1. KC 1. Ecological restoration practice is based on an appropriate local native reference ecosystem, taking environmental change into account

According to the SER, selecting and describing a reference ecosystem is the first step when considering a restoration activity (McDonald et al., 2016). The reference ecosystem is a conceptual guide towards a desirable local native ecosystem (Aronson et al., 1993). It helps to design a pathway towards the recovery of an ecosystem, which can be achieved through a "family of restorative activities" that help reinstate missing ecosystem attributes. These attributes collectively provide desirable ecosystem functions, goods and services (Aronson et al., 2017), helping conserving biodiversity and human well-being.

When suitable pristine sites are available, reference ecosystems may be built upon natural, undisturbed, analogue sites; i.e. sites that are similar to the ecosystem to be restored, but which have not gone through degradation. Otherwise, a reference ecosystem should be built on the best available knowledge of the ecosystem to be restored including species composition, structural diversity and ecosystem functionality attributes, as well as the environmental settings in which the ecosystem is self-sustaining (see KC 2, section 4.2). According to the SER, a reference ecosystem should account for natural spatial and temporal variability of particular ecosystem's attributes in time (Aronson et al., 1995; Clewell and Aronson, 2013); not only for building a robust reference model but also for understanding the trajectory towards full recovery (see KC 4, section 4.4). This information should later feed into decision-making relevant to the spatial extent of the restoration site as well as understanding succession phases, seasonality and resilience (Yates and Hobbs, 1997).

In order to account for the spatial and temporal variability, a reference ecosystem needs to consider all available past and present information on the processes and drivers shaping the ecosystem (Balaguer et al., 2014) from different sources of ecological knowledge (see KC 5, section 4.5), such as analogue sites, historical records, ecological time-series, expert knowledge, and local ecological knowledge (Josefsson, 2009; Balaguer et al., 2014). This knowledge is useful to understand site particularities, different stages on the path to ecosystem recovery and how adaptive management measures can be applied.

In addition, a 'control site' should be identified for locations where the same level of degradation has occurred as the site where restoration will take place. A 'control site' is kept without any restorative activities and serves to evaluate the rates of spontaneous natural regeneration and as a comparison to how successful restoration activities were at the restored location (Falk et al., 2006; McDonald et al., 2016). If a suitable pristine analogue site is available, then it can also be used to monitor the analogue site and the restoration site concurrently; as a form of dynamic reference ecosystem (Hiers et al., 2012). This might be crucial owing to the many uncertainties on the trajectory towards full recovery of the restoration site in the context of climate change, as well as the resilience of existing ecosystems. In addition, the continuous monitoring of one site can fill many of the knowledge gaps on variations in ecosystems with time which currently is a major constraint on planning deep-sea restoration.

4.1.1. *Challenges posed to the description of a reference ecosystem for the deep sea*

Deep-sea environment includes a variety of different ecosystems, such as abyssal plains, seamounts, hydrothermal vents, trenches, canyons, cold seeps, cold-water coral reefs and gardens, sponge grounds (Ramirez-Llodra et al., 2010; Levin and Sibuet, 2012). Each of these ecosystems differ, making the deep sea not only the largest environment on Earth, but probably the home to the highest biodiversity. Describing a reference ecosystem for deep-sea ecosystems has to be site specific and when possible based on local native ecosystem.

This can, however, be extremely challenging because of the major knowledge gaps many deep-sea ecosystems face. Scientific exploration of the deep sea started in the mid-19th century, but it is only in mid-20th century that new methods and technologies have allowed significant progress in describing these remote environments (Ramirez-Llodra et al., 2010 and references within; Danovaro et al., 2014). As a result, only a relatively small part of these ecosystems have been describe (e.g. Kvile et al., 2014), making the deep sea the least studied environment on Earth (Ramirez-Llodra et al., 2010), and from where ecosystem attributes will likely be the most difficult to describe (see KC 2, section 4.2).

The vastness and remoteness of the deep sea means that it still nurtures some largely pristine ecosystems, except to the pervasive spread of microplastics and climate change, and therefore natural, undisturbed, analogue sites may be available. In contrary to some deep-sea areas, analogue sites are not readily available for most coastal water and terrestrial ecosystems, since these have been heavily impacted by human activities. Even though some "quasi-pristine" areas might be available on land (e.g. boreal forests in Fennoscandia, tropical rainforests in Congo basin, coral reefs in Northern Line islands), they may not be truly pristine as they experienced have some form of direct human impact, either by indigenous people in the past or recent sporadic events, such as military tests (Willis et al., 2004; Josefsson, 2009; Sandin et al., 2008). Therefore, some deep-sea restoration projects may have the unique advantage of using baseline data from analogue sites. However, some of those sites may not be known highlighting, once again, major knowledge gaps hampering the description of a reference ecosystem and the need for more scientific exploration that can yield baseline knowledge.

Although the deep sea still shelters some ecosystems that might be considered pristine, other have already been impacted by direct human activities (Ramirez-Llodra et al., 2011) or by climate change and microplastics (Woodall et al., 2014; Courtene-Jones et al., 2017). In these cases, where analogue sites are not available due to degradation, reference ecosystems should be built upon all available knowledge, including historical data. There might be cases in the deep sea where degradation happened before any baseline or historical data was collected, therefore completely hampering a proper description of the reference ecosystem.

Finally, understanding natural spatial and temporal variability in most deep-sea ecosystems can be very challenging, due to the lack of long data time-series for most ecosystem attributes. As stated above, this information is, however, crucial for successful ecological restoration and for understanding the trajectory towards full recovery. Although not common for most deep-sea ecosystem, there are some examples of available long time-series of data (Larkin et al., 2010); such as for the Porcupine Abyssal Plain (e.g. Billett et al., 2001; Bailey et al., 2009), deep Canadian waters of the northwest Atlantic (Devine et al., 2006), Station M abyssal site in the northeast Pacific (Smith and Druffel, 1998; Smith et al., 2013), Lucky Strike hydrothermal vent systems (e.g. Legrand et al., 2016). They can provide background on environmental conditions and natural variability or detect trends. The development of autonomous robotic systems is leading to a radical change in how deep-sea ecosystems can be monitored in the future, reducing costs and increasing data capture rates (see KC 5, section 4.5). Combining Autonomous Underwater Vehicle (AUV) surveys with targeted sampling and *in situ* experiments by Remotely

Operated Vehicles (ROVs) can reveal associations between species, the influence of topographical features and the 3-D structure, nature and spatial mosaic of many biologically mediated habitats.

Where possible, multiple analogue sites may be used to provide greater information on the natural spatial and temporal variability of ecosystems as well as different stages that an ecosystem may pass through on the trajectory towards full recovery (Aronson et al., 2017; Suganuma and Durigan, 2015). This approach may be problematic in the deep sea, as there should be substantial amount of knowledge of each analogue site and costs of obtaining the original baseline information and the subsequent monitoring need to be considered. In addition, using a 'dynamic reference ecosystem' provides options to change actions in a restoration project and may be particularly important in the deep sea because of the very slow dynamics of these ecosystems and hence possibly the very long time frames over which restoration projects will have to take place. The slower pace of life in most deep-sea ecosystems is one of the key differences between land and deep-sea restoration projects (Van Dover et al., 2014).

4.1.2. *Local native reference ecosystems in four deep-sea case studies*

As explained above, describing local native reference ecosystems in deep-sea may be extremely challenging and encompass additional sources of uncertainties. Here, we used four different but complementary deep-sea case studies (see section 3) to evaluate the likely availability of pre-disturbance sites that can inform the reference ecosystem and control sites to explore the trajectory towards full recovery (Table 2). We have also evaluated the challenges posed to the description of an appropriate local native reference ecosystem for all deep-sea case studies (Table 3-

Table 6).

The description of the reference ecosystems followed the White and Walker (1997) framework based on four types of data sources: 1) *here and now*, when the reference ecosystem is described with information for the current state of the target ecosystem; 2) *there and now*, when it's described with information for the current state of a second location that is not significantly different from the target ecosystem; 3) *here and then*, when the reference ecosystem is described with only historical information of the target ecosystem; or 4) *there and then*, when it's described with only historical information of a second location that is not significantly different from the target ecosystem.

This framework is also useful to produce a general evaluation of the level of confidence associated with the description of the reference ecosystems. Reference ecosystems based on "*here and now*" are assumed to have high degree of confidence, "*here and then*" and "*there and now*" medium degree of confidence, and "*there and then*" low degree confidence. More than one option might be used to describe a reference ecosystem.

In general, reference ecosystems can be described for all deep-sea case studies (Table 2), however based on different types of data sources and therefore with different degrees of confidence. For the case studies CCZ and HV, pre-disturbance sites are available since no exploitation has started yet. While for the CCZ analogue sites are available and can be used to monitor progress towards full recovery, for HV analogue sites are not available since every hydrothermal vent field is considered to be unique and the disturbance from mining will likely impact the whole vent field (Van Dover et al., 2018). For CWC and SB case studies, no pre-disturbance sites may be available since these ecosystems have been previously degraded by bottom fishing and rock drilling, respectively. However, while SB analogue sites may be available outside the much localised impacted area in Palinuro seamount, analogue sites may not be available for CWC since fishing may have impacted most coral gardens and there is currently limited knowledge on existence of pristine similar adjacent ecosystems.

The description of the reference ecosystems were based on different types of data sources resulting on different degrees of confidence (Table 3-

Table 6). Baseline data is available prior to disturbance for the CCZ and the HV case studies, resulting in important information *here and now,* which is largely missing for the CWC case study. In this case study, most of the information is originated *here and then* from historical records (e.g. Braga-Henriques et al., 2013; Braga-Henriques, 2015). *Here and then* information is also be available for the HV case study since its discovery 25 years ago, including changes that have occurred over time (Escartin et al., 2015). Information from locations that are not significantly different from the target ecosystem may also be available for some case studies with the exception of the HV where *there* data sources are inexistent since every vent field is unique. In the CWC case study, *there* data could be available for specific information such as cold-water coral's life history (e.g. growth rates, longevity), but probably not useful as analogue sites as there is currently limited knowledge on similar adjacent ecosystems.

However, there are significant knowledge gaps that may hamper the proper description of the reference ecosystems for all the case studies, although in different forms in each case. All case studies face severe lack of knowledge on biodiversity, ecology and ecosystem functioning, including species ranges and connectivity. The CCZ area, however, is so vast and the sampling intensity comparatively low, with unexpected heterogeneity at medium to small spatial scales (metres to tens of kilometres) that it will be a long time before adequate data sets are generated. In contrast, the HV cover much smaller areas, some of which have been well studied. The major knowledge gaps relate to natural temporal variability and the connectivity of different species along apparently rare discontinuous habitats along a linear ridge system within each ocean basin. The greatest challenge, however, is that each vent field is unique in terms of the balance of species.

Although dealing with different knowledge gaps and peculiarities, each case study was able to identify information needed to describe the reference ecosystem. For undisturbed areas such as the CCZ emphasis should be given to keep pristine analogue sites preserved for future use as reference ecosystems (where applicable) to monitor progress towards full recovery and for filling in the existing knowledge gaps. For disturbed areas as the CWC and SB, emphasis should be given to remove human impacts in the control site so they can be used to monitor restoration progress. Additionally, in the CWC case study freezing the fishing footprint could be an appropriated measure to increase the chance of discovering hypothetically pristine coral gardens that may serve as analogue sites and that are not known yet. For the HV no analogue or control sites may be available to monitor progress towards full recovery or to monitor natural regeneration processes.

Table 2. Can a reference ecosystem be described for each deep-sea restoration case study? Availability of pre-disturbance sites to inform the reference ecosystem and control sites to explore the trajectory towards full recovery (as described in KC4).

Case study	Pre-disturbance site	Analogue site	Reference ecosystem
Cold-water coral (CWC) garden; Condor seamount	N	N	Y
Nodule rich abyssal plain; the Clarion Clipperton Zone (CCZ)	Y	Y	Y
Active hydrothermal vent (HV); Lucky Strike	Y	N	Y
Soft bottom (SB); Palinuro seamount	N	Y	Y

Table 3. Challenges posed to the description of an appropriate local native reference ecosystem for cold-water coral (CWC) gardens in Condor seamount.

Is an analogue site available?	Analogue site for coral gardens in Condor is not available. It is the best studied seamount in the Azorean EEZ, but has been impacted by bottom longline fishing since the 1980's and there is limited historical data that can compensate for missing or degraded attributes.
Challenges posed to the selection of the analogue site	Within the Azores EEZ there may be areas where pristine coral gardens with the same ecosystems attributes may still exist and that could be selected as analogue site. However, there are no records of such pristine places with the current available knowledge, having in mind that the major impact on coral gardens in the Azorean EEZ is bottom longline fishing. The impact is the greatest for morphologically complex coral species (large and old colonies that also provide habitat for associated fauna and fish). As there is limited historical knowledge on the distribution of these large species it is difficult to determine whether they were originally present in the ecosystem selected for restoration, and therefore if they should be present in the analogue site.
How feasible is it to describe the reference ecosystem?	There is high confidence on the coral species composition, but major knowledge gaps exist on reproductive cycles, the age/size of the first maturity, growth rates, maximum size, genetic diversity and connectivity within/among seamounts, recruitment and early life histories. The knowledge gaps can be minimized by using data from historical records in the North-eastern Atlantic, especially regarding colony size and age. We have a medium level confidence on the species composition of the associated fauna, and good confidence on the commercial fish communities and the trophic complexity. The major uncertainties are in the ecosystem functioning and recovery capacity of each component of the ecosystem. The environmental data needed to describe the abiotic setting of the reference ecosystem can be marked as of high confidence. For all components mentioned, the common uncertainty is spatial and temporal variability, in biological and ecological terms. High uncertainty is related to the management landscape that can support coral garden restoration in the long term. Another unknown related to spatial and temporal variability are changes that might occur because of climate change. Paleoenvironmental and paleoecological records might provide some insight into biological community changes due to past environmental variability. Therefore a reference ecosystem can be reasonably described for CWC gardens in Condor seamount.
Overall confidence	In summary, the reference ecosystem will have medium to low confidence since we will gather information mainly from 2 different categories: *here and then* and *there and then*.
Reference ecosystem	See section 3.1

Table 4. Challenges posed to the description of an appropriate local native reference ecosystem for nodule rich abyssal plains in the CCZ.

Is an analogue site available?	The CCZ is in the unusual position that the vast majority of the abyssal plain in nodule rich areas is not degraded by local anthropogenic disturbances. Therefore, analogue sites are available but no generic analogue site can be selected for the whole CCZ owing to considerable spatial and temporal variation in many of the key attributes of the abyssal nodule rich environment that may functionally form multiple ecosystems. However, even these remote areas are experiencing some effects from broad-scale climatic changes. Our understanding is hampered by low levels of baseline knowledge and the lack of comparisons of data over different spatial scales.
Challenges posed to the selection of the analogue site	Although potential analogue sites abound, selection of appropriate reference ecosystems requires knowledge of the biodiversity and ecology of the areas. Representativity of analogue sites is thought to decrease with increasing distance between them. The disturbance from mining is likely to extend over large areas, but its spatial and temporal extent is poorly known. As a result, we face a challenge in defining appropriate analogue sites that are both representative of disturbed areas (i.e. close together in space) but are isolated from disturbance (i.e. far from each other in space). Selection of analogue sites is likely to be based on their physical characteristics (for example acoustically-derived morphology, sediment hardness etc.). The spatial and temporal variation in baseline conditions is not generally known, complicating quantitative comparison. At the most fundamental level, the vast majority of species are new to science: unnamed, undescribed and of uncertain importance, function and vulnerability. This uncertainty is also common for many community metrics, which may form potential indicators, particularly those linked to biodiversity.
How feasible is to describe the reference ecosystem?	We have some reasonable descriptions of small areas of abyssal nodule-rich seafloor and therefore reference ecosystems can be described. These include a wide range of metrics spanning multiple characteristics of the ecosystem (physical, chemical, biological). We also have some indications of the variability in the physical and biological conditions on the seafloor, although these are likely under-represented. The ~6 million km^2 of the CCZ area of interest is very sparsely sampled and scale mismatches between investigations and the wider ecosystem may complicate interpretation.
Overall confidence	The confidence level will depend on the area and spatial scale of reference ecosystem, but probably at least three categories (*here and now*, *here and then*, and *there and now*) could be used leading to the overall medium to low confidence level.
Reference ecosystem	See section 3.2.

Table 5. Challenges posed to the description of an appropriate local native reference ecosystem for hydrothermal vent communities in the Lucky Strike.

Is an analogue site available?	In the case of the Lucky Strike HV field analogue sites are unlikely to be found owing to the high spatial variability between vent fields, which are characterized by distinct faunal compositions and different environmental conditions. HV has not been impacted by any major human activity besides scientific research and it has been studied since its discovery in 1993. Therefore, pre-disturbance sites exist to inform the description of the reference ecosystem.
Challenges posed to the selection of the analogue site	Analogue sites may not be available after deep-sea mining exploration starts however pre-disturbance sites exist to inform the description of the reference ecosystem. The Lucky Strike vent field is a well-studied vent field on the Mid-Atlantic ridge. Besides annual scientific sampling and experimentations, no other anthropogenic activity is impacting this site. Years of research have generated a relatively good knowledge pool on the Lucky Strike vent field, including physical and chemical conditions, species composition and diversity on various edifices and genetic connectivity of selected species. The major challenge is that there is no knowledge on species life-history traits, natural succession patterns on Lucky Strike or on any other hydrothermal site in the Mid-Atlantic region. Early faunal colonization and ecological succession processes are only known for highly unstable system like the fast-spreading East Pacific Rise (volcanically driven system) The knowledge from the East Pacific Rise cannot be transferred to an old, tectonically-driven system, like the slow-spreading Mid-Atlantic Ridge. There is very little knowledge of connectivity between different populations along a mid ocean ridge system
How feasible is to describe the reference (or model) ecosystem?	A reference ecosystem can be described based completely on pre-disturbance data (i.e. baseline data) collected at the site which may eventually be impacted. Descriptions of mega-and macro-fauna are generally good, but life history and reproductive cycles have been documented only for the most dominant species. A number of colonization experiments have taken place at the HV site, thus gathering some information on recruitment and settlement. Connectivity has been studied among the shallower Mid-Atlantic vent fields for key taxa. Meiofauna and microbial compositions have received more attention recently, which will be considered as of medium confidence. There is no knowledge on the times of ecological successions and the growth rates of organisms. Environmental settings (e.g. geology, fluid composition, temperature variations and flux) of the Lucky Strike vent field are described and have been more extensively studied over time and can be marked with high confidence. A higher degree of uncertainty is linked to the spatial variation occurring among the hydrothermal edifices situated across the vent field and the temporal dynamics of the community.
Overall confidence	Overall information from Lucky Strike fits within 2 categories with medium to high confidence: *here and now*, and *here and then*, with low confidence on past times considering the stability of the system since its discovery. The other categories including *there* do not apply due to the high spatial variability between vent fields, which are characterised by distinct faunal compositions
Reference ecosystem	See section 3.3.

Table 6. Challenges posed to the description of an appropriate local native reference ecosystem for soft bottom communities in Palinuro Seamount.

Is an analogue site available?	Potential multiple analogue sites are available which have not experienced the impact of rock drilling activities, which share the environmental, hydrodynamic and biotic conditions of the impacted site. The analogue sites can be maintained without impact throughout the time required to assess natural recovery if fishing can be controlled.
Challenges posed to the selection of the analogue site	The biggest challenge to the selection of the reference sites is the fact that there are no pre-disturbance baseline data for the impacted sites and the overall knowledge on the Palinuro seamount is limited. The geological characteristics of Palinuro seamount are relatively well known, but biological and ecological data are scarce. In addition, there is no clear idea on the current anthropogenic impacts on the soft bottom communities of the Palinuro seamount, mainly concerning fishing activities which have been observed as lost fishing gear on the summit of the seamount. The analogue site should be chosen on the same seamount because soft bottom communities tend to differ between deep-sea habitats and environmental conditions.
How feasible is it to describe the reference (or model) ecosystem?	A reference ecosystem can be reasonably described based on information available through the analogue site. However, the lack of data before human impacts, the knowledge gaps on the benthic communities, ecosystem functioning and environmental characteristics of the Palinuro seamount, and the lack of detailed information on the life cycle of different taxa, their species migration and spatial distribution at large spatial scale will decrease confidence associated with the description of the reference ecosystem.
Overall confidence	In summary, the reference ecosystem described has a medium level of confidence since we will gather information from all 4 different categories: *here and now*, *here and then*, *there and now*, and *there and then*.
Reference ecosystem	See section 3.4.

4.2. KC 2. Identifying the target ecosystem's key attributes is required prior to developing longer term goals and shorter-term objectives

An essential part of a restoration project is the definition of goals and objectives to achieve a clearly defined target (McDonald et al., 2016). The goals and objectives are used to monitor the progress of the restoration project over time, and to enable adaptive management approaches, when necessary. The target of the restoration project is the reference ecosystem (see 4.1) to which the restoration project is being directed to and will include a description of the attributes requiring reinstatement and which have been selected for monitoring and evaluation. The goals describe the status of the target that is aimed to achieve in the medium to long term, which are translated into shorter-term specific objectives that should be measurable, achievable, time-bound, and directly connected to key attributes. These attributes in combination can then be used to evaluate progression towards full recovery in a five-star rating system (see KC 4, section 4.4) that enables practitioners, regulators, and industry to track restoration progress over time.

4.2.1. *Key ecosystem attributes in the context of deep-sea restoration*

A pre-assumption for establishing clear goals and measurable objectives is thus a good knowledge of the target and identifying ecosystem's key attributes. The target for the hypothetical deep-sea restoration projects (see 3.1-3.4) can be interpreted as the reference ecosystems described in KC1 (see 4.1) and should include a description of key ecosystem attributes for monitoring and evaluation purposes (McDonald et al., 2016). The international standards for the practice of ecological restoration suggest the description of six categories of key attribute including threats, physical condition and ecosystem attributes (e.g. compositional, structural, and functional). These categories of attributes are considered broad enough to be applicable to the deep-sea case studies. However, an additional category on Ecosystems Goods and Services (EGS) attributes was added to capture the ecological functions and the economic value of these ecosystems which contribute to human well-being. Deep-sea EGS comprise mainly provisioning services (e.g. fish catch, pharmaceuticals), regulation services (e.g. carbon storage, nutrient remineralization) and cultural services (e.g. inspiration for the arts) (Armstrong 2012; Thurber et al., 2014). Valuing EGS and assessing the costs and benefits of deep-sea exploitation has become very important with the increased exploitation of deep-sea resources, and the need to balance the sustainable use and conservation of deep-sea ecosystems (Thurber et al., 2014).

4.2.2. *Key ecosystem attributes for four deep-sea case studies*

Site specific sub-attributes reflecting the particular ecological characteristics for each reference ecosystem were identified for each case study (**Errore. L'origine riferimento non è stata trovata.**). These include the description of the types of threats and impacts that need to be removed, physical-chemical conditions of substrate and water column, as well the description of biological components in terms of key species, associated species, and their roles in the ecosystem. For all these ecosystems, large gaps were identified in the basic biological knowledge of the species, e.g. on life cycles, reproductive biology (including age and size at the first reproduction), connectivity, recruitment and growth rates, lifespan and population structure (see also KC1 section 4.1, and Table 3-

Table 6). At the ecological level, although some information exists on species diversity, ecological interactions and ecosystem structure and functioning are poorly known. This lack of knowledge is related to difficulties in surveying and sampling these deep and remote environments, requiring the use of expensive technological means (ROVs, AUVs, submersibles) (Ramirez-Llodra et al., 2010; Danovaro et al., 2014). Thus, research on deep-sea ecosystems is considerably more recent (>50 years) when compared to terrestrial and coastal ecosystems (>100 years), especially in terms of time-series studies, which are essential for understanding community succession and dynamics (Glover et al., 2010).

4.2.3. *Long-term goals and specific objectives for four deep-sea case studies*

For each of the deep-sea case studies, we identified the overarching long-term ecological and socio-economic goals and defined the specific objectives needed to attain these goals (Table 8-Table 11). While the goals were kept broad and were similar between case studies, the objectives were specific to the reference ecosystem. Care was taken to select objectives that were linked to the attribute or sub-attribute identified in the reference ecosystem, specifying an achievable desirable outcome (e.g., increase, decrease, maintain), the magnitude of effect (e.g., X% increase or decrease) and the time frame estimated to achieve the objective, so that practitioners could track restoration progress over time. A common aspect between the case studies is that the goals and some of the long-term objectives of the restoration projects may require centuries to millennia to be accomplished, and thus are not achievable during the typical lifetime of a restoration project. Time scales for the deep sea exceed the ranges seen for the recovery of some shallow water coastal and terrestrial restoration projects although in some cases full recovery might take decades to centuries also in the latter provinces (Bayraktarov et al., 2016, Clewell and Aronson, 2007). This extended timescale is related both to the specific geochemical conditions of the particular ecosystem and to the biological characteristics of deep-sea species, including slow growth, high longevity, late reproduction and low rates of recruitment.

Restoration of coral gardens through the transplantation of key coral species may accelerate the initial recovery of the ecosystem, but the life history traits of the species will condition the slow recovery of the ecosystem, including its full biodiversity, structure and functioning, which will likely require more than 100 years (Table 8). A meta-analysis of published studies about restoration activities performed through transplantation of sessile species demonstrate a trade-off between initial transplantation efforts and the speed of recovery (Montero-Serra et al., 2017). Transplantation of slow-growing species will tend to require lower initial effort due to higher survival after transplanting, but the period required to fully recover habitat complexity will tend to be long. Demographic projections by Montero-Serra and colleagues for this restoration technique in the octocoral *Corallium rubrum* predict that 30 to 40 years may be necessary for newly established *C. rubrum* populations to show a colony size distribution comparable to those observed in natural populations and to allow the development of associated organisms.

For both the CCZ (Table 9) and the HV (Table 10), the hypothetical restoration projects involved active intervention to correct abiotic damage, i.e. replacement of destroyed active vent edifices with an artificial 3-dimensional conical edifices and replacement of polymetallic nodules with artificial nodules, respectively (KC3, see 4.3). The reconstruction of the abiotic environment in both of these cases would accelerate the process of natural geological formation of vent edifices and polymetallic nodules, which otherwise may take hundreds to thousands of years. Nevertheless, the successional process for community development from microbial to megafauna communities on the artificial vents and nodules would still require another hundred to thousands of years for both of these case studies (Table 9, Table 10). For example, results from disturbance experiments simulating deep-sea polymetallic nodule mining in the CCZ suggest limited ecosystem recovery even after almost three decades, particularly in sessile and larger fauna (Jones et al., 2017). The re-colonization of newly formed vent edifices requires the recovery of native microorganism communities before the colonization by bioengineering megafauna species. While studies conducted on the fast spreading East Pacific Rise showed the recolonization of microbial community after 9 months following an eruption, there is no such data available on the slow-spreading Mid-Atlantic Ridge. Initial colonizers, including bacterial mats, can develop on artificial substrata or in *in situ* colonization chambers deployed within a venting area after few days, with times varying depending on the type of substrata (Guezennec et al., 1998; Corre et al., 2001; Reysenbach et al., 2000). However, these constitute a subset of the full microbial community and rapid colonisation is more likely to be facilitated by the presence of microorganisms in the direct vicinity.

The natural recovery of soft bottom communities in terms of abundance and biomass can occur after few years from the end of disturbance. The spontaneous regeneration of meio- and macrofauna assemblages has been observed in different deep-sea ecosystems, after the end of different mechanical impacts (Vopel and Thiel 2001; Gollner et al., 2017; Radziejewska et al., 2001a, 2001b; Miljutin et al., 2011). The period of recovery for benthic fauna is highly variable and site-specific depending on the type of disturbance. However, the period of recovery in terms of species composition and functions can be much longer (Miljutin et al., 2011; Vanreusel et al., 2016; Jones et al., 2018).

The very large time scales required for the reinstatement of the biological and ecological attributes of deep-sea ecosystems challenges the setting of measurable achievable objectives within the lifetime of a restoration project and even human time scales. Therefore, restoration efforts for these ecosystems should aim at identifying the essential initial components that will need to be in place so that other components of the ecosystem can recover over longer timescales. This was acknowledged in our effort to define objectives for the different case studies by defining objectives that could be measured on a scale of decades, even if this meant that only a small portion of the attributes would have been achieved, e.g. 10% recovery of dominant sessile species within 20 year for the CCZ case study (Table 9).

The lack of knowledge of the succession patterns of deep-sea ecosystems further complicates the setting of specific measurable objectives. The occurrence of alternative successional trajectories has been documented for terrestrial and coastal marine systems (McCook, 1994; Sousa, 2001). This has also been studied in deep-sea hydrothermal vent communities on the East Pacific Rise, by following faunal succession after a catastrophic seafloor eruption has destroyed faunal communities (Mullineaux et al., 2012). Here, the trajectory of succession after the eruption differed both qualitatively and dynamically from that of the pre-disturbed community, with new pioneer species previously absent from the area that also impacted undisturbed nearby communities. Therefore restoration for deep-sea ecosystems may require relatively broad goals and objectives, such as restoring functional group presence or particular ecosystem function rather than particular species or community type (Jones et al., 2018).

Indeed, Hiderbrand's et al. (2005) essay on 'the myths of restoration ecology' suggests that unsuccessful restoration projects have resulted from a failure to recognize and address uncertainty, and from a focus on inappropriate time scales. One of the major problems identified by the authors aroused from the inability to accept that systems are dynamic and may have multiple trajectories leading to numerous possible outcomes. Thus, ignoring uncertainty may result in failure because the restored ecosystem is not capable of adapting or responding to future drivers or events. Therefore, restoration requires periodic re-evaluation and adaptive management to increase the chances of responsive, adaptive, and successful projects. In terrestrial systems requiring long times for recovery (e.g. forests), modelling approaches have been used to predict rates and directions of succession and estimate the time to achieve long-term restoration goals and objectives, and so to aid in strategy corrections and adaptive management (e.g. Prach et al., 1999). However, these approaches require some information on life history (age, growth, recruitment) and ecological (species interactions, functioning) attributes which in most cases, are not available for the deep sea.

Monitoring of restoration projects is essential to identify underperformance relative to the objectives set and allow for adaptive management actions. Ideally, monitoring plans should be design to collect data from 'before' (B) and 'after' (A) the restoration 'intervention' occurs (I) from the site to be restored, as well as data from degraded 'control' (C) site and, when possible, from the reference (R) site (a.k.a. analogue site); allowing for a 'Before, After, Reference, Control, and Impact' BARCI design (Lake, 2001;

McDonald et al., 2016). The success of the monitoring plans depends again on a good knowledge of the ecosystems to be restored. However, for some deep-sea ecosystems, such as coral gardens, fishing impacts have occurred before the ecosystems were studied. Therefore, 'before impact' data or pre-disturbance sites may not be available. For other cases, such as hydrothermal vents and abyssal plain communities, pristine ecosystems still exist, but information on the biodiversity and ecosystem functioning are extremely scarce. In addition, the pristine or analogue site is often the site where the impact will occur. This means that where restoration is planned to be used as a mechanism for remediation of impacts of extraction industries, such as sea-floor mining, the impacts on ecosystems will occur before the ecosystem is well characterized.

The long-time period necessary for the recovery of deep-sea ecosystems means that any monitoring plan would require a mechanism for long-term commitment that exceeds typical business and political cycles (financing, managing, regulating, monitoring and enforcement). This is particularly challenging for extraction industries, such as sea-floor mining, where questions then arise as to where responsibility for remediation of a former mine site lies once a mining contract has expired but the recovery of the impacted site is still not complete (Niner et al., 2018).

Table 7. List of attributes and sub-attributes for each case study.

Attribute	**Sub-attributes**			
	Cold-water coral gardens	**Nodule rich abyssal plain**	**Hydrothermal vents**	**Soft sediments on seamounts**
Absence of threats	Cessation of fishing	Cessation of mining-related impacts (removal of nodules, chemical contamination, light/noise from machinery, sediment plumes)	Mining-related impacts (removal of substrate, chemical contamination, light/noise from machinery, sediment plumes)	Cessation of scientific drilling activities
	Cessation of impacts due to scientific use (destructive sampling)	Pollution from shipping (litter, discharged sewerage, oil)	Cessation of chemical contamination by mining	Pollution from shipping (litter, discharged sewerage, oil)
	Pollution from shipping (litter, discharged sewerage, oil)	Alteration of food supply by epipelagic and upper water column fishing	Elimination of noise/light by mining machinery	
		Physical disturbance from other industries (e.g. cable laying)	Cessation of particle load by mining	

Attribute	Sub-attributes			
	Cold-water coral gardens	**Nodule rich abyssal plain**	**Hydrothermal vents**	**Soft sediments on seamounts**
		Cessation of impacts due to scientific use (destructive sampling)	Cessation of impacts due to scientific use (destructive sampling)	
Physical conditions	Physical condition of the substrate (seafloor integrity)	Physical condition of the substratum	Geochemical composition and rate of the vent fluid (not scored in KC4) Physical condition of the substrate (3D topography) Physical condition of the substrate (mineralogy)	Physical condition of the substrate (change in grain size, sediment structure, compaction)
	Chemical condition of the substrate (TOC, nutrients)	Chemical condition of the substrate (metal and organic matter re-deposition at seafloor)	Chemical condition of the substrate (metal and organic matter re-deposition at seafloor)	Substrate chemical (TOC, nutrients)
	Water column conditions (turbidity, bottom currents)	Water column conditions (seawater mixing, nutrients, organic matter, metals)	Water column conditions (turbidity, bottom currents)	Water column conditions (pore water, benthopelagic, water column)
Species composition	Characteristic native microorganisms Characteristic native coral species Characteristic native associated macro- and megafauna	Characteristic native microorganisms Characteristic native metazoan fauna (meio-, macro-, megafauna)	Characteristic native microorganisms Bioengineering species (large symbiotic invertebrates) Native faunal communities (meio-, macro-, megafauna)	Characteristic native microorganisms characteristic meiofauna characteristic macrofauna
Structural diversity	Structural layers (3D complexity of coral colonies) All trophic levels Spatial heterogeneity of seafloor habitats	Structural species / Bioengineers (e.g. sponges) All trophic levels Spatial heterogeneity of seafloor habitats	Structural layers (3D biogenic structure) All trophic layers Spatial heterogeneity of seafloor habitats (e.g. diversity of hydrothermal venting types)	 All trophic levels Representativeness of habitats (e.g. covering depth gradients, different sub-habitats, spatial heterogeneity)
Ecosystem functionality	Faunal and habitat interactions (related to trophic structure) Secondary productivity (faunal biomass) Reproduction, dispersal and recruitment of native species	Faunal and habitat interactions (related to trophic structure) Primary and secondary productivity (chemoautotrophy, faunal biomass) Reproduction, dispersal and recruitment of native species	Faunal and habitat interactions (related to trophic structure) Primary and secondary productivity (chemoautotrophy, faunal biomass) Reproduction, dispersal and recruitment of native species	Faunal and habitat interactions (related to trophic structure) Secondary productivity (faunal biomass) Reproduction, dispersal and recruitment of native species

Attribute	Sub-attributes			
	Cold-water coral gardens	**Nodule rich abyssal plain**	**Hydrothermal vents**	**Soft sediments on seamounts**
	Nutrient and carbon cycling	Nutrient and carbon cycling	Decomposition, nutrient and metal cycling	Nutrient cycling, organic carbon degradation rate
	Ecosystem resilience (resistance, recovery)	Ecosystem resilience (resistance, recovery)	Ecosystem resilience (resistance, recovery)	Ecosystem Resilience (resistance and recovery)
External exchanges	Connectivity (gene flow, sink and sources populations)	Connectivity (gene flow, sink and sources populations)	Connectivity (gene flow, sink and sources populations)	Connectivity (gene flow, sink and sources populations)
	Species migration between habitats (e.g. fish, crustaceans)	Species migration between habitats (e.g. fish, crustaceans)	Species migration between habitats (e.g. fish, crustaceans) (energy export)	Species migration between habitats (e.g. fish, crustaceans)
		Pelagic benthic coupling and bathyal to abyssal supply		
	Cooperation with stakeholders	Cooperation with stakeholders	Cooperation with stakeholders	Cooperation with stakeholders
Ecosystem goods and services	Provisioning services (Fish, biomaterials)	Provisioning services (Minerals, fish, biomaterials)	Provisioning services (Minerals, biomaterials)	Provisioning services (biomaterials)
	Supporting and regulating services (nutrient cycling and carbon sequestration)	Supporting and regulating services (nutrient cycling and carbon sequestration)	Supporting and regulating services (nutrient cycling, carbon sequestration, metal cycling)	Regulating services (nutrient cycling and carbon sequestration)
	Cultural services (aesthetic and existence values)	Cultural services (aesthetic and existence values)	Cultural services (aesthetic and existence values)	Cultural services (aesthetic and existence values)

Table 8. Target, goals and objectives for the restoration of cold-water coral gardens in the Condor seamount (Azores, NE Atlantic) impacted by fishing.

Target	Goals categories	Goals	Objectives
Reference ecosystem in section 3.1	**Ecological**	Re-establishment of biodiversity, composition, structure and functionality of coral gardens > 100 years	Re-establishment 10% densities of dominant species compared to the reference ecosystem within 10 years
			Re-establishment 25% densities of dominant species compared to the reference ecosystem within 20 years
			Re-establishment 80% densities of dominant species compared to the reference ecosystem within 30 years
			25% of the new colonies are reproductively active (presence of gametes, evidence of spawning) within 20 years
			80% of the new colonies are reproductively active (presence of gametes, evidence of spawning) within 30 years
			Re-establishment of viable reproductive populations and presence of new young colonies after 20-30 years
			Number of dominant coral species recruits not significant different from the reference ecosystem within 20-30 years
			Size structure and complexity of 10% of dominant species not significant different from the reference ecosystem within 50 years
			Size structure and complexity of dominant species not significant different from the reference ecosystem within 200 years
			Species richness and densities of corals are >10% of that of the reference ecosystems within 15 years
			Species richness and densities of associated fauna are >10% of that of the reference ecosystems within 15 years
			Trophic complexity not significant different from the reference ecosystem within 70-100 years
	Ecological	Reinstatement of goods and services (supporting, regulating, and provisioning services) within 100 years	Increased nutrient regeneration by microbial communities within 30 years
			Increased carbon sequestration within 30-50 years
			Concentrations of N, P and C (nutrient cycling) in the coral garden not significantly different to the reference ecosystem within 30-50 years
			Fish stocks within MSY limits within 30-70 years and Increased biomass of commercial fish species within 50-100 years
	Socio-economic	Increased community engagement on deep-sea conservation within 20-30 years	Deep-sea ecology theme encouraged by local NGOs through their activities with children and fisherman within 5-10 years

Target	Goals categories	Goals	Objectives
			75% of professional fishermen know the importance of coral gardens as essential fish habitats within 10-15 years 75% of professional fishermen support the establishment of deep-sea MPAs within 10-15 years
		Increased governmental engagement on deep-sea conservation within 20-30 years	A permanent no-take zone covering at least 20% of the area is implemented within 20-30 years
		Improved fishing stocks for a sustainable fisheries within 30-70 years	Fish stocks within MSY limits within 30-70 years

Table 9. Target, goals and objectives for the restoration of abyssal plain communities in nodule rich areas in the Clarion Clipperton Fracture Zone (Eastern Central Pacific) impacted by deep-sea mining.

Target	Goals categories	Goals	Objectives
Reference ecosystem in section 3.2	**Ecological**	Re-establishment of composition, structure and function of nodule areas within 1 million years	Re-establishment of 10% of densities of dominant sessile species compared to the reference ecosystem within 20 years Number of recruits of dominant species is 10% that of reference ecosystem within 20 years Presence of individuals of >50% of the maximum size of individuals in the reference ecosystem within 100 years Species richness of sessile fauna is 10% of that of the reference ecosystem in 50 years. Microbial cell numbers are >10% that of the reference ecosystem in 50 years. Respiration of sediment community is >50% of that of reference ecosystem in 25 years At least one representative species from each trophic level of the reference ecosystem is present after 10 years
	Ecological	Reinstatement of supporting, regulating, and provisioning services within 200 years	Fluxes of N, P and C across the sediment water interface in ecosystem are >10% that of the reference ecosystem within 15 years Carbon sequestration is >10% that of the reference ecosystem within 30 years
	Ecological	Reinstatement of genetic connectivity with other natural areas within 200 years	Genetic diversity is >10% that of the reference ecosystem in 50 years
	Socio-economic	Increased community engagement on deep-sea conservation within 20-30 years	Deep-sea ecology introduced in official teaching programmes for 10-14 years old students within 10 years across 10% of countries with mining contractors Awareness-raising campaigns by NGOs around the world within 5 years 10% of states support restoration activities in 10-15 years as an appropriate mechanism for mitigation of impacts (once avoidance and minimization have been achieved) 50% of states support the establishment of deep-sea MPAs within 20 years A permanent APEI network covering all representative ecosystems and areas in the CCZ and beyond is established by 10 years A permanent network of within-claim protected areas is established in 20% of claim areas within 10 years. A dedicated guidance document for restoration provided by the ISA in 10 years

Table 10. Target, goals and objectives for the restoration of the Lucky Strike hydrothermal vent community in the Mid Atlantic Ridge (NE Atlantic) impacted by deep-sea mining.

Target	Goals categories	Goals	Objectives (active)
Reference ecosystem in section	**Ecological**	Re-establishment of composition, structure and functionality (i.e. supporting services) of hydrothermal vents after more than 1000 years	Stabilization of mineral deposition on the deployed artificial vent edifice within 2-5 years
			10% of characteristic native microorganisms communities (hyper-, thermophilic microorganisms) in all habitats compared to the reference ecosystem within 2-5 years
			25% of characteristic native microorganism communities in all habitats compared to the reference ecosystem after 100 years
			Re-establishment of characteristic native microorganism communities in all habitats compared to the reference ecosystem within 100 years
			Presence of bioengineering and dominant species recruits at 10-25% of the initial occupancy (proportion of sites where they were present) within 100 years
			Acquisition of symbionts by the bioengineering species within 50 years
			Re-establishment of characteristic engineering species at 10-25% of the initial occupancy (proportion of sites where they were present) within 100 years
			Re-establishment 25% densities of dominant species compared to the reference ecosystem within 100 year after 3D consolidation and microorganism communities being established
			Size distribution of engineering and dominant species not significant different from the reference ecosystem within 100 years after the stabilization
			Re-establishment of all initial faunal assemblages compared to the reference ecosystem within 100 years after stabilization
			Species richness not significantly different from the reference ecosystem within 1000 years after stabilization
			25% of functional groups similar to the reference ecosystem within similar 100 years after stabilization
	Ecological	Reinstatement of supporting, regulating, and provisioning services within 200 years	Re-establishment of metals (e.g. iron, copper, zinc) export in the global ocean within 200 years
			Re-establishment of 10% of carbon export in the global ocean within 200 years
			Re-establishment of nutrient regeneration by microbial communities within 200 years

Target	Goals categories	Goals	Objectives (active)
	Socio-economic	Increased community knowledge and engagement on deep-sea restoration and conservation issues within 20 years	Deep-sea ecology theme encouraged by local NGOs through their activities with children and science communicators within 10-20 years
			Engagement of the local population in the public consultation for the establishment of deep-sea MPA and restoration projects within 2-3 years
			Engage local communities in monitoring programs through citizen sciences project within 2 years
			Develop effective communication plans towards the local communities on exploitation activities and restoration measures within 1 year
		Increased governmental engagement on deep-sea conservation within 20-30 years	A monitoring plan is directly implemented along with the restoration measures within the 1st year
			Ensure that all the above objectives towards community knowledge and engagement are on the government agenda within the 2 years

Table 11. Target, goals and objectives for the restoration of the soft bottom communities on the Palinuro seamount in the Mediterranean Sea impacted by scientific drilling.

Target	Goals categories	Goals	Objectives
Reference ecosystem in Box 4	**Ecological**	Re-establishment of biodiversity, community composition and functioning of soft-bottom communities within 100 years	Meiofauna species richness is 10% of that of reference sites within 10-20 years Meiofauna species richness is 50% of that of reference sites within 50-100 years Meiofauna species richness not significant different from the reference sites within 100 years Macrofauna species richness is 10% of that of reference site within 10-50 years Macrofauna species richness not significant different from the reference sites within 100 years Trophic structure not significant different from the reference ecosystem within 10-50 years
	Ecological	Recovery of the ecosystem functioning (biomass production, organic C degradation rate and heterotrophic prokaryotic C production) to support, regulate and provision of services within 30 years	Increased nutrient regeneration by microbial communities within 30 years
	Socio-economic	Increased community engagement on deep-sea conservation within 5-10 years	Promote awareness campaigns for deep-sea habitats to children and the wider public within 5-10 years

4.3. KC 3. The most reliable way to achieve recovery is to assist natural recovery processes, supplementing them to the extent natural recovery potential is impaired

The ability for natural recovery depends on the state of the ecosystem and its restoration potential. The state of the ecosystems that may require recovery is dependent on the nature and degree of the degradation; i.e. how serious in extent and impact and whether it is still ongoing. Many of the activities (forcing factors) impacting the deep sea have been reviewed in Smith et al. (2008) and Ramirez-Llodra et al. (2011). The main sources of impacts in the deep sea (see also section 1) include fishing, cable or pipeline laying, hydrocarbon extraction, deep-sea mineral mining and accidents for example from shipwrecks (e.g. the tankers Erica and Prestige off France and Iberian Peninsula), pipeline breaks or well head blowouts (Deepwater Horizon). Protective systems are being put in place with either designation of Marine Protected Areas and Fisheries Restricted Areas covering, for example, seamounts, coral banks, caves, hydrothermal vent and seep areas, as well trawling bans in the Azores EEZ, beyond 1000 m depth in the Mediterranean and 700 m in the North Atlantic with calls for shallower limits (Clarke et al., 2015) or the move-on rule when vulnerable marine ecosystem indicator species are encountered (Auster et al., 2011). It has only been with the Deepwater Horizon event in the Gulf of Mexico that restoration of degraded deep-sea benthic habitats was brought to the political and financial agenda (D.H.N.R.D.A.T., 2016). Future restoration programmes will most likely be aimed at obvious damaging events, as they may be high-impact but the source is stoppable (prevent fishing (Clarke et al., 2015), remove oil from a shipwreck (Parker and Moller, 2008), cap a leaking well (Biello, 2015).

4.3.1. *Natural spontaneous regeneration potential in the deep sea*

The restoration potential of deep-sea ecosystems is directly linked to its resilience. Resilience is the ecosystem's ability to maintain its structure and patterns of behaviour in the face of stress (Boesch and Paul, 2001). Therefore, a resilient ecosystem can withstand sustained or repeated stress, maintaining its recovery capacity. An ecosystem may go beyond its recovery capacity when:

- The environmental structure/fabric been damaged beyond a tipping point that the original biodiversity can be supported;
- The ecosystem biodiversity has been damaged to such a point that there is no longer full representation of the biodiversity in the area;

- The populations have been damaged or linkages broken such that they cannot recover themselves.

Whilst the first point is an immediate call for some form of physical intervention to reintroduce the structure either by artificial means or by introducing species that facilitate structure, the other issues are much more dependent on the characteristics of deep-sea species and their environment. Biodiversity is relatively high in the deep sea (Snelgrove and Smith, 2002) relating to a combination of small-scale natural disturbances (e.g. feeding activities, bioturbation) and periodic and episodic events (e.g. phytodetritus and food-falls) (Rex and Etter, 2010).

Deep water ecosystems, however, are generally characterised by low biological productivity; mostly detritus based systems dependent on surface production and particulate flux (Smith et al., 2008). This organic flux is very low, relating to a small percentage of primary production in overlying waters (Smith and Demopoulos, 2003). Consequently abundances of many larger organisms are low and energy constraints drive a decrease in average organism size with depth, although it can be high in special habitats with elevated food supply (Rex and Etter, 2010). The low input of food or episodic nature of food inputs also accounts for characteristic low metabolic rates. For some deep-sea species, growth and time of first maturity times are on the same timescale as shallow water species (Scheltema, 1987), but this is not the case for many species, particularly sessile and structural. Many deep-sea species may be long lived (centennial or multi-centennial for corals – Roark et al., 2009; Watling et al., 2011) with slow growth (coral growth may range from millimetres per year to hundredths of millimetres per year – Roberts et al., 2009; Prouty et al., 2011, Montero-Serra et al., 2017). The age of maturity may be delayed considerably, for example 50-60 years for a bivalve (Turekian et al., 1975) and 30 years age for the fish orange roughy (Fenton et al., 1991). In the latter case maximum age of the fish is thought to approach or exceed 150 years (Horn et al., 2016). Reproductive capacity may be low with long periodicity and recruitment dependent on whether there is a dispersal stage, good settlement conditions and high survival of post-larvae. Recruitment may also be dependent on good connectivity with other reproducing populations, both to produce new recruits and also ensure gene flow. Connectivity is of major importance in colonisation, but is still a largely unknown subject due of the lack of knowledge on deep-sea dispersal and potential dispersal distances (Hilário et al., 2015). Connectivity is also confounded by sink-source populations where a low condition sink population may always be dependent on a higher conditions source population for recruitment purposes (Rex et al., 2004).

The exceptions to low productivity may be found in hydrothermal vents, and to a lesser degree cold seeps, where energy is based on *in-situ* chemosynthetic microbial processes (Smith et al., 2008). Although vent areas may be active on geological timescales, at any one site the hydrothermal vent community may persist for only several decades (Grassle, 1986), or even thousands of years. The age of

Lucky Strike is between a few thousands of years to few tens of thousands of years (Humphris et al., 2002; Barreyre et al., 2012). Vents are now recognised as not to be completely isolated/individual ecosystems, but able to interact over a wider areas; over time major spatio-temporal transitions are generated and create links with the surrounding area, often forming identifiable ecotones or successional stages (Levin et al., 2016a).

Deep-sea natural spontaneous regeneration potential is extremely uncertain mostly in whether there is sufficient connectivity to allow for a full recovery of biodiversity and then over the potentially longtime scales required for some species to fully recover to their original state. This long time period may assist in the divergence from the original ecosystem to a different or variant ecosystem.

It is difficult to equate deep-sea system with terrestrial analogues. Shallow water corals have been compared to redwood or tropical forests where the habitat is defined by the species that occur rather than a range of environmental conditions (Connell, 1978; Petraitis, 2013). The US Redwoods are the better analogy with deep-sea corals because of their centennial longevity. But they have the advantage of being highly visible and about 82% of remaining ancient coast redwood forest is protected in parks and reserves with 90% of giant sequoia forests protected in national parks and forests (savetheredwoods.org). Restoration of forests and corals is similar in that threats must be removed and transplantation or seeding carried out. Whilst hydrothermal vents do occur in the freshwater ecosystems, with possible similarities in microbial diversity and activity (Pontefract et al., 2017), there is no analogue with the marine chemosynthetic large multicellular organisms communities. Rex and Etter (2010) have noted that successional changes in community structure following physical disturbance can take much longer in the deep-sea than in coastal sediments. Coastal processes may be thought to be similar to terrestrial environments with similar changes in conditions (daily and seasonal). Coastal marine and terrestrial ecosystems are typically sustained by local production which contrasts sharply with most deep-sea food webs that are purely detrital based (Polunin et al., 2001).

4.3.2. *Need to reinstate missing biotic and abiotic elements (generic)*

Abiotic elements essential to habitats may be removed through anthropogenic activities, for examples mining for polymetallic nodules and hydrothermal vent chimneys (seafloor massive sulphide deposits). These abiotic elements are important to the ecosystem, defining habitats and acting as substrates for the attachment, settlement, congregation of species. The spacing of substrates is important for many ecosystem processes, such as feeding, reproduction, shelter and connectivity. Interactions between substrates and the hydrographic regime (e.g. current baffling) are also important (MIDAS, 2016). High densities of surface polymetallic nodules have been shown by Vanreusel et al. (2016) to be a vital requirement for the preservation of attached fauna and abyssal biodiversity as a whole. The authors also point out that the presence of nodules may still enable the recovery of the local fauna in the long term – indicating that some nodules need to be left in place during mining operations or should be replaced with some similar substrate allowing for quicker recolonisation by dependent communities. With most substrates being produced over geological timescales, polymetallic nodules have growth rates of millimetres per million years, and manganese nodules, quicker forming nodules, may still have an age of several millions of years (Kuhn et al., 2017). Growth rates in metallic/sulphur rich chimneys can be extremely high with rates up to 15 m height in 25 months reported by Nozaki et al. (2016), created after drilling wide boreholes in a 1000 m depth vent area. Growth is dependent on area and activity, but growth rates at 2200 m on the Juan de Fuca ridge have been estimated at 1.2. cm per year (Kadko et al., 1985); active chimneys were estimated to be as young as 2 years old (Stakes and Moore, 1991). Vent areas also have an abundant associated fauna (Boschen et al., 2016) partially attributable to the varied environmental gradients both in space and in time (Sarrazin et al., 1997). With high dependency on abiotic environmental factors, removed substrates and structures would need some form of replacement, for example, replacement nodules or artificial chimneys to allow for the recruitment of original faunal communities.

Biotic elements could be added to facilitate recovery of the ecosystem where it has been degraded. This may be where these elements have been removed, are not able to recover (breeding stock is at a too low level or there is a lack of connectivity with another breeding population) or the timespan for natural recovery is to slow and needs speeding up. This should be targeted at key species, those that are promoting biodiversity and life cycles of other species. Cold water corals are typical examples of key species defining an ecosystem where they are part of the structure

There are considerable challenges to deep-sea restoration through access to the environment often at distance offshore and at considerable depths that would require expensive technologies including large support vessels, and remotely operated or autonomous vehicles. Van Dover et al. (2014) estimated that 80% of the direct costs for a deep-sea mining restoration programs would be associated with ship and underwater vehicle use. Whilst the scientific facilities required to support offshore restoration endeavours may be in limited and in decline (Kintisch, 2013), industry does have these capabilities which are often underutilised, which have been opened to scientific access (www.serpentproject.com), but could and should be used in industry-led restoration related actions in parallel with deep-sea exploitation, as long as there is sufficient knowledge transfer from science to industry. Specifically technologies are needed that can repeatedly work on the same sites for assessment, restoration/remediation work and monitoring. Assessment and monitoring for the most part needs at least the use of video if not physical sampling, whereas remediation/restoration may involve manipulation at the seabed through medium to large ROVs or manned submersibles. Some restoration attempts could be made blind by remote deployment of substrate/transplantation packages and there might also be future possibilities for bottom deployed laboratory reared larvae. In the terrestrial environment remote restoration has been undertaken by "aerial seeding" or "seed bombing". This may be transferable to marine waters but the deployment would have to be close to the seabed to ensure correct/precise distribution negating water column dispersal. Corals for example may need specific orientation or positioning related to current or food supply or adjacent settled species (De Mol et al., 2012; Vertino et al., 2010).

For transplantation there are many challenges including 1) the collection of organisms, 2) how easy they are to collect, 3) whether they are from the original population (genetically linked), 4) how they might be reproduced in the laboratory (fragmenting or sexually/asexually reproducing) and 5) how they might be transplanted into the area to be restored. In terms of scale, there are issues relating to how many or how much biomass of a species may need to be restored, whether a discrete (restricted) area should be seeded a vent or reef area, or whether large areas should be covered, for example in nodule areas and whether transplantation should occur several times over a long period.

4.3.3. *Identify appropriate ecological restoration approaches in four deep-sea case studies*

The four cases demonstrate (Table 12-Table 15) the different approaches that could assist or supplement natural recovery following cessation of harmful activities. The Palinuro seamount SB case study requires the fewest interventions (i.e. no addition of artificial structures or biotic elements) and employs the natural spontaneous regeneration approach building on the associated medium to low degradation levels and the medium recovery capacity potential of the key seamount attributes (for example seamount meio- and macrofauna). The CWC case demonstrated a case where natural recovery is assisted, supplemented and fast-tracked through the transplantation of key gorgonian species against a background of medium to low associated degradation levels and the medium to low recovery capacity potential of the key coral attributes. In contrast to the other cases where various biotic and abiotic elements are missing, in the CWC the only missing elements are biotic and this is where the restoration efforts are directed. The remaining 2 cases represent hypothetical restoration projects in which both the recovery capacity of all the attributes is low and the degradation level is high (for all the attributes except food web structure in the HV case where this is moderate). In addition, in both cases, recovery of these ecosystems is not perceived as possible without the replacement of essential abiotic elements and physical structures removed during the hypothetical mining operations. However adding these structures (false nodules with appropriate chemical coating in CCZ and 3-D chimneys in the HV case) is just a very first step in providing a substrate to allow further complicated processes to take place (for example for the chimneys to have the right coverage and conditioning allowing the fauna the possibility to colonize).

Whilst general restoration principles remain the same as terrestrial actions with respect to cessation of harmful activities, physical interventions to enhance abiotic parameters/structure and replanting of biological material, there are massive challenges in the deep-sea restoration projects presented by working underwater, accessibility with distance offshore and depth to the seabed. The underwater environment is complex, characterised by a corrosive fluid medium and great pressure requiring specialised equipment.

Submersibles have the advantages of placing humans at the seabed, but have limited deployment times, are very expensive to operate and are limited in number of operational vehicles available. ROVs have become widely available in the last decades, with differing levels of size, power, payload and manipulation capacity (Smith and Rumohr, 2013; Rogers et al., 2015). They can reach considerable depths and stay operational on the seabed for as long as the operating surface vessel can remain on site. AUVs may not require surface vessel requirements (no need to remain on site) but they have poorer intervention capabilities and payloads, being pre-programmed for missions with low possibilities for re-tasking during a mission (Jamieson et al., 2013). Landers can deliver and recover instruments (imaging, sensing, tracking and sampling) or materials to the seabed. Hybrid AUV/lander systems in the form of bottom crawlers can moving around with sensor and sampling packages over extended periods of months (e.g. Sherman and Smith, 2009).

Another challenge of deep-sea restoration is in the provision of material for transplantation. As with terrestrial analogues, progenitor or donor material needs to be collected and multiplied in a nursery/culture facility. This could be targeted with the collection of material from specific sites or from on-going activities in the area e.g. from fishermen collecting corals in bycatch or fauna recovered from harvested nodules. These need to be carefully transported to culture areas with necessary facilities, maintaining clean constant water conditions under low light regimes. Current issues also include the genetic origin of transplanted material, how close it is to the original of the restoration site as well as the possibility to breed resistant strains that might have higher survival in restoration or may be more resistant to future climate change than the original stock. There are also issues of maintaining the genetic diversity of populations.

New innovations, methodologies and technologies are certainly needed and will help with deep-sea restoration. Current methodologies and technologies are being used in the experimental deep-sea restoration, but it is questionable about how these can currently be used for scaling up in time and space. The time to undertake simple tasks such as transplanting may be considerable (taking into account access, payload and manipulation speeds) and this becomes a cost multiplier for deep-sea restoration and may direct how restoration strategies are developed if large areas are needed to be addressed. This may not be an issue for discrete patch restoration may be required for coral or vent areas, but is more of an issue for more contiguous areas such as nodule zones.

Table 12. Restoration approaches required with respect to key attributes, degradation level and recovery capacity to supplement natural recovery of cold-water coral gardens in Condor seamount.

Cold-water coral gardens: assisted restoration of 3 gorgonian species with transplantation									
		Recovery Capacity		**Restoration approaches**					
Degradation level		Attribute	Recovery capacity	Missing biotic and/or abiotic elements	Natural regeneration (NR)	Assisted regeneration (AR) with biotic interventions (BI)	AR with physical interventions (PI)	Combination	Mosaic
M	M	Key coral species composition	L	B		X		X	X
	M	Structural complexity	L	B	X				
	L	Diversity and biomass of associated fauna	M	B	X				
	L	Food web structure	M	B	X				

Degradation Level: L=Low (green, perhaps only natural recovery needed), M=Medium (yellow), H=High (red, reconstruction will be required)
Attributes: degradation scoring for the same common attributes for the different case studies
Recovery Capacity: based on information from the Case Study Boxes: L=Low (red), M=Medium (yellow), H=High (green)
Missing Elements: Prior to any restoration action, A=abiotic (e.g. structures), B=Biotic (species missing and perhaps requiring transplantation)
Restoration approaches: marked as X for: natural regeneration (NR), assisted regeneration (AR) with biotic interventions (BI e.g. transplantation), and physical interventions (PI, e.g. artificial substrates/structures/hard engineering/bio-engineering and coating)
Combination: marked as X if more than 1 approach is needed in one area
Mosaic: marked X if different approaches are needed in separate areas in one overall area.

Table 13. Restoration approaches required with respect to key attributes, degradation level and recovery capacity to supplement natural recovery of nodule rich abyssal plain communities in the CCZ. Assisted regeneration with physical interventions (PI) in the form of artificial substrates (AS) and chemical coating (CC).

Nodules: removal of nodules but replacement with false nodules (with same chemical conditions)									
		Recovery Capacity		**Restoration approaches**					
Degradation level		Attribute	Recovery capacity	Missing biotic and/or abiotic elements	Natural regeneration (NR)	Assisted regeneration (AR) with biotic interventions (BI)	AR with physical interventions (PI)	Combination	Mosaic
H	H	Key nodule species composition	L	A, B	X				
	H	Structural complexity	L	A, B			X		
	H	Diversity and biomass of associated fauna	L	A, B	X				
	M	Food web structure	L	A, B	X				

Table 14. Restoration approaches required with respect to key attributes, degradation level and recovery capacity to supplement natural recovery of hydrothermal vent communities in the Lucky Strike 3D structure of the chimney is provided by physical interventions (PI) in the form of an artificial structure (AS), no species added.

Hydrothermal vent communities in the Lucky Strike field (Mid-Atlantic Ridge, Atlantic Ocean): reconstruction of the 3D structure of the chimney by an artificial structure									
		Recovery Capacity		**Restoration approaches**					
Degradation level		Attribute	Recovery capacity (100 years)	Missing biotic and/or abiotic elements	Natural regeneration (NR)	Assisted regeneration (AR) with biotic interventions (BI)	AR with physical interventions (PI)	Combination	Mosaic
H	H	3D topography (chimneys)	L	A			X		
	H	Key vent species composition (Mussels-*Bathymodiolus azoricus* and Alvinocatidae shrimps)	L	A, B	X			X	X
	H	Structural complexity (Bioengineering species, 3D biogenic structure-mussels, and the mineral precipitation mediated by microbes)	L	A, B	X				
	H	Diversity and biomass of associated fauna (all the fauna that lives inside and above the mussels beds and on the walls of chimneys- polychaetes, amphipods, nematodes, copepods, crabs, fish, ophiuroids)	L	A, B	X				
	M	Food web structure	L	A, B	X				

Table 15. Restoration approaches required with respect to key attributes, degradation level and recovery capacity to supplement natural recovery of soft bottom communities on Palinuro seamount.

Case Study: Soft bottom communities on Palinuro seamount (Mediterranean Sea): spontaneous natural regeneration after rock drilling.									
		Recovery Capacity		Restoration approaches					
Degradation level		Attribute	Recovery capacity	Missing biotic and/or abiotic elements	Natural regeneration	AR biotic interventions	AR physical interventions	Combination	Mosaic
M	M	Key seamount species composition	M	A, B	X				
	M	Structural complexity	M	A, B	X				
	L	Diversity and biomass of associated fauna	M	A, B	X				
	L	Food web structure	M	A, B	X				

4.4. KC 4. Restoration seeks 'highest and best effort' progression towards full recovery

International standards for the practice of Ecological restoration (McDonald et al., 2016) suggest that "restoration projects should adopt the goal of achieving a secure trajectory to full recovery relative to an appropriate local native reference ecosystem (see section 4.1)". However, McDonald et al. (2016) acknowledges that full recovery may not be possible everywhere within reasonable timescales. Recent meta-analyses covering several hundreds of studies (McCrackin et al., 2017; Moreno-Mateos et al., 2017; Jones et al., 2018) suggested that full recovery from large-scale disturbances is rarely achieved and that marine restoration projects (mostly coastal and shallow waters) showed some of the furthest deviations from the reference ecosystems. Therefore, it is reasonable to ask if a secure trajectory to full recovery is achievable in the deep-sea ecosystems.

4.4.1. *Progression towards full recovery in the deep-sea*

Due to the specific characteristic of many deep-sea species and ecosystems (see KC 2, section 4.4) recovery processes can be slow (e.g. Grassle, 1977; Smith and Hessler, 1987; Gollner et al., 2017; Jones et al., 2017) and take much longer than in terrestrial or shallow water marine ecosystems (Moreno-Mateos et al., 2017; Borja et al, 2010). In many cases the expected time scales to full recovery may span into time periods where local climate conditions may have changed (Sweetman et al., 2017), increasing the overall uncertainties on the recovery trajectories (Harris et al., 2006). Therefore, it is likely that full recovery may not be possible or appropriate everywhere in the deep sea. This may suggest that restoration goals in deep-sea ecosystems may need to be adjusted so they are more realistic to the ecosystems' ability to recover from degradation (Jones et al., 2018).

4.4.2. *Progression towards full recovery in four deep-sea case studies*

To address these issues we used the five-star recovery system (McDonald et al., 2016) to evaluate the likely progress towards full recovery of deep-sea restoration projects. The five-star recovery system assumes that each restoration project has its reference ecosystems described (see KC 1, section 4.1), the targets, goals, objectives, and key ecosystem attributes are defined and measurable (see KC 2,section 4.2), and that the appropriated ecological restoration approaches are identified (see KC 3, section 4.3). As discussed in previous sections, all these aspects come with high degree of uncertainties that may jeopardize the application of the system to our deep-sea case studies. Nevertheless, we have tried to score the likely time-range to achieve each recovery level based on the best available knowledge. We have also addressed the potential sources of uncertainties for our scores. The general standards for 1 to 5 star recovery levels (Table 16) were extracted from McDonald et al. (2016) and adapted to our deep-sea restoration cases studies.

For most case studies with the exception of the CCZ, absence of threats is an achievable goal within reasonable time scales and with some degree of confidence (Figure 6). This is because the CWC, SB, and HV case studies are in areas within national jurisdiction where management measures are easier to implement both within the restoration site and in adjacent areas. The CCZ case study lies in "the Area", where fishing policy are harder to be changed to favor restoration actions. Additionally, nearby areas may continue to be mined, slowing down the absence of threats from adjacent areas. In the case of the HV, there's a high degree of uncertainty on the time required to chemical contamination to be absent.

Re-instatement of physical conditions is perceived to be reasonably achieved within acceptable time scales for the CWC and SB case studies (Figure 6). For the CCZ, natural nodules only grow ca. 1 mm each ky, therefore once removed it results in total removal on ecological timescales. It is, however, assumed that the restoration activity will successfully replaces the nodules in a short period of time, but the chemical conditions that are reliant on both metals and organic material being redeposited, will take much longer time (Mewes et al., 2014). In the HV case study, the physical interventions is expected to replace appropriately shaped artificial structures mimicking hydrothermal chimneys. However, the substratum type and the complex 3D topography achieved with the natural regeneration of the chimneys may take thousands of years (Rouxel et al., 2004; Jamieson et al., 2013). Nevertheless, for most cases studies with the exception of the CWC, reinstating the physical conditions come with a very high degree of uncertainty both on the likelihood to achieve it and on the time-scales that will be needed.

For most other ecosystem components (e.g. species composition, community structure, and ecosystem functioning) progress towards full recovery will be more difficult, slower, and uncertain (Figure 6). Some progress is expected within tens of years for the CCZ, CWC and SB, but full progress may take centuries or millennia. This is mostly because most natural processes in the deep-sea are extremely slow. For example, in the CWC case study the structural complexity will be achieved with the continuous of growth of the transplanted corals which has been showed to be slow for many species (Watling et al., 2011; Roark et al., 2009; Carreiro-Silva et al., 2013). In the CCZ, not only the growth rates are extremely slow (McClain et al., 2012) but the presence of many rare species implies that species richness recovery is also slow (Jones et al., 2017). On the SB case study, some progress on the biological components is expected, but the major knowledge gaps on the overall trophic structure of macrofaunal assemblages, connectivity, and recovery time scales make all the scoring very uncertain. As for HV, there is no data available on the early colonisation and natural succession patterns and most biological process are expected to take considerable time to recover, if they can recovered at all.

Most deep-sea case studies considered external changes as one of the major knowledge gaps, since rarely any information on connectivity or migration patterns is available (Figure 6). However, potential effective connectivity and exchanges with surrounding environment is expected for CWC, CCZ and SB, but not for HV. Finally, EGS will only be marginally achieved within reasonable time scales for most case studies with cultural services (aesthetic and existence values) being the one showing better progress towards full recovery. Supporting and regulating services (e.g. nutrient cycling, carbon sequestration) are highly dependent on a healthy and functional ecosystem and therefore will be the last attribute to be achieved full recovery.

In conclusion, this theoretical exercise highlighted the considerable uncertainties, for most sub-attributes of the four the deep-sea case studies, on the likelihood to achieve a certain star level and on the time-scales that will be needed (Figure 6). It therefore also highlighted, that there is limited information to make informed predictions on the trajectories of recovery on deep-sea ecosystems. As described in previous sections the expected time scales to full recovery may span into time periods where local climate conditions may have changed, increasing the overall uncertainties on the recovery trajectories. Therefore, achieving a secure trajectory to full recovery seems uncertain for most deep-sea ecosystems; highlighting the need for developing an agenda for continued deep-sea research that could fill most knowledge gaps, reduce uncertainties and better inform how restoration in the deep-sea can be better implemented.

Table 16. Summary of generic standards for 1-5 star recovery levels extracted from McDonald et al. (2016) to deep-sea restoration cases studies.

Number of stars	**Summary of recovery outcome relative to the reference ecosystem**
1	Ongoing deterioration prevented. Substrates remediated (physically and chemically). Some level of native biota present; future recruitment niches not negated by biotic or abiotic characteristics. Future improvements for all attributes planned and future site management secured.
2	Threats from adjacent areas starting to be managed or mitigated. Site has a small subset of characteristic native species and low threat from undesirable species onsite. Improved connectivity arranged with area spatial management measures (e.g. network of marine protected areas).
3	Adjacent threats being managed or mitigated and very low threat from undesirable species onsite. A moderate subset of characteristic native species are established and some evidence of ecosystem functionality commencing. Improved connectivity in evidence.
4	A substantial subset of characteristic biota present (representing all species groupings), providing evidence of a developing community structure and commencement of ecosystem processes. Improved connectivity established and surrounding threats being managed or mitigated.
5	Establishment of a characteristic assemblage of biota to a point where structural and trophic complexity is likely to develop without further intervention. Appropriate cross boundary flows are enabled and commencing and high levels of resilience is likely with return of appropriate disturbance regimes. Long term management arrangements in place.

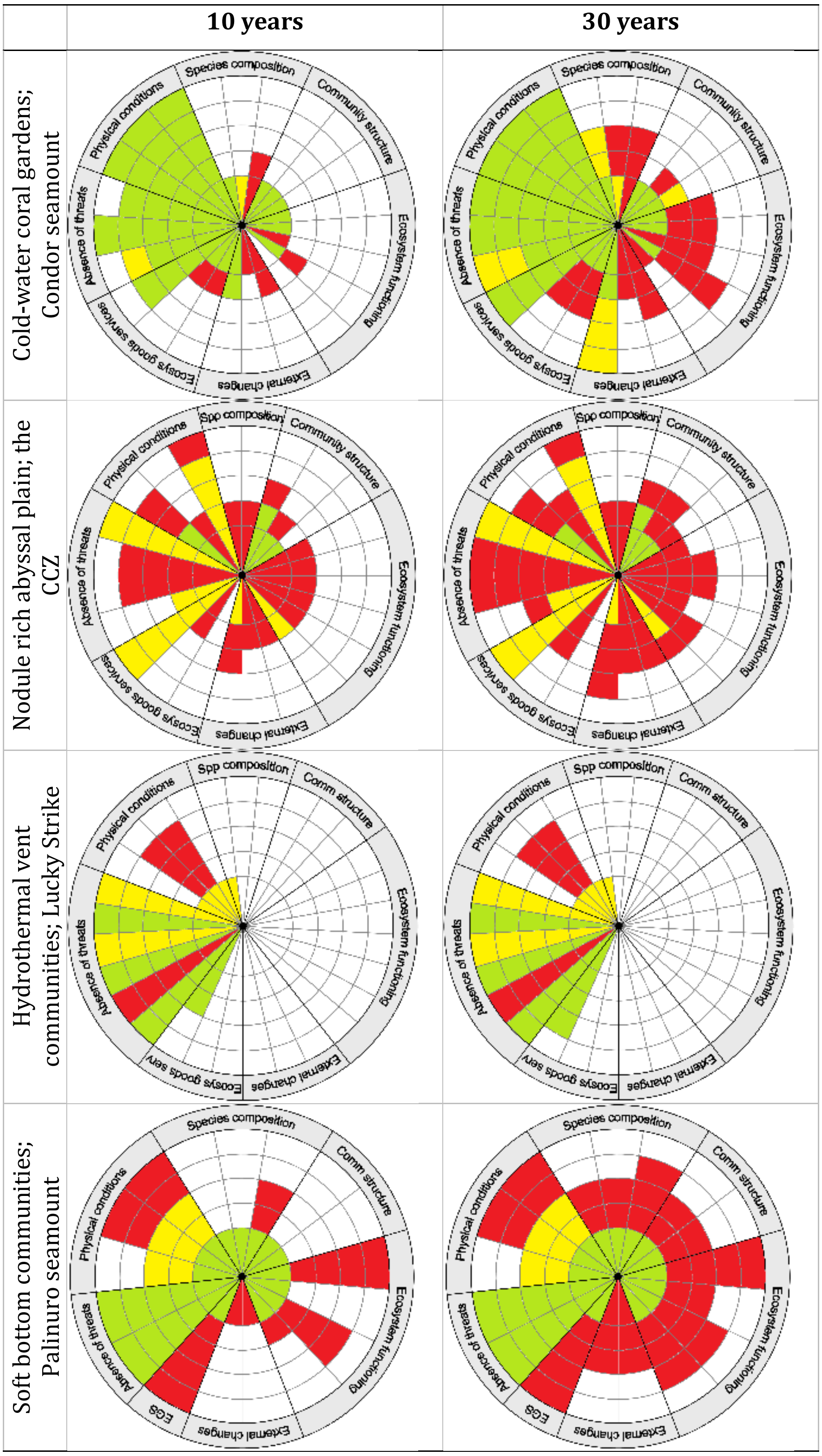

Figure 6. Theoretical evaluation of progress towards a self-organizing status using the recovery wheel approach for the different case studies. Progress is evaluated after 10, and 530 years from the start of the restoration project. See Table 16 for a summary of generic standards for 1–5 star recovery levels and Annex 1 and 2 for details on the scoring system.

4.5. KC 5. Successful restoration draws on all relevant knowledge

4.5.1. *Types of Knowledge*

Key concept 5 concerns the notion that successful restoration draws on all relevant knowledge (McDonald et al., 2016) with background knowledge underpinning all phases of restoration including planning implementation and monitoring. The types of knowledge required may be from a wide range of disciplines, but can be characterised into three groupings used by Van Dover et al. (2014) for characterisation of restoration decision parameters and include ecological, technological and socio-economic knowledge.

- Ecological knowledge should include the information on the natural state of the ecosystem or reference state – its biological, chemical and physical state, including biodiversity, ecosystem functions and processes. The ecological state of degradation is required to be known, as to what aspects have been degraded and what is the extent of that degradation. Finally ecological knowledge is required on the targets of restoration, those species that may be transplanted or seeded, their life histories, and features. This knowledge is particularly important to support the attributes and sub-attributes of Key Concept 2.

- Technological knowledge is needed in terms of the actual techniques for restoration, the know-how to source material for restoration, collect, and reproduce it, the jump to industrial scale restoration if scaling up techniques to wider areas and finally the techniques to monitor the recovery process. Technological knowledge will be relevant to the restoration actions planned and how these could help aid or speed up recovery and therefore could be important for Key Concepts 3 and 4.

- Socio-economic knowledge is required concerning the sector activities and their relevance in the area, the regulatory frameworks in place from local to international levels, the costs associated to proposed restoration from specific techniques to supporting long-term monitoring and the benefits that the restoration will provide through change in ecosystem goods and services, which may require valuations and cost-benefit analyses. It is this final area of benefits that might be the overall 'selling' point for the restoration activity proposed. Ecosystem goods and services represent essential attributes of the system and the recovery wheel visualization under KC 4, section 4.4.

As well as identifying the knowledge required for restoration it is also important to identify who has that knowledge (also relating to the stakeholders in KC 6, section 4.6), any gaps in particular, or specific areas of knowledge, as well as their importance that may direct or require separate initiatives to bridge or fill.

4.5.2. *Knowledge owners*

In recognising that background knowledge underpins all phases of restoration, McDonald et al. (2016) place emphasis on “local peoples” as prime holders of detailed local knowledge of sites and ecosystems. Whilst this may be true in many cases in terrestrial ecosystems, it is less relevant in deep-sea ecosystems. Here, local knowledge may be in the hands of the few, those with historical interacting activities, primarily fishing (Gass et al., 2005). Data has been collected to investigate fish communities and populations going back several thousand years from discarded bones on ancient sites (Barrett et al., 1999; Erlandson and Rick, 2010). Information on biodiversity may also be collected through the cultural artefacts depicting species and groups in ancient times (Eleftheriou, 2004). Traditional knowledge concerning ecological interactions (locations, linkages, biotic and abiotic factors) can be held and accumulated in the local peoples through several generations (Drew, 2005). This type of knowledge may become more detailed reliable and useful when within recent memory as part of part of Local Ecological Knowledge (Bender et al., 2014). There may also be supporting written material (diaries, logs, catch reporting) or annotated charts with data on species, sizes or localities. Although historical bycatch data of other non-target species such as corals might be limited, museum specimens can be found from original oceanographic expeditions or from fishermen’s catches (Braga-Henriques et al., 2013). Museum specimens or archive data such as photographs may also form part of the earliest scientific knowledge available on an ecosystem. Even though some ancient anecdotal information shows the existence of deep-sea knowledge from seafaring nations several thousand years ago (Oleson, 2000), effective exploration started from approximately 150 years ago with firstly deep-sea soundings and then targeted expeditions.

The knowledge of current ecosystems is also backed up in some cases by knowledge of historical ecosystems from the study of stratigraphic records e.g. coral mounds from the Pleistocene in the Atlantic (Roberts et al., 2006). Other scientific knowledge remains in the realms of the experts (government, institutional, academic), whether in archives, data collections, published observations/analyses and grey literature reports, from a wide range of disciplines with knowledge acquisition aided by various technological advances for example in sampling, underwater vehicles and imaging (Lonsdale, 1977; Van Dover 2014; Doughty et al., 2014). More recently, in the last few decades knowledge is being acquired and held beyond institutional frameworks, by independent environmental consultancy companies, NGOs (e.g. Pew Trust, OCEANA), regulators (e.g. International Seabed Authority) and Industry (e.g. specific deep-sea mining companies) (Lodge et al., 2014; Vanreusel et al., 2016).

4.5.3. *Case study knowledge owners*

Summaries of knowledge owners and key major knowledge gaps impeding progress in restoration for each case study are presented in Table 17-Table 20. This approach followed Van Dover et al. (2014) key parameters. Whilst each of the case studies is unique (location/environment, restoration target, degradation type), they all have several commonalities mostly in the lack of detailed knowledge of the ecosystems, whether it is colonisation, early life stages or connectivity, all impinging on the knowledge of how the recovery trajectory might proceed. Existing knowledge is primarily in the hands of the scientists, knowledge may only be in the hands of the locals (e.g. fishermen) in two case studies, the CWC and SB because of their relatively shallow depths and proximity to coastlines. In the CCZ case study knowledge may be spread beyond the scientists and held by industry that may also in the future develop and hold the technological knowledge. For the case studies involving interventions (abiotic or biotic), knowledge is still theoretical for all sites although for CWC there are existing shallow techniques that may allow technology transfer. While costs for all cases may be calculated for intervention work, scaling up costs, and the longer term costs including monitoring, are all unknown. There is also a common lack of knowledge in all cases on the lack of information on ecosystem benefits that might result from restoration and how these could be valued/monetised.

Table 17. Summary of knowledge owners and key knowledge gaps impeding progress in restoration of cold-water coral gardens in Condor seamount. Theme: follows the Van Dover et al. (2014) organisation of key parameters, Areas – Strands – Detail: subsets of Theme towards fine detail (case study), RP=restoration practitioners.

Theme	**Area**	**Strand**	**Case Study Detail**	**Owner**	**Major Gaps**
Ecological	Natural State	Reference system	Biological community, populations, size etc.	Scientists, NGO, fishermen, government	Spatial and temporal variability. Ecosystem functioning.
	State and Extent of degradation	Substrate, biology, chemistry	Specific substrate or structural damage and to what extent. Missing biotic elements, impaired function. Alteration in content or cycles.	Scientists	
	Targets of Restoration	Species	Life history traits e.g. growth, resilience, reproduction, connectivity.	Scientists	Connectivity
Technological	Restoration techniques	Actual techniques	Artificial substrates, Transplanting species	Scientists, engineers, RP	Test techniques used for shallow water corals (e.g. mid-water nurseries)
		Sourcing of biological material		Scientists, fishermen, aquarists	Early life stages of corals, reproductive modes and genetic variability
		Scaling up	Industrial solutions	Scientists, engineers, industry, RP	Lack of technological tools to scale up, e.g. innovative techniques, landers, ROVs, etc.
		Monitoring	Physical, biological biogeochemical, and ecological parameters	Scientists, engineers, consultants, industry, RP	Which indicators to monitor and the technological feasibility to do it; knowledge and legislation gaps
Socio-Economic	Activities	Sectors and relevance	Fisheries, mining, shipping, oil and gas, telecommunications	Scientists, NGOs, government, industry	Gaps in extent, frequency, mode of operations/impacts, gaps in assessments of socio-economic importance
	Regulatory	Relevant regulatory frameworks	Local, National, Regional and International authorities and organisations	Scientists, government, authorities, conventions, organisations	Gaps in addressing 'what is a significant impact' and in establishing thresholds
	Costs	Costs of restoration	Costs of specific techniques	Scientists, engineers, RP, government	Not all the cost items are known or fully assessed. Scaling-up issues.
	Benefits	Benefits of restoration	Change in ecosystem goods and services	Natural and social scientists, NGOs, economists, government, local and global society	Gaps in assessing and valuing changes in EGS and in the anticipated benefits from restoration (which benefits, which time frames etc.)

Table 18. Summary of knowledge owners and key knowledge gaps impeding progress in restoration of Abyssal plain communities in nodule rich areas in the CCZ. ISA: International Seabed Authority. RP=restoration practitioners.

Theme	Area	Strand	Case Study Detail	Owner	Major Gaps
Ecological	Natural State	Reference system	Biological community, populations, size etc.	Scientists, NGO, mining companies, ISA, sponsoring states, industry, consultants	Spatial and temporal variability, structure and function, species present.
	State and Extent of degradation	Substrate, biology, chemistry	Specific substrate or structural damage and to what extent. Missing elements, impaired function.	As above	The extent, impact and effects of plumes.
	Targets of Restoration	Species	Potential to focus on common or functionally important species, e.g. sponges.	Scientists, policy makers (selection of species of conservation interest)	Identification of appropriate species including their traits, e.g. growth, resilience, reproduction, connectivity.
		Nodules	What is the value of nodules for the ecosystem and how are they recolonised.	Scientists, managers	Settlement requirements (e.g. chemical conditions) of nodule dwellers and larvae.
Technological	Restoration techniques	Actual techniques	Artificial nodules (hard substrata)	Scientists, engineers, managers	How to make artificial nodules, and their chemical composition
		Scaling up	Industrial solutions	Scientists, engineers, industry, RP	Feasibility, deploying significant quantities of artificial substrata without causing impacts
		Monitoring	Physical, biological biogeochemical, and ecological parameters	Scientists, engineers, consultants, industry, RP	Which indicators to monitor and the technological feasibility to do it; knowledge and legislation gaps.
Socio-Economic	Activities	Sectors and relevance	Mining, pelagic fisheries, shipping, telecommunications	Scientists, NGOs, government, industry	Unknown importance and nature of all impacts and effects.
	Regulatory	Relevant regulatory frameworks	Regional and International authorities, organisations, conventions	Scientists, government, authorities, conventions, organisations	No exploitation regulation for mineral resources.
	Costs	Costs of restoration	Costs of specific techniques	Scientists, engineers, RP	Limited information on costs.
	Benefits	Benefits of restoration	Change in ecosystem goods and services	Natural and social scientists, NGOs, economists, government	No knowledge on benefits.

Table 19. Summary of knowledge owners and key knowledge gaps impeding progress in the hypothetical restoration of hydrothermal vent communities in the Lucky Strike field. RP=restoration practitioners.

Theme	Area	Strand	Case Study Detail	Owner	Major Gaps
Ecological	Natural State	Reference system	Biological community, populations, size etc.	Scientists	Succession, connectivity, species life history, ecosystem function.
	State and Extent of degradation	Substrate, biology, chemistry	Structural damage, removal of chimneys, biotic and abiotic elements, increased particulate load and induced chemistry changes.	Scientists	The extent, impact and effects of exploration and exploitation.
	Targets of Restoration	Chimneys	What is the value of chimneys for the ecosystem and how are they recolonised.	Scientists	Settlement requirements, microbial conditioning of the chimney (e.g. chemical conditions) and ecological succession.
Technological	Restoration techniques	Actual techniques	Artificial chimney frame (hard substrata)	Scientists, engineers,	How artificial frame could be made to deal with the harsh extreme environment that the end-member fluids create.
		Scaling up	Industrial solutions	Scientists, engineers, industry, policy makers, RP	Feasibility of deployments, how could significant quantities of artificial frames be deployed without causing additional impacts
		Monitoring	Physical, biological biogeochemical, and ecological parameters	Scientists, engineers, consultants, industry, RP	Which indicators to monitor and the technological feasibility to do it; knowledge and legislation gaps.
Socio-Economic	Activities	Sectors and relevance	Mining, pelagic fisheries, shipping	Scientists, government, industry	Unknown nature and importance of all impacts and the cumulative effects.
	Regulatory	Relevant regulatory frameworks	Local, national, regional, international authorities	Azores, Portugal, OSPAR, EU, IMO, UNCLOS, UNESCO, UNEP	No regulation for mineral resources exploration and exploitation.
	Costs	Costs of restoration	Costs of specific techniques	Scientists, engineers, RP	Limited information on costs.
	Benefits	Benefits of restoration	Change in ecosystem goods and services	Natural and social scientists, economists, government	No knowledge on benefits evaluation and quantification.

Table 20. Summary of knowledge owners and key knowledge gaps impeding progress in restoration of soft bottom communities on Palinuro seamount

Theme	Area	Strand	Case Study Detail	Owner	Major Gaps
Ecological	Natural State	Reference system	Community, populations, size, life history features, e.g. growth, resilience, reproduction, connectivity for certain soft bottom groups.	Scientists, NGO, Government (national monitoring)	Spatio-temporal variability
	State and Extent of degradation	Substrate, biology, chemistry	Specific substrate or structural damage and to what extent. Missing biotic elements. Impaired function.	Scientists, NGO	
	Targets of Restoration	Species	Not applicable		
Technological	Restoration techniques	Actual techniques	Natural regeneration: biology and chemistry	Scientists	Uncertainty in the monitoring programme
		Monitoring	Natural regeneration	Scientists	Funding to allow a monitoring plan to follow the spontaneous regeneration of benthic communities
Socio-Economic	Activities	Sectors and relevance	Fisheries, shipping	Scientists, government, industry	Gaps in extent, frequency, mode of operations/impacts, gaps in assessments of socio-economic importance
	Regulatory	Relevant regulatory frameworks	National, Regional authorities, conventions	Scientists, government, authorities, conventions, organisations	Gaps in addressing 'what is a significant impact' and in establishing thresholds
	Costs	Costs of restoration	Monitoring costs (personnel, ship time, laboratory costs, equipment)	Monitoring managers	Unknown: no evaluation yet
	Benefits	Benefits of restoration	Recovery in ecosystem goods and services	Natural and social scientists, NGOs, economists, government	Unknown: no evaluation yet

4.6. KC 6. Early, genuine and active engagement with all stakeholders underpins long-term restoration success

4.6.1. *Stakeholders*

A stakeholder is a person, organisation or group with an interest (professional or societal) or an influence on the marine environment or who is influenced directly or indirectly by activities and management decisions (Newton and Elliott, 2016). As part of the participatory process stakeholder involvement should begin in project planning stages (Portman et al., 2013). The engagement of stakeholders helps define ecological goals, objectives, and methods of implementation, with involvement throughout a restoration project to ensure social needs are also being met (McDonald et al., 2016). Their overall involvement can be regarded as consisting of four steps; integration, adaptation, participation, and collaboration (Carvalho and Fidélis, 2013). By involving stakeholders, a dialogue is opened to all involved parties, which allows an improved understanding of environmental and social issues and will lead to better decision making, increased trust and buy-in, therefore leading to better compliance and operation (Soma et al., 2018). Stakeholder forums have demonstrated both the necessity and desire among stakeholders for consensus regarding deep-sea ecosystem management (Collins et al., 2013)

4.6.2. *Stakeholder Type*

Stakeholders concerned with any deep-sea restoration action may not be obvious because of the remote and inaccessible nature of the deep-seabed and the lack of people living and working in a degraded area when compared to many terrestrial or even coastal ecosystems. However they can be wide-ranging if analysed. Stakeholders have been characterised into 6 groups by Newton and Elliott (2016) as extractors, inputters, beneficiaries, affectees, regulators and influencers, where an individual stakeholder may be represented in more than one, even opposing type, in a restoration action. Definitions of stakeholder type and example groups are given in Table 21.

In the deep sea where the public/society are the main beneficiaries of the goods and services created through resource exploitation, they are also the main affectees from loss of other goods and services from ecosystem degradation. However, their direct knowledge is limited, mostly gained through the last decades from movies, documentaries or popular articles, and they are for the most part separated from deep-sea exploitation issues. Some goods and services may be reasonably understandable such as supporting, regulating and provisioning services, whilst cultural services, the non-material benefits humans enjoy (Thurber et al., 2014), are much more difficult to understand and it is often NGOs and lobby groups that represent public/society stakeholders as guardians and ecosystem protectors.

4.6.3. *Stakeholder Engagement and Challenges*

It is essential to identify all categories and individual stakeholders that need to be involved in a restoration programme and to get them engaged in the programme which may be over a considerable timescale. Stakeholders may not have complete knowledge concerning their interest and could be assisted by other stakeholders and with the dissemination and exchange of new knowledge. Accessible knowledge helps to facilitate stakeholder engagement (Collins et al., 2013). Not all stakeholders are equal and it is important to understand their values, aspirations and alignment through objective criteria. A transparent, well-designed and executed stakeholder programme needs to balance the weight and view of the stakeholders to reduce conflict towards a positive project outcome (Ramos et al., 2015; Lester et al., 2017; Soma et al., 2018).

Table 21. Stakeholder typology, definition/role and deep-sea ecosystem restoration examples. Modified from Newton and Elliott (2016)

Type	Definition/Role	Typical deep-sea examples
Extractor	Those using space or taking biotic and abiotic resources from the marine systems	Mining companies, fishermen, oil and gas, telecommunications.
Inputter	Those discharging or placing materials or infrastructure into the marine system	Mining, fishing, oil and gas, shipping, telecommunications, scientists, military, waste dumpers.
Beneficiaries	Those benefiting from the ecosystem services and goods created by the system and delivered by the users, downstream in the value chain.	Society, industries
Affectees	Those affected by the uses and users (incur costs rather than acquire benefits), affected by the policy decisions, impacted by the decisions whether positive or negative.	Society, all other relevant stakeholders, NGOs, lobby groups
Regulators	Those giving permission to occupy space or extract/input materials, those with a controlling role on the users of the system. Hard and soft regulators	International organisations, statutory bodies, regional sea conventions, pan-national, national and local government
Influencers	Those influencing policy and use/users	Expert groups, NGOs, lobby groups, scientists, educators, public figures.

4.6.4. *Stakeholders relevant for the long term restoration success of the deep-sea case studies*

The stakeholders listed for the case studies (Table 22-Table 25) are reflected by the individual nature of the case studies. Studies closer to shore within national boundaries involve more local and national stakeholders and may have more public interest or local/national NGOs. With the offshore case studies, the public may be more represented by larger more world-wide NGOs and other influencers, whilst regulation may still be national within EEZs (hydrothermal vents) or governed by international authorities or conventions in ABNJs. For the CCZ cast study, the industry related stakeholders may become more important, particularly the financial backers, sponsoring states or industry associations. The spatial scale of the case study may have an impact on the number, diversity and importance of the involved stakeholders.

Table 22. Stakeholders relevant for the long term restoration success of cold-water coral gardens in Condor seamount.

Type	Stakeholder	Detail/Notes
Extractor	Local fisherman	Long-line fishermen
	Scientists	Sampling
Inputter	Scientists	Ballast weights, instruments/platforms
	Local fisherman	
	Communications	Potential cables
Beneficiaries	Society	Benefits from restored goods and services
	Scientists	Knowledge
	Local community and tourists	Cultural and heritage
Affectees	Society	Local community and tourists
Regulators	National Government	Portugal, Azores local government
	Pan-national governance	EU (Directives: CFP, HD, MSFD, Biodiversity Strategy)
	Regional Authorities	OSPAR
	International Authority	UNCLOS, IMO
Influencers	Scientists	Biologists, Fisheries-ichthyologists, Geologists
	NGOs	Greenpeace, OMA (local)
	International Authority	ISA
	Lobby groups	Local association

Table 23. Stakeholders relevant for the long term restoration success of abyssal plain communities in nodule rich areas in the CCZ.

Type	**Stakeholder**	**Detail/Notes**
Extractor	Mining	Nodule mining contractors
	Fishing	Pelagic (tuna) fisheries
	Scientists	Sampling
Inputter	Mining	Chemical contaminants (oils, flocculants), plumes
	Fishing	Lost fishing gears
	Shipping	Pollution, litter, organic enrichment (sewerage and waste food), waste water
	Communications	Cables
	Scientists	Ballast weights, structures, lost equipment
Beneficiaries	Society	Benefits from extracted products and restored goods and services
	Mining service companies	
	Mitigation banks	
Affectees	Society	
	Nations	Surrounding nations
	Potentially fishermen	
	Cable laying industry	
Regulators	International Authority	International Seabed Authority, IMO, International Cable Protection Committee, UNEP, UNESCO.
	Regional Authorities	Regional Fisheries Management Organisations
Influencers	Scientists	Different types of scientists, expert groups
	Financial backers	Financiers of mining companies, venture capitalists, pension funds, other industry
	Sponsoring states	Mining contractors are sponsored by a state, who may influence their activities
	Industry associations	International Marine Minerals Society
	States	Members of assembly/council of ISA, individual states
	NGOs	Pew Charitable Trusts, Greenpeace, WWF, Avaaz, Seas At Risk
	Society (Public)	Individuals e.g. media popular presenters
	Educators	Academic institutions, Schools

Table 24. Stakeholders relevant for the long term restoration success of hydrothermal vent communities in the Lucky Strike field.

Type	Stakeholder	Detail/Notes
Extractor	Mining	Mining sulphide deposits
	Fishing	Pelagic fishing
	Scientists	Sampling
	Biotechnology companies	Sampling
Inputter	Mining	Plumes, contaminants
	Fishing	Potential lost fishing gears
	Shipping	Litter, waste water
	Scientists	Ballast weights, structures, lost equipment,
Beneficiaries	Society	Benefits from extracted products and restored goods and services
	Industry	Benefits from testing equipment in harsh systems
	Mining service companies	
	Mitigation banks	
Affectees	Society	
	Nations	
Regulators	National Government	Portugal, Azores government
	Pan-national governance	EU (various directives)
	Regional Authorities	OSPAR, London Convention
	International Authority	UNCLOS, IMO, UNESCO, UNEP
Influencers	Scientists	Different types of scientists, expert groups
	Restoration practitioners	Industry?
	NGOs	Seas at Risk, Pongo, WWF, Deep-sea Alliance, Greenpeace, Pew Charitable Trusts
	Society (Public)	Individuals, DOSI, Kaplan
	Lobby groups	International Marine Mining Society
	International Authority	ISA, RFMO
	Educators	Academic institutions, Schools

Table 25. Stakeholders relevant for the long term restoration success of soft bottom communities on Palinuro seamount.

Type	Stakeholder	Detail/Notes
Extractor	Scientists	Sampling activities for monitoring
	Fishing	Potential
	Mining	Potential
Inputter	Mining	Potential: e.g. plumes
	Fishing	Potential: e.g. lost fishing gears
	Shipping	Potential: e.g. litter, waste water
	Scientists	Ballast weights, instruments/platforms
Beneficiaries	Society,	Benefits from extracted products and restored goods and services
	Scientists	Knowledge
	Local Community	Cultural and heritage, etc.
Affectees	Not applicable	Impact too low to cause changes to welfare
Regulators	National Government	Italy
	Pan-national governance	EU (various Directives and Strategies)
	Regional Authorities	Barcelona Convention
	International Authority	UNCLOS, IUCN
Influencers	Scientists	Different types of scientists, expert groups
	NGOs	Greenpeace, WWF
	Society (Public)	Individual politicians

5. Conclusions and key considerations

Deep-sea ecosystems are among the world's most pristine. Although mounting evidence shows anthropogenic change to deep-sea systems (e.g. Ramirez-Llodra et al., 2011; Jones et al., 2014), being far from land many areas have escaped some of the direct effects of human activities. This provides a number of benefits for setting the approach to restoration. Firstly, the reference ecosystem is clear and in many cases temporally stable (although it may not be well studied), which removes problems encountered in terrestrial environments of setting a specific reference ecosystem against a backdrop of frequent land-use associated ecosystem changes. Secondly, the restoration agenda is being set before major impacts have occurred, potentially enabling data collection and small-scale experimental trials to be established before major impacts are made. Restoration, however, also has many challenges in the deep sea (Van Dover et al., 2014) and we know of no examples of any active restoration activities in the deep sea other than small-scale experimental trials. As a result, appropriate restoration techniques have not been validated for deep-sea ecosystems.

The analysis presented in this document shows that the SER framework is generally applicable to deep-sea systems. However, developing restoration approaches for deep-sea systems is hampered by a lack of knowledge on the environments and particularly their responses to disturbance and trajectories for recovery. Very little of the standard knowledgebase drawn on repeatedly for terrestrial systems is developed, for example successional dynamics, growth rates, ecological organisation, critical species, effective controls on key organisms. In addition, working in the deep sea presents technical and economic challenges that will limit restoration practices. This ultimately results in low current capacity for restoration and its management. Restoration approaches also require deep-sea expert knowledge that is in the hands of the few. However, a huge opportunity exists for development of restoration technologies and approaches relevant to the deep sea.

The deep sea biome is the largest on Earth, and also one of the least studied. Although some specific sites have been studied extensively, most of deep seafloor and its associated ecosystems has never been surveyed or sampled biologically (Ramirez-Llodra et al., 2010). Although the ecosystems at some specific sites have been studied extensively and can provide robust data from which to develop restoration plans, for most deep-sea ecosystems, baseline studies pre-disturbance are lacking (Van Dover et al., 2014) challenging our capacity to plan restoration and assess restoration success.

Biodiversity is the foundation that promotes natural **ecosystem functions** and enables the range of **ecosystem services** provided by the deep ocean (Thurber et al., 2014). Most deep-sea ecosystems sustain very high biodiversity, but with low abundances and relatively high number of rare species (Ramirez-Llodra et al., 2010), challenging the recognition of indigenous versus non-indigenous species (Van Dover et al., 2014) and, thus, the assessment of restoration success. Although the full species composition and community structure of many deep-sea ecosystems is still not fully known, a growing array of scientific research is available to explain the patterns and source of biodiversity in the deep ocean. Understanding the processes that shape and sustain biodiversity are essential to ensure that restoration methods will facilitate these processes. The fundamental scientific principles that have emerged include 1) the positive relationship between substrate heterogeneity and biodiversity; 2) the high biodiversity sustained by biogenic habitats (e.g. cold-water corals); 3) the key role played by connectivity in sustaining populations and resilience, and thus maintaining biodiversity. **Population connectivity** is a key process in maintaining gene flow and facilitating recovery from impact. Understanding population connectivity (i.e. exchange of individuals) is essential to assess recovery potential in disturbed ecosystems, and it is particularly important for fragmented habitats such as hydrothermal vents or seamounts, where populations are spatially isolated. However, studies on the processes that drive deep-sea connectivity, including larval ecology and environmental factors, are still scarce, because quantifying dispersal through *in situ* sampling and experimental work is challenging in the deep sea. Modelling larval dispersal, through either biophysical or genetic models, has already gained momentum in shallow water systems, but this field of research is still in its infancy for deep-sea species (Hilário et al., 2015; Baco et al., 2016). **Ecological succession** and the drivers that shape it are almost non-existent for most deep-sea ecosystems. Additionally, regional differences can result in very different succession sequences, in structure and time, for similar ecosystems, challenging our capacity to extrapolate the limited available knowledge. For example, recovery of vent communities following a volcanic eruption has been estimated to 10 years on the East Pacific Rise (Shank et al., 1998) and Juan de Fuca Ridge (Marcus et al., 2009) and these observations have often been used as an indication of the time necessary for the recovery of vent ecosystems from seabed mining. However, these sites are located on fast-spreading ridges, with high volcanic activity, which differ significantly from the more stable, long-lived vents on slow-spreading mid-ocean ridges.

The technological and economical limitations of working in the deep sea continues to hinder our capacity to fully understand the composition, structure and functioning of many deep-sea ecosystems, and, together with the lack of pre-disturbance baseline data at local scales, increase uncertainty in potential expected results of restoration projects. Continued research and advances in restoration technology are imperative in order to develop deep-sea restoration.

Time scales for the recovery of deep-sea ecosystems, in the most part, will exceed timescales seen for some shallow water coastal or terrestrial restoration systems even though, for some of these, full recovery might take decades to centuries (Bayraktarov et al., 2016; Clewell and Aronson 2007). The extended deep-sea timescales are related to physical, chemical and biological features for specific ecosystems, in particular biological characteristics of deep-sea species, and input rates of externally sourced particulate organic matter (with the exception of hydrothermal vents). Whilst some common species may have relatively high connectivity (although decreasing with depth, Glover et al., 2016), with growth and maturation times on a similar timescale to shallow water species (Scheltema, 1987), this is not true particularly for some sessile structural, species that may be habitat defining, for example, cold water corals.

Some structural aspects of deep-sea ecosystems may be the specific target for exploitation including polymetallic nodules in the abyssal plain and sulphide deposits in hydrothermal structures. These features have geological sources with nodules formed over millennia and although hydrothermal chimneys may have relatively quick growth, their conditioning to allowing colonisation may be of decadal or centurial range. It is evident that not only will different ecosystems recover at different rates depending on their attributes, but that there may be a key bottleneck feature (e.g. structural), which is further complicated by lesser bottlenecks (e.g. colonisation) where different ecosystem attributes may recover at different rates having different dependencies.

Whilst time cannot be sped up in a recovery process, short-cuts can be made. Management should be able to identify key bottlenecks in order to jump over, e.g. the introduction of required structures or the transplantation of key species. The prolonged timescales of a deep-sea recovery may exceed multiple human generations, which needs to be well factored into any management plan (long-term commitments). With potentially no end-result in view, management actions need to achieve a start and maintain a recovery trajectory towards the ultimate target of a recovered ecosystem. With extreme time-scales, uncertainty is also much higher in the trajectories and management must be adaptive as potential interventions may be required at multiple points in time.

Ecological restoration in the deep-sea is at its infancy, which is an opportunity to explore questions and new research areas. There are considerable knowledge gaps, from ecological to technical, that need to be addressed before committing to large scale restoration. Firstly, a clear definition of scaling-up in the deep sea is needed. Using the terrestrial realm for guidance, the word '*landscape*' is often used, but for the marine world the term seascape is an emerging field. (Chazdon, 2017; Pittman, 2017). It would probably include the pelagic realm which has not yet been addressed in context of the ecological restoration. More research and experiments are needed to evaluate in depth the achievability of proposed restorative techniques in respect to different ecosystems (Cuvelier et al., subm.). Caution should be given to extrapolating small scale experiments to large scale restoration activates in order to avoid potential harm or pollution.

The socio-economic aspect of ecological restoration in the deep sea is crucial due to long time scales, management frameworks and high costs. More discussion is needed in the field of environmental ethics defining the current obligations for future generations in the context of deep sea and ecological restoration. Conclusively, there is a need for a more vivid engagement of the global society in the deep sea. This could contribute to the necessary *paradigm shift* from 'business as usual' to a society that accepts necessary lifestyle adjustments (Aronson et al., 2017; Woodworth, 2017).

As described previously in this report the slower pace of life in the deep sea presents a particular challenge to environmental managers and to societal expectations of how quickly deep-sea ecosystems will recover from mining and other impacts, such as from bottom trawling. The low inputs of food into deep-sea ecosystems, other than those based on chemosynthetic trophic pathways, has led to trade-offs in life processes and most notably in reproductive cycles. Most species are reliant on the rain of organic matter falling from the sea surface and derived from photosynthetic primary production. Reworking by different organisms in the water column means that only about 1% of the organic matter originally produced at the sea surface reaches depths of 4000m, placing severe restrictions on life in the deep sea. Seamounts denuded by bottom trawling have shown little to no recovery after 5 to 10 years (Williams, 2010) while large impacts can still be seen in abyssal sediments 26 years after experimental disturbance experiments (Jones et al., 2017). This means that environmental managers will have to develop long-term plans that should include restoration measures that speed up natural recolonisation rates, but even so might have to plan for periods of decades to detect measurable improvements in ecosystem health in some cases.

This means that restoration activities require a mechanism for long-term commitment that exceed typical business and political cycles (financing, managing, regulating, monitoring and enforcement). This issue is being considered by the International Seabed Authority (ISA) in the current discussions on the draft regulations for the exploitation of deep-sea minerals with regard to a 'Closure Plan' and how long contractors, sponsoring states and the ISA should be responsible for monitoring areas that have been impacted by mining after production ceases. It has been suggested at present in the draft regulations that a ten-year post closure environmental monitoring period is included, but this will require greater debate by the ISA Council. In stakeholder responses to a recent consultation by the ISA[1]

[1] https://www.isa.org.jm/files/documents/EN/Regs/2017/List-1.pdf

the United Kingdom Government noted that in UK waters monitoring in perpetuity is expected of industries leaving impact to the marine environment. However, there are a wide variety of views on the period a Closure Plan should cover.

In this respect the Society for Ecological Restoration (SER) guidance to set a target, with intermediate goals and short-term objectives would be a useful way forward, with contractors and their sponsoring states responsible for periodic monitoring over several decades (i.e. over longer periods than might be currently expected for impacts by industry in shallow water and coastal regions). This would require short-term objectives are set that can monitor progress over period of 5 to 30 years. The period over which monitoring should last could be dependent on certain ecosystem functioning and biodiversity thresholds being met.

All industries should be required to produce an Environmental Management and Monitoring Plan (EMMP) to prevent or avoid adverse impacts on the environment. The plan should identify ways to minimise or mitigate against adverse impacts, and where this is not completely possible steps to restore should be undertaken. It follows that the greater efforts taken in avoidance and minimisation will reduce the need for restoration, or at least the time required for reaching restoration thresholds and hence monitoring responsibilities and costs. The consideration of restoration measures, their longevity and their costs are therefore important in driving greater consideration of avoidance and minimisation of impacts. Over the timescale of any commercial activity this is likely to lead to lower costs and reduced impacts on the environment. They are two reasons why the use of the tiered “Mitigation Hierarchy” is integral to the International Finance Corporation’s Performance Standard 6.

While the costs of restoration in the deep sea may be high owing the need in many cases to use sophisticated technologies such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) (Van Dover et al., 2014) this should not preclude the consideration and implementation of restoration measures.

While major industries, such as in mining and offshore oil and gas, are being regulated effectively with the requirements for Environmental Impact Statements, Environmental Management and Monitoring Plans and Closure Plans, the issue of remediation and restoration following impacts remains a challenge for other industries, such as fishing, especially in international waters. A consistent approach to ocean management is required across all industries. Greater research is required on generic approaches to the restoration of deep-sea ecosystems which can then be modified to meet the needs of particular localities and ecosystems. This requires the greater, archiving and sharing of existing knowledge and the stimulation of large-scale and long-term experiments in the deep ocean to test theories and approaches for restoration.

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Website links:

MERCES link project website: http://www.merces-project.eu/

8. Annexes

Annex 1. McDonald's et al. (2016) generic 1-5 star recovery scale interpreted in the context of the six key ecosystem attributes used to measure progress towards a self-organizing status. This 5-star scale represents a cumulative gradient from very low to very high similarity to the reference ecosystem. The new attribute "Ecosystem Goods and Services" was added.

Attribute	1-star	2-star	3-star	4-star	5-star
Absence of threats	Further deterioration discontinued and site has tenure and management secured.	Threats from adjacent areas beginning to be managed or mitigated.	All adjacent threats managed or mitigated to a low extent.	All adjacent threats managed or mitigated to an intermediate extent.	All threats managed or mitigated to high extent.
Physical conditions	Gross physical and chemical problems remediated (e.g., contamination, erosion, compaction).	Substrate chemical and physical properties (e.g., pH, salinity) on track to stabilize within natural range.	Substrate stabilized within natural range and supporting growth of characteristic biota.	Substrate securely maintaining conditions suitable for ongoing growth and recruitment of characteristic biota.	Substrate exhibiting physical and chemical characteristics highly similar to that of the reference ecosystem with evidence they can indefinitely sustain species and processes.
Species composition	Colonising native species (e.g., ~2% of the species of reference ecosystem). No threat to regeneration niches or future successions.	Genetic diversity of stock arranged and a small subset of characteristic native species establishing (e.g., ~10% of reference). Low onsite threat from exotic invasive or undesirable species.	A subset of key native species (e.g., ~25% of reference) establishing over substantial proportions of the site. Very low onsite threat from undesirable species.	Substantial diversity of characteristic biota (e.g. ~60% of reference) present on the site and representing a wide diversity of species groups. No onsite threat from undesirable species.	High diversity of characteristic species (e.g., >80% of reference) across the site, with high similarity to the reference ecosystem; improved potential for colonization of more species over time.
Structural diversity	One or fewer strata present and no spatial patterning or trophic complexity relative to reference ecosystem.	More strata present but low spatial patterning and trophic complexity, relative to reference ecosystem.	Most strata present and some spatial patterning and trophic complexity relative to reference site.	All strata present. Spatial patterning evident and substantial trophic complexity developing, relative to the reference ecosystem.	All strata present and spatial patterning and trophic complexity high. Further complexity and spatial pattering able to self-organize to highly resemble reference ecosystem.
Ecosystem functionality	Substrates and hydrology are at a foundational stage only, capable of future development of functions similar to the reference.	Substrates and hydrology show increased potential for a wider range of functions including nutrient cycling, and provision of habitats/resources for other species.	Evidence of functions commencing - e.g., nutrient cycling, water filtration and provision of habitat resources for a range of species.	Substantial evidence of key functions and processes commencing including reproduction, dispersal and recruitment of species.	Considerable evidence of functions and processes on a secure trajectory towards reference and evidence of ecosystem resilience likely after reinstatement of appropriate disturbance regimes.
External exchanges	Potential for exchanges (e.g. of species, genes, water, fire) with	Connectivity for enhanced positive (and minimized negative) exchanges arranged	Connectivity increasing and exchanges between site and external environment	High level of connectivity with other natural areas established, observing control of pest species and undesirable disturbances.	Evidence that potential for external exchanges is highly similar to reference and long term integrated

Attribute	1-star	2-star	3-star	4-star	5-star
	surrounding landscape or aquatic environment identified.	through cooperation with stakeholders and configuration of site.	starting to be evident (e.g., more species, flows etc.).		management arrangements with broader landscape in place and operative.
Ecosystem Goods and Services	Ecosystem capable of providing some regulation services (microbial nutrient regeneration, nutrient cycling)	Ecosystem shows increased potential for a wider range of functions including nutrient cycling, carbon storage, and provision of habitats and resources (refuge, nursing, feeding) for other species.	Evidence of supporting and regulation services (nutrient cycling, carbon sequestration, primary and secondary production). Presence of species with commercial value (e.g. fish, crustaceans).	Substantial evidence of key supporting and regulation services (nutrient cycling, carbon sequestration in sediments and megafauna skeletons, primary and secondary production, waste absorption), and some provisioning services, such as sustainable resource extraction (fish, pharmaceuticals and biomaterials). Educational benefits, aesthetics and inspiration for the arts.	Ecosystem fully functional, capable of supporting biogeochemical cycles for climate regulation and waste absorption and detoxification, provisioning services contribute to economic growth and food security. Ecosystem able to provide economic benefits from scientific and educational knowledge, ocean literacy.

Annex 2.1. Likely time to achieve each star in the context of the six key ecosystem attributes used to measure progress towards a self-organizing status for cold-water gardens in Condor seamount. Uncertainty levels on the time to achieve each start and on the outcome are shown as low (green), medium (yellow) and high (red).

		Likely time (in years) to achieve each Star							
Attribute	**Sub-attribute**	**1-star**	**2-star**	**3-star**	**4-star**	**5-star**	**Overall uncertainty level**	**Climate change influence on sub-attributes**	**Comments**
Absence of threats	Cessation of fishing	1	1	5	10	15	L	No	
Absence of threats	Impacts due to scientific use (destructive sampling)	1	1	1	3	5	L	No	
Absence of threats	Pollution from shipping (litter, discharged sewerage, oil)	1	1	3	5	20	L	No	
Physical conditions	Physical condition of the substratum (seafloor integrity)	1	1	1	1	5	L	No	
Physical conditions	Chemical condition of the substrate (TOC, nutrients)	1	1	1	1	5	L	No	
Physical conditions	Water column conditions (turbidity, bottom currents)	1	1	1	1	5	L	H	
Species composition	Characteristic native coral species	3	15	15-100	100-300	300-1000	M	H	Uncertainties in recruitment time, rare species
Species composition	Characteristic native associated native macrofauna and megafauna	3	15	30	75	300-1000	H	M	Limited information on macrofauna associated with corals
Species composition	Characteristic native microorganisms	3	10	20	50	150-1000			Limited information on microorganisms associated with corals
Species composition	Absence of invasive and/or opportunistic species	1	10	30	100	150-1000	M	M	parasitic zoanthids as opportunistic; less chance of colonization with cessation of fishing
Structural diversity	Structural layers (3D complexity of coral colonies)	3	50	50-200	200	300-1000	M	H	Evidence of growth of transplanted corals after 1 year, limited knowledge on times required for growth and increased branching complexity
Structural diversity	All trophic levels	3	15	30	50	75	M	M	Some associated fauna after 1 year, limited knowledge on times required to reinstate other trophic layers
Structural diversity	Spatial heterogeneity of seafloor habitats	3	30	50	75	100	H	M	same spatial heterogeneity is there but maybe not all the species, no information on recruitment

Attribute	Sub-attribute	Likely time (in years) to achieve each Star: 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Ecosystem functionality	Secondary productivity (faunal biomass)	3	15	15-100	100-300	300-1000	M	H	Some growth on transplanted corals and surviving corals from impacts. Limited information on ecosystem functioning
Ecosystem functionality	Faunal and habitat interactions	3	15	30	75	300-1000	M	M	Limited information on ecosystem functioning
Ecosystem functionality	Reproduction, dispersal and recruitment of species	3	15-20	20-30	100	150-1000	M	M	Limited knowledge life history, specially larval stages and recruitment
Ecosystem functionality	Nutrient and carbon cycling	3	5-10	20	30-50	150-1000	M	H	Substrate not impacted by fishing, therefore some nutrient cycling earlier on, not sure on the trajectories of recovery for corals
Ecosystem functionality	Ecosystem resilience (resistance, recovery)	30	50	60	75	150-1000	L	H	No knowledge
External changes	Connectivity (gene flow, sink and sources populations)	3	10	30	100	150-1000	H	H	No knowledge
External changes	Species migration between habitats (e.g. crustaceans, fish)	3	30	50	75	100	H	H	Depends on spatial heterogeneity, check experimental demersal fisheries data
External changes	Cooperation with stakeholders	1	5	15	20	30	L	No	consultation of stakeholders would be conducted within MSP and would at least match the cessation of fishing
Ecosystem goods and services	Provisioning services (fish, biomaterials)	3	5-10	20	50-100	100-1000	M	M	Substrate not impacted by fishing, therefore some nutrient cycling earlier on, not sure on the trajectories of recovery for corals
Ecosystem goods and services	Supporting and regulating services (nutrient cycling, carbon sequestration)	3	5-10	20	50-100	100-1000	M	H	Substrate not impacted by fishing, therefore some nutrient cycling earlier on, not sure on the trajectories of recovery for corals
Ecosystem goods and services	Cultural services (aesthetic and existence values)	1	3	5	10	15	L	No	Until now good cooperation with local NGOs, we try to keep that on a good track

Annex 2.2. Likely time to achieve each star in the context of the six key ecosystem attributes used to measure progress towards a self-organizing status for nodule rich abyssal plain communities in the CCZ. Uncertainty levels on the time to achieve each start and on the outcome are shown as low (green), medium (yellow) and high (red).

Attribute	Sub-attribute	Likely time (in years or other when noticed) to achieve each Star					Overall uncertainty level	Climate change influence on sub-attributes	Comments
		1-star	2-star	3-star	4-star	5-star			
Absence of threats	Cessation of mining-related impacts	1	10	20	40	50-100	M	L	based on an estimated mine life of 50 years and the possibility of mining in adjacent blocks
Absence of threats	Alteration of food supply by fishing	1-3	3-5	5-10	10-20	20-30	L	L	based on the estimated time required for fishing policy to be changed to favour restoration actions
Absence of threats	Pollution from shipping (litter, discharged sewerage, oil)	1	2	3-10	10-20	20-30	M	H	based on the estimated time required for Pollution policy to be changed to favour restoration actions
Absence of threats	Physical disturbance from other industries (e.g. cable laying)	1	1	1	1	2	L	L	Based on the estimated length of time for other industries to respond to demands to reduce activities after cessation of deep-sea mining
Physical conditions	Physical condition of the substratum	0	0	5-100	10-500	> 500	H	H	We are assuming that the restoration activity replaces the nodules, which covers the short-term assessments
Physical conditions	Chemical condition of the substratum (metal and organic matter re-deposition at seafloor)	0-10	10-30	30-100	100-500	> 500	H	H	The chemical conditions are reliant on both metals and organic material being redepositied, both of which will take a long time (Mewes et al., 2014)
Physical conditions	Water column conditions (seawater mixing, nutrients, organic matter, metals)	0	5	5	5	5	H	H	Based on Ledwell et al. (2000)
Species composition	Characteristic native metazoan fauna (meio-, macro-, megafauna)	1-20	20-100	100-500	500+	> 1000	H	H	Our classification is based on the presence of lots of rare species, so sp. richness recovery is slow. Values are based on preliminary results of the DISCOL recovery assessments done in JPI-O and Jones et al. (2017)
Species composition	Characteristic native microorganisms	1-10	10-50	50-125	125-500	> 500	H	H	Based on preliminary results of JPI-O work at DISCOL
Structural diversity	Structural species / Bioengineers	0	0	0-50	100-500	> 500	H	H	The one and two star assessments are green because the substratum for structural species will be replaced by the restoration activities
Structural diversity	All trophic levels	0	0-100	20-100	100-500	> 500	H	H	The one star confidence is based on very little trophic complexity being required, which is effectively provided immediately

Attribute	Sub-attribute	Likely time (in years or other when noticed) to achieve each Star 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Structural diversity	Spatial heterogeneity of the seafloor	0	20-100	100-500	500+	1000s	H	H	The one star confidence is based on very little spatial heterogeneity being required, which is effectively provided immediately
Ecosystem functionality	Primary and secondary productivity (chemoautotrophy, faunal biomass)	0-10	10-30	30-100	100-500	> 500	H	H	Based on preliminary results of JPI-O work at DISCOL and ABYSSLINE
Ecosystem functionality	Faunal and habitat interactions	0-10	10-30	30-100	100-500	> 500	H	H	
Ecosystem functionality	Ecosystem resilience (resistance, recovery)	0-10	10-100	100-200	200-500	> 500	H	H	
Ecosystem functionality	Reproduction, dispersal and recruitment of native species	0-10	10-30	30-100	100-500	> 500	H	H	
Ecosystem functionality	Nutrient and carbon cycling	0-10	10-30	30-100	100-1000	> 1000	H	H	Based on Khripounoff et al. (2006)
External changes	Connectivity	0-10	10-30	30-100	100-500	> 500	H	H	Based preliminary results of MIDAS
External changes	Pelagic benthic coupling and bathyal to abyssal supply	0-10	10-30	30-100	100-500	> 500	H	H	
External changes	Species migration between habitats (e.g. crustaceans, fish)	1-20	20-100	100-500	500+	> 1000	H	H	
External changes	Cooperation with stakeholders	0	0-10	10-20	20-30	>30	H	L	This will start automatically as existing stakeholder networks exist
Ecosystem goods and services	Provisioning services (fish, biomaterials)	>1 million	>1 million	>1 million	>1 million	>1 million	L	Mium	based on mineral accretion rates
Ecosystem goods and services	Supporting and regulating services (nutrient cycling, carbon sequestration)	0-10	10-30	30-100	100-1000	> 1000	Mium	H	
Ecosystem goods and services	Cultural services (aesthetic and existence values)	0	0	0	0	0	H	H	cultural services will be based primarily on knowledge of reference ecosystem

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Annex 2.3. Likely time to achieve each star in the context of the six key ecosystem attributes used to measure progress towards a self-organizing status for hydrothermal vent communities in Lucky Strike. Uncertainty levels on the time to achieve each start and on the outcome are shown as low (green), medium (yellow) and high (red).

Attribute	Sub-attribute	Likely time (in years or other when noticed) to achieve each Star					Overall uncertainty level	Climate change influence on sub-attributes	Comments
		1-star	2-star	3-star	4-star	5-star			
Absence of threats	Cessation of removal of substrate by mining	1	1	1	1	1	L	No	As soon as the machinery stops, the removal of substrate stops, but it may take up to 1 year to decommission the site.
Absence of threats	Cessation of chemical contamination by mining	>1	>1	>1	>1	>1	H	No	Although no more contaminant is added, chemical reactions will continue and the threat is still there. But huge knowledge gap on contamination. As there will be a depression, the water with chemicals can be trapped, and due to the low current velocities in the deep-sea, the chemical contamination might stay trapped for several years
Absence of threats	Elimination of noise/light by mining machinery	1	1	1	1	1	L	No	As soon as the machinery stops, light and noise will stop, but it may take up to 1 year to decommission the site.
Absence of threats	Cessation of particle load by mining	1-2	1-2	1-2	1-2	1-2	M	No	Time for particles to settle
Absence of threats	Pollution from shipping (litter, discharged sewerage, oil)	1-2	1-2	1-2	1-2	1-2	M	No	Hard to control because can be the consequence of other activities
Physical conditions	Physical condition of substrate (Complex 3D topography)	>5				>1000	H	No	Age of the Endeavour chimneys showed that hydrothermal venting at the active High Rise, Sasquatch, and Main Endeavour fields began at least 850, 1450, and 2300 years ago. Endeavour is an intermediate spreading ridge and Lucky Strike is a slow, so we estimate that it might be even older (Jamieson et al, 2013). This way, the 5 stars recovery might take >1000y until full recovery (Jamieson et al., 2013)
Physical conditions	Physico-chemical conditions (major chemical processes from mining stabilised)	>5	>5	>5	>5	>5	H	M	The age of Lucky Strike is between a few thousand of year to few tens of thousands of years (Humphris et al., 2002; Barreyre et al., 2012).

Attribute	Sub-attribute	Likely time (in years or other when noticed) to achieve each Star 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Physical conditions	Water column conditions (turbidity, bottom currents)	>5	>5	>5	>5	>200	H	H	Bottom currents affected by the topography (Thurnherr et al., 2008). Until the same topography type (size, etc.) is attained, there will be no full recovery.
Physical conditions	Substratum mineralogy	>5	>100	>100	>100	>1000	H	No	Some features might never come back as they were generated in geological times. Petrographical studies showed that black smokers at Lucky Strike are mineralogical structures, with zonation, that reflect s complex growth history. The massive sulfides are thought to represent a very late stage of the maturation of active deposits and are composed largely of fragments of collapsed chimneys (Rouxel et al., 2004).
Species composition	Native microbial communities	>2	>100	>100	>100	>1000	H	L	A number of different sulphide structures and morphologies form depending on hydrothermal fluid composition, temperature, velocity, the degree of mixing with seawater and potentially biotic factors (Hannington et al., 1995; Tivey 1995).
Species composition	Bioengineering species (large symbiotrophic invertebrates)	>100	>100	>100	>100	>1000	H	H*	As we do not know if the mussels are the first pioneers or the latest (as at EPR and Lau Basin, the first star might take several decades to be attained)
Species composition	Native faunal communities (meio-, macro-, meagfauna)	>100	>100	>100	>100	>1000	H	H	
Structural diversity	Structural layers (3D biogenic structure)	>100	>100	>100	>100	>1000	H	H	
Structural diversity	All trophic layers	>100	>100	>100	>100	>1000	H	M	
Structural diversity	Spatial heterogeneity of seafloor habitats	>100	>100	>100	>100	>1000	H	No	
Ecosystem functionality	Primary and secondary productivity (including symbiotic association)	>100	>100	>100	>100	>1000	H	H	

Attribute	Sub-attribute	Likely time (in years or other when noticed) to achieve each Star 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Ecosystem functionality	Faunal and habitat interactions	>100	>100	>100	>100	>1000	H	M	
Ecosystem functionality	Ecosystem resilience (resistance, recovery)	>100	>100	>100	>100	>1000	H	H	
Ecosystem functionality	Decompositon, nutrient and metal cycling	>100	>100	>100	>100	>1000	H	L	
Ecosystem functionality	Reproduction, dispersal and recruitment of native species	>100	>100	>100	>100	>1000	H	H	
External changes	Connectivity (gene flow, sink and sources populations)	>100	>100	>100	>100	>1000	H	H	
External changes	Species migration between habitats	>100	>100	>100	>100	>1000	H	L	
External changes	Cooperation with stakeholders	1	1-2	10-20	20-30	50	L	No	
Ecosystem goods and services	Provisioning services (Minerals, molecules of interest, heat, hydrogen)	>1000	>1000	>1000	>1000	>10000	H	No	Age of the TAG hydrothermal vent deposits at the Mid-Atlantic Ridge is estimated to be 20,000 to 50,000 years (Lalou et al., 1995).
Ecosystem goods and services	Supporting and regulating services (carbon sequestration, detox, nutrient cycling, metal cycling, contribution to global ocean chemistry)	>100	>100	>100	>100	>1000	H	L	
Ecosystem goods and services	Cultural services (aesthetic and existence values)	1	1-2	10-20	20-30	50	L	No	We cannot interest people without the full system in place

* Mostly for larvae in terms of surface conditions-pH/ adults: change in currents linked to storm intensity-POC.

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Annex 2.4. Likely time to achieve each star in the context of the six key ecosystem attributes used to measure progress towards a self-organizing status for soft bottom communities in Palinuro Seamount. Uncertainty levels on the time to achieve each start and on the outcome are shown as low (green), medium (yellow) and high (red).

Attribute	Sub-attribute	Likely time (in years) to achieve each Star 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Absence of threats	Cessation of scientific drilling	<1	<1	<1	<1	1	L	No	Localized impacts
Absence of threats	Pollution from shipping (litter, discharged sewerage, oil)	<1	<1	<1	<1	1	L	No	Localized impacts
Physical conditions	Substrate physical (change in grain size, sediment structure, compaction)	1-7	7-10	10-15	15-50	50-100	M	No	Based on preliminary results,
Physical conditions	Substrate chemical (TOC, nutrients)	1-7	7-10	10-15	15-50	7-10	M	M	localized impacts
Physical conditions	Water chemo-physical (pore water, benthopelagic, water column)	<1	1	1	1	1	L	H	very localized impacts
Species composition	Characteristic native meiofauna	7-20	20-30	30-40	40-50	50-100	M	H	Based on preliminary results, uncertainty in recruitment, rare species, singletones
Species composition	Characteristic native macrofauna	7-20	20-30	30-40	50-100	100-200	M	H	Based on preliminary results, uncertainty in recruitment, rare species, low rate
Species composition	characteristic native microbiota	7-10	10-20	10-20	20-50	50-100	H	H	no data available
Structural diversity	All trophic levels	7-20	20-30	30-40	50-100	100-200	H	H	based on preliminary results
Structural diversity	Representativeness of habitats (e.g. covering depth gradients, different sub-habitats, spatial heterogeneity)	7-20	20-30	30-40	50-100	100-200	H	M	based on preliminary results
Ecosystem functionality	Nutrient cycling, organic carbon degradation rate	7-10	10-15	10-20	10-20	10-50	M	H	based on preliminary results
Ecosystem functionality	Secondary productivity (faunal biomass)	7-20	20-30	30-40	50-100	100-200	H	H	based on preliminary results
Ecosystem functionality	Reproduction, dispersal and recruitment of species	7-20	20-30	30-40	50-100	100-200	H	H	

Attribute	Sub-attribute	Likely time (in years) to achieve each Star 1-star	2-star	3-star	4-star	5-star	Overall uncertainty level	Climate change influence on sub-attributes	Comments
Ecosystem functionality	Faunal and habitat interactions	7-10	10-20	10-20	10-20	10-50	H	H	based on preliminary results
Ecosystem functionality	Ecosystem Resilience (resistance and recovery)	7-10	10-20	20-30	30-40	40-50	H	H	based on preliminary results
External changes	Connectivity (adults, juveniles, propagules, gene flows)	7-20	20-30	30-40	50-100	100-200	H	H	no data available
External changes	Species migration between habitats (e.g. crustaceans, fish)	7-20	20-30	30-40	50-100	100-200	H	H	no data available
Ecosystem goods and services	Provisioning services (fish, biomaterials)	7-10	10-155	15-20	10-20	10-50	M	H	
Ecosystem goods and services	Supporting and regulating (nutrient cycling)	7-10	10-155	15-20	10-20	10-50	M	H	based on preliminary results
Ecosystem goods and services	Cultural services (aesthetic and existence values)	1	3	5	10	15	L	No	