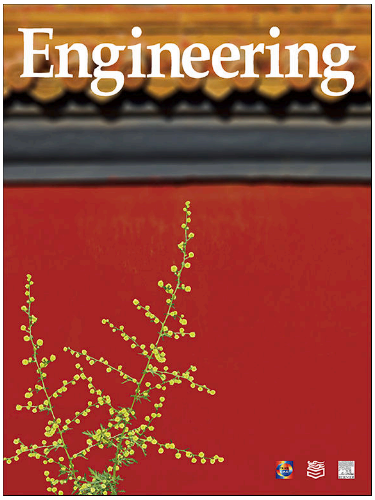

Review

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Research

Ocean Engineering—Article

New Technologies for Monitoring and Upscaling Marine Ecosystem Restoration in Deep-Sea Environments

Jacopo Aguzzi [a,b,*], Thomsen Laurenz [c], Sascha Flögel [d], Nathan J. Robinson [a,e], Giacomo Picardi [a], Damianos Chatzievangelou [a], Nixon Bahamon [a], Sergio Stefanni [b], Jordi Grinyó [f], Emanuela Fanelli [g], Cinzia Corinaldesi [g], Joaquin Del Rio Fernandez [h], Marcello Calisti [i], Furu Mienis [f], Elias Chatzidouros [l], Corrado Costa [m], Simona Violino [m], Michael Tangherlini [2], Roberto Danovaro [g,*]

[a] Instituto de Ciencias del Mar (ICM-CSIC), Barcelona 08003, Spain

[b] Stazione Zoologica Anton Dohrn, Naples 80121, Italy

[c] University of Gothenburg, Göteborg 405 30, Sweden

[d] GEOMAR Helmholtz Centre for Ocean Research, Kiel 24148, Germany

[e] Fundación Oceanogràfic de la Comunitat Valenciana, Valencia 46013, Spain

[f] Royal Netherlands Institute for Sea Research (NIOZ), Den Burg Texel 1790 AB, The Netherlands

[g] Polytechnic University of Marche (UNIVPM), Ancona 60131, Italy

[h] SARTI-MAR of the Universitat Politecnica de Catalunya (UPC), Vilanova i la Geltrú 08800, Spain

[i] Lincoln Institute for Agri-food Technology, University of Lincoln, Lincoln LN2 2LG, UK

[l] Engitec Systems International Limited, Limassol 3083, Cyprus

[m] Consiglio per la Ricerca in Agricoltura e L'analisi Dell'economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Monterotondo 00015, Italy

* Corresponding authors.

E-mail address: jaguzzi@icm.csic.es (J. Aguzzi), r.danovaro@univpm.it (R. Danovaro)

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ABSTRACT

The United Nations (UN)'s call for a decade of "ecosystem restoration" was prompted by the need to address the extensive impact of anthropogenic activities on natural ecosystems. Marine ecosystem restoration is increasingly necessary due to increasing habitat loss in deep waters (> 200 m depth). At these depths, which are far beyond those accessible by divers, only established and emerging robotic platforms such as remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), landers, and crawlers can operate through manipulators and their multiparametric sensor technologies (e.g., optoacoustic imaging, omics, and environmental probes). The use of advanced technologies for deep-sea ecosystem restoration can provide: ① high-resolution three-dimensional (3D) imaging and acoustic mapping of substrates and key taxa; ② physical manipulation of substrates and key taxa; ③ real-time supervision of remote operations and long-term ecological monitoring; and ④ the potential to work autonomously. Here, we describe how robotic platforms with *in situ* manipulation capabilities and payloads of innovative sensors could autonomously conduct active restoration and monitoring across large spatial scales. We expect that these devices will be particularly useful in deep-sea habitats, such as ① reef-building cold-water corals, ② soft-bottom bamboo corals, and ③ soft-bottom fishery resources that have already been damaged by offshore industries (i.e., fishing and oil/gas).

1. Introduction

Anthropogenic activities are impacting marine ecosystems on a global scale, leading to losses in biodiversity [1,2]. These effects are so widespread that even the most remote deep-sea ecosystems are now affected by industrial exploitation via fishing, oil/gas exploration and extraction, bioprospecting, and pollution, among others [3,4]. This has led to the progressive loss of key and vulnerable ecosystems along continental margins, such as cold-water coral reefs, coral gardens, sponge grounds, and soft-bottom grounds [5,6]. In fact, soft-bottom deep-sea habitats are arguably the most extensively impacted habitats worldwide [7,8]. Additional future threats to deep-sea habitats include climate change [9,10] and mineral extractions (e.g., the mining of polymetallic nodules or massive sulfide deposits from hydrothermal vent areas) down to abyssal depths [11,12].

These anthropogenic stressors also cause severe consequences to ecosystem functioning [13,14]. As the deep sea is the largest ecosystem on this planet [15], degradation of the deep sea could have extensive ecological impacts—including effects on carbon dioxide (CO_2) storage [16]—that will reverberate on a global scale. Since the efficient functioning of deep-sea ecosystems depends on both high levels of biodiversity [17] and the presence of habitat-forming, bioengineering species [18], the continuing loss of such ecosystems is leading to an unprecedented erosion of the deep-sea natural capital and related ecosystem services [19]. Healthy ecosystems provide food and food security, clean water, carbon sinks, and protection against the natural hazards caused by climate change. Indeed, they are essential for our long-term survival, well-being, prosperity, and security and are the basis of economic and societal resilience [20].

1.1. The need for ecological restoration in the deep sea

Biodiversity loss and the degradation of ecosystems continue at an alarming rate and are transforming European seas, resulting in harm to people's welfare, the economy, and the climate [21]. This has been widely documented, notably in reports by the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the Biodiversity Aichi Targets progress report, and *The Economics of Biodiversity: The Dasgupta Review*.

Strong conservation and management actions were lacking until recently, largely due to several failures of governance and implementation [22]. Many environmental policies have been designed to address the emerging issues, but coordinated cross-sectoral planning remains poor—primarily because of the complexity of more holistic approaches (given our limited baseline knowledge) and the diversity of policy approaches, society contexts, and stakeholders [23,24]. However, there are upcoming efforts to address these issues moving forward (i.e., the UN High-Seas BBNJ Treaty 2023 "on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction").

The United Nations launched a call for "ecosystem restoration" for the decade 2021–2030 [25] to reverse the declining trends for all ecosystems. The restoration of deep-sea habitats is a pressing need from an ecological, societal, and operational point of view [26], particularly in cases where a habitat is either rare or provides a specific service, and it is demonstrated that restoration accelerates or qualitatively betters natural recovery in a long-term, financially sustainable way. Such restoration requires policies and tools for remediating environmental degradation, along with societal actions to improve ecosystem resilience, as well as innovative management strategies and the use of technology-facilitated interventions to restore keystone and vulnerable species to pre-impact levels.

1.2. The EU legal framework for marine restoration

The European Union (EU) Biodiversity Strategy for 2030 sets out targets to further protect nature in the EU. Nevertheless, it also states that reversing biodiversity loss will require greater efforts in protected areas and beyond, at all depths of the continental margin, including the deep sea. Therefore, the European Commission has proposed legally binding targets to restore degraded EU ecosystems, with particular emphasis on the ecosystems of the deep sea, that have the most potential to remove and store carbon and to prevent and reduce the impact of natural hazards. In addition, the Mission Board on Healthy Oceans, Seas, and Coastal and Inland Waters has proposed Mission Starfish 2030: Restore our Ocean and Waters by 2030, which has five overarching objectives: ① filling the knowledge gap between humanity and the ocean, ② regenerating marine and freshwater ecosystems, ③ zero pollution, ④ decarbonizing our ocean by CO_2 removal, and ⑤ revamping governance. Mission Starfish 2030 emphasizes that weak international governance has currently led to inconsistencies, overlaps, and gaps between jurisdictions. As such, the "need to consider governance issues in the mission of restoring degraded marine habitats" is evident.

The European Green Deal acknowledges that a healthy ocean plays a key role in the fight against global warming and ecological collapse, stating: "lasting solutions to climate change require greater attention to nature-based solutions, including healthy and resilient seas and oceans." Among the concrete actions/targets proposed, the Green Deal includes: ① fisheries (i.e., the Common Fisheries Policy) to reduce the adverse impacts that fishing can have on ecosystems; ② marine biodiversity, by designating additional properly managed Marine Protected Areas according to the Biodiversity Strategy; ③ Blue Economy, by planning to boost aquaculture and offshore renewable energy; ④ shipping, by extending European emissions trading to the maritime sector; and ⑤ a circular economy against microplastics. Since the year 2008, the Marine Strategy Framework Directive [27] and the Maritime Spatial Planning Directive [28] have been promoted to assess and improve the environmental status of European marine ecosystems and to plan the sustainable use of marine resources. The Directives also foresee that ecosystems that have not yet reached a good environmental status (GES), will require recovery/restoration actions with assessments of their operative reliability, environmental sustainability, economical effectiveness, and social acceptance.

1.3. Technological requirements for marine restoration

To have a meaningful impact worldwide, current protocols and technologies for marine ecosystem restoration must be effective over larger spatial scales [29]. Typically, restoration practices adopt a slow, "passive" approach based on the removal of stressors and allowing the system to recover naturally (e.g., in Marine Protected Areas). Therefore, many studies have mentioned the necessity for more "active" approaches involving the reintroduction of key species (e.g., ecosystem engineers such as seagrasses, corals, and sponges) or substrates for colonization [4–30,31].

However, most active restoration efforts in marine habitats are currently limited to depths < 60 m, which are accessible by self-contained underwater breathing apparatus (SCUBA) divers [32]. As 99% of marine habitats exceed these depths, and as active restoration in the deep sea is economically and operationally challenging, technological solutions are urgently required, especially for the deep sea (i.e., at depths > 200 m), based on geomorphology, physical oceanography, and the light penetration supporting photosynthesis [33,34]. First, deep-sea restoration's reliance on vessels increases its costs compared with those of shallow habitats [35,36]. The operational costs of an 85-m-long research vessel (RV), such as the Spanish fleet's "Sarmiento de Gamboa," working round the clock with a crew of 25 and equipped with one ROV (model: LIROPUS-2000), CTD (referring to a set of instruments measuring conductivity, temperature, and depth), and multibeam mapping devices currently costs 35 000 EUR (approx. 39 000 USD, 275 000 CNY) per day. For an ordinary 12-day data-collection cruise in deep-sea continental margin areas, this translates to 420 000 EUR (approx. 465 000 USD, CNY 3 297 000). Second, deep-sea areas will require the use of novel technologies that can enable interventions over broad enough spatial scales similar to coastal zones [37,38] and can measure success through long-term, post-intervention, ecological monitoring (as well as dynamically adapt efforts to unpredicted environmental events; see below).

We propose that a strategic increase in deep-sea active restoration capacity should be based on three interdependent and consecutive steps:

(2) Active restoration. The next step involves reintroducing bioengineering sessile and motile umbrella species to accelerate the demographic recovery of other targeted taxa (e.g., stocks biomass enhancement) and overall biodiversity (e.g., favoring the reconstruction of ecosystem functions based on predator-prey relationships). This will be achieved by deploying bioengineering species in the sites identified in Step 1, prioritizing a surface delimited by an *in situ* network of fixed and mobile sensor platforms.

(3) Feedback monitoring. The third step involves measuring the progress of interventions and post-intervention ecological results and planning eventual adjustments. This will require long-term multiparametric data collection to quantify ecosystem recovery, with the possibility of adaptive interventions in response to stochastic environmental events (e.g., landslides, cascading, and turbidites).

Achieving these three steps would require the development of new (or the adaptation of already available) technologies (i.e., marine robotics) [39] equipped with manipulators [40] and various sensors [41]. Furthermore, these technologies must be able to function in an at least partially autonomous manner [42,43], which will lower the costs associated with operating vessels—a major constraint on the duration and frequency of cruises [30–44].

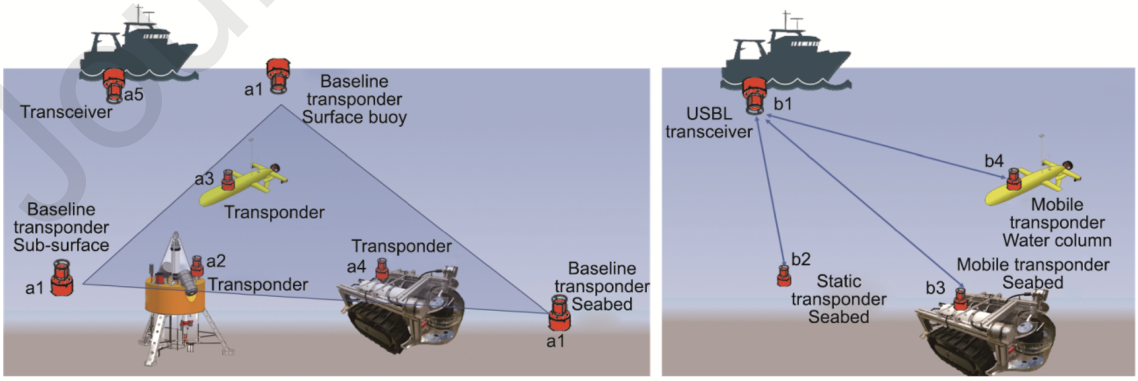
1.4. Marine restoration in relation to precision agriculture developments

Marine restoration could benefit from recent innovation in robotics, as the latter field is moving from the structured environments of factories to natural and unstructured environments [45]. In this manner, active marine restoration will likely follow a similar path to agricultural robotics. Below, we describe the parallels of technological development in robotics within precision agriculture and marine restoration. We focus on the coordination capability of platforms that perform cooperative missions in which sessile organisms' manipulation for transference is similar to agricultural monoculture approaches. Nevertheless, we are aware that the restoration of ecosystem function requires the reintroduction of a wider pool of bioengineering sessile species to better promote the recovery of overall biodiversity, which would make it more similar to silviculture than to monoculture. In this framework, for example, the specifications of robotic manipulators may differ in suitability among species, elevating the complexity of the envisaged technological development (see Section 3).

Examples of technology-assisted plant seeding on land support the idea that the large-scale robotic restoration of marine habitats could be feasible on the seafloor, achieving similar accuracies to the more than 90% precision planting expected on land [46,47]. Internet-operated vehicles (IOVs) such as crawlers [48] are the best current equivalents for agricultural robots, and their high-precision positioning and manipulation capabilities (see Section 3) could be used to undertake marine restoration operations similarly to how they are used in land restoration [49]. Such operations would include simulating functionalities similar to those of agricultural robots (AgBots) at various stages of the crop cycle, from planting and weeding [50] to harvesting [51] and sorting [52]. Crawlers may alter the substrate, depending on geomorphological conditions, and its composition (e.g., eroding and resuspending silts and clays in deep-sea muddy seafloors) [53]. A strategy to mitigate operational impact could consist of using crawlers as a pre-seeding ploughing exercise in certain terrains based on transferring items to be implanted from trays on the back of the vehicle with robotic arms. Next, it would be preferable to have the crawlers move along constant transect lines at a very slow speed (i.e., a stepping-stone progression mode, in which large pauses serve to reduce sediment resuspension) for post-intervention monitoring. In any case, the design of the crawlers' caterpillar wheels should reflect the need to minimize their footprint.

Autonomous operations in marine restoration would require the precise definition of the reciprocal positioning of mobile platforms in real time. In marine networks, this can be achieved through acoustic communication (Section 2). In precision agriculture, reciprocal positioning is measured via real-time kinematic (RTK) positioning using a high-precision global navigation satellite system (GNSS), radio beacons (into closed environments), and visual simultaneous localization and mapping (vSLAM) [54,55]. Of these technologies, only vSLAM is relevant in a marine context, as it uses cameras and computer vision algorithms to create a map of an area in order to determine the position of platforms in real time [54].

In marine operations, area reckoning relies on seabed mapping (by means of acoustics and photogrammetry; see Section 4) via hoovering platforms such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) (Fig. 1). These platforms require underwater positioning, based on long base line (LBL) or ultra-short base line (USBL) acoustics, as the most used approaches for the geo-localization of the robots in relation to the vessels operating in the surveyed areas [42].



(a) (b)

Fig. 1. LBL and USBL communication procedures for the spatiotemporal coordination of benthic and pelagic platforms operating in restoration and monitoring networks. (a) The LBL system uses three or more spread baseline transponders (a1) in the area, which allow for underwater devices such as (a2) static, or (a3) AUVs or (a4) moving seabed stations equipped with other transponders, to be geo-localized, taking the baseline transponders' position as a reference. Also, boats can include a Global Navigation Satellite System (GNSS) receiver to calibrate the underwater baseline

transponders (where the GNSS signal is not available; a5). The transceiver will accurately determine the position of the baseline transponders in real-world coordinates. (b) The USBL system uses (b1) a USBL transceiver, which integrates the baseline transponders within a very small volume (cm^3). Underwater devices (b2: landers; b3: seabed crawlers; b4: AUVs) are geo-localized using the USBL position as a reference. In addition, transponders and transceivers permit underwater communications between the devices and the vessel, for the exchange of position information.

Another relevant aspect of precision agriculture that could be adapted for marine restoration is proximal sensing for monitoring. Field-based sensors in contact with (or within a few meters of) soil, plants, crops, and so forth are deployed for temporally intensive and long-lasting environmental measurements [56]. When deployed into networks, sensors can facilitate the collection of vast amounts of multiparametric data with a consequent spatiotemporal scaling of proximal sensing [57]. A similar approach should be pursued in the ecological monitoring of marine restoration (Section 4), based on long-lasting deployments of biological and environmental sensors into intervention areas.

Here, we describe how a combination of established and innovative marine robotic platforms with different levels of vessel autonomy and adaptable sensor arrays can perform *in situ* autonomous or semi-autonomous restoration interventions, spatial upscaling, and monitoring in deep-sea habitats. Accordingly, we detail three potential case studies for such a combination of platforms, where different *in situ* manipulative actions are envisaged for sessile and motile fauna in iconic deep-sea environments.

2. Technological requirements for maintaining and upscaling marine restoration

A variety of fixed and mobile platforms are already in use for restoration interventions and/or monitoring in specific and focused areas of interest (Table 1 [31,58–86]). These include both autonomous robots with (remotely) controlled missions and vessel-assisted and tele-operated platforms. Alternatively, larger sites can be monitored using passively drifting buoys or mobile marine megafauna equipped with bio-logging devices that may move transiently through areas of interest [60]. With the capacity to collect data over what are often larger spatial scales than autonomous or remotely controlled robots, passively drifting or animal-borne technologies could represent interesting solutions for understanding the ecological results of restoration via a geographical upscaling of monitoring (even though a detailed spatial coverage is difficult).

Table 1
Fixed and mobile robotic platforms (see Fig. 1 for schematic features), autonomous and partially autonomous (i.e., vessel-assisted, tele-operated), with potential for use in restoration interventions and monitoring, including a summary of their operational spatiotemporal ranges and degrees of mission autonomy.

Platform	Operational environment	Range of action	Contribution to active restoration	Monitoring tasks	Vessel-relationship	Autonomy duration	Source
ROVs	Pelagic/benthic	Mobile (kilometers)	Collection, transplanting and post-reintroduction manipulation (e.g., lifting, reorienting, displacing) of organisms and colonizing substrates	Multi-parametric data collection, video-images	At operations (controlled by vessel pilots)	None	[31]
Towed sledges (tethered video systems)	Benthic	Mobile (kilometers)	None	Multi-parametric data collection, video-images	At operations (controlled by vessel pilots)	None	[58–61]
Gliding AUVs	Pelagic/benthic	Mobile (kilometers)	Precise *in situ* dropping of organisms	Multi-parametric data collection, video-images	Limited (deployment can also be from shore)	Months	[62,63]
Unmanned surface vehicles	Surface	Mobile (kilometers)	None	AUV powering and data collection transfer	Limited (deployment can also be from shore)	Months	[64]

(USVs)							
Moored profilers (including yo-yo buoys)	Pelagic/benthic	Fixed	None	Multi-parametric data collection, video-images	At deployment and maintenance (sending data via satellite)	Months	[65]
Anchored surface buoys	Surface	Fixed	None	Meteorological and oceanographic data collection	At deployment and maintenance (sending data via satellite)	Years	[66]
Passive drifting buoys	Surface/pelagic	Mobile (passive)	None	Multi-parametric data collection	At deployment and retrieval (requires research or opportunity vessels)	Days/years	[67,68]
Cabled observatories	Benthic	Fixed	None	Multi-parametric data collection, video-images	At deployment and maintenance (connected to shore for powering and data transfer)	Years	[69,70]
Autonomous landers	Benthic	Fixed (but re-deployable)	Deposition of organisms kept in trays with individual cells	Multi-parametric data collection, video-images, fluxes (sediment trap)	At deployment and retrieval (requiring research vessel-R/V or opportunity vessels)	Months	[71,72]
Benthic chambers (including those with micro-profilers; on landers)	Benthic	Fixed (but re-deployable)	None	Metabolism, sediment fluxes, nutrient and carbon fluxes	At deployment and retrieval (requiring R/V or opportunity vessels)	Hours to days (or longer terms when deployed on landers)	[73,74]
Crawlers	Benthic	Mobile (hundreds of meters to kilometers)	Active planting/seeding of organisms, plus collection, transplanting, and post-reintroduction manipulation (e.g., lifting, reorienting, displacing) of organisms and colonizing substrates	Multi-parametric data collection, video-images	At deployment and maintenance (docked to observatories or operating with surface wireless fidelity (Wi-Fi) buoys)	Years	[75,76]
Rovers	Benthic	Mobile (hundreds of meters)	None	Multi-parametric data collection, video-images	At deployment and retrieval (requiring R/V or opportunity vessels to land the garage)	Days to months	[77,78]
Autonomous underwater helicopters (AUH)	Pelagic/benthic	Mobile (hundreds of meters)	None	Multi-parametric data collection, video-images	At deployment and maintenance (could be docked to observatories)	Months	[79,80]
Underwater logged robots (URLs)	Benthic	Mobile (hundreds of meters)	Active planting/seeding of organisms, plus collection, transplanting, and post-reintroduction manipulation (e.g., lifting, reorienting, displacing) of organisms and colonizing	Multi-parametric data collection, video-images	At operations (still at prototype level)	Hours to days	[81,82]

			substrates				
Autonomous bio-logger platforms for large megafauna	Depends on species	Mobile (depends on species)	None	Multi-parametric data collection	At deployment	Days to months	[83]
Soft robotic grippers	Depends on host vehicle	Depends on host vehicle	Collection and manipulation of fragile specimens	None	Depends on host vehicle	Hours to days	[82–85]
Soft robotic bioinspired vehicles	Pelagic/benthic	Mobile (depends on design)	None	Multi-parametric data collection, video-images	At deployment and retrieval	Hours to days	[59,86]

Autonomous restoration procedures, their monitoring, and the spatial scaling of both operations could be achieved via the deployment of a group of fixed and mobile autonomous platforms. Such networks could be assembled in multiple ways, according to the principles of "modularity" (i.e., different types and numbers of platforms) and "spatial scalability" (i.e., reciprocal positioning and distance, and defining polygonal intervention areas of variable size). Both aspects would grant the network deployment adaptability to different geomorphological contexts. The following avenues of research are therefore being explored:

(1) The use of acoustic communication devices (i.e., modems) between various platforms to enable reciprocal positioning via the simultaneous localization and mapping (SLAM) of mobile (e.g., crawler) and fixed (i.e., lander) platforms [87], to allow the precise geo-referencing of sentinel restoration sites (i.e., those to be revisited);

(2) The development of edge-computing navigation functionalities of autonomous mobile platforms to enable the on-board, real-time data processing of navigation data in order to extract relevant information making it possible to adaptively adjust transects' trajectories (e.g., obstacle avoidance, via three-dimensional (3D) laser scanning or optoacoustic vision) [48,88,89];

(3) The development of robotic arms with species-compliant manipulators to enable direct restoration interventions by means of mobile platforms (Section 3);

(4) The development of fuel cells for the recharging of autonomous platforms, ensuring the long-lasting operational autonomy of mobile and fixed platforms [90,91];

(5) The development of remote data transmission capability from the seabed to the ocean surface via central lander stations that download data from mobile platforms and transmit it through moored projections (see below); these methods could include satellite transmitting pop-up buoys that are released by the landers [92];

(6) The development of receiving autonomous surface vehicles (ASV) [64] that bear submerged acoustic modems for water-column data recollection from central-lander stations with satellite constellations such as ARGOS or Iridium, or cellular network connection capacity (depending on the distance to shore).

Data transmission from most platforms would need to occur via distant control centers. Unfortunately, such remote data transfer is frequently bandwidth limited, so this would require a certain level of automation in the treatment of acquired information, which would be largely image-based, in relation to restoration mapping, active restoring, and monitoring. In cases of data transmission constraints, alternative strategies must be:

(1) Sending processed data instead of raw data, such as sending the counts of specific organisms identified from photo imagery instead of sending the entire photos; alternatively, it may be possible to use onboard software to define a "bounding box" around each animal and erase all the background [93];

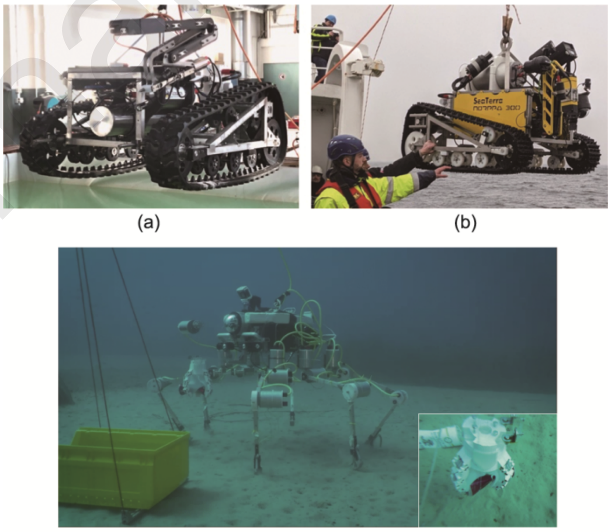
(2) Sending only summarized information by codifying the functioning status of the platforms (and their sensors) and sending low-computational-weight numerical information via commercially available networks such as satellites; or, if the distance to shore allows, using cellular or ad hoc networks, such as long-range radio (LoRa) data transmission [94].

3. Advanced robotic manipulator technologies as key tools for active restoration intervention

Since marine robots are achieving edge-computing capabilities for navigation autonomy [42], they can be modified to reintroduce sessile species (e.g., by seeding or planting), as well as supporting tasks such as the localization of motile animals and navigation with obstacle avoidance (Section 5). The robots can work either in tele-operated mode (i.e., being operated from vessels) or in fully autonomous mode for transplanting in large soft-bottom areas. While promising initial design studies have already been completed for the automatic planting of seagrass [95], the controlled and exact transplantation of, for example, sponges on ropes and meshes is a challenge that has not yet been attempted and that would require advancements in robotic manipulation. In particular, non-commercial experimental approaches include developing robotic arms endowed with end-effector materials and automated routines adapted to interaction with different species (see below on "manipulation codified procedures; i.e., operational taxonomies").

Marine tasks that require some level of manipulation must typically be tele-operated [96,97]. These tasks are usually carried out by equipping ROVs with one or two commercially available robotic arms or manipulators featuring rigid grippers as end-effectors [40]. However, this generally requires the ROV to be tethered to a vessel, which increases the complexity of the piloting task and the handling of delicate objects such as biological samples. Mainstream manipulators and grippers are usually designed for heavy tasks (e.g., pipeline inspection and maintenance) [41] and are thus less frequently used for scientific collection purposes.

Advancing the state of the art of underwater manipulation and autonomy tasks is becoming strategically relevant to active restoration procedures, especially regarding the reintroduction and correct placement of sessile and mobile organisms on large spatial scales. Robotic advanced manipulation taxonomies and abilities are crucially important for fixing restoration interventions or preparing the ground for restoration action (examples of actions preliminary to restoration include the removal of litter or ghost nets). In such a context, manipulation ability is currently essential for the reintroduction of sessile or motile and slow-moving organisms with different body consistencies (e.g., ranging from sponges to sea cucumbers and soft-bodied corals; Section 5) without physical damage. This biology-compliant automated manipulation taxonomy can be currently achieved with various implementations of robotic arms on crawlers and underwater legged robots (ULRs) (Fig. 2 [98]), considering that the effective implantation of restored organisms must be accompanied by the capability to estimate and maintain the desired densities of patches (Section 5.4).


(a) (b)

(c)

Fig. 2. Details of robotic arm installation on benthic mobile platforms such as crawlers. (a) UXO Crawler with sensor arm; (b) crawler with manipulator; (c) Underwater logged robots (URLs) SILVER2, to be used in future active restoration. In particular, the URL is equipped with a tendon-driven soft-gripper that collected a tin aluminum can during field trials ((d) real-time operator view of the manipulation). While the crawlers allow extended payloads for precise implantation along transects and the movement of heavier loads, the URLs can place objects on the seabed with a minimally invasive effect on sediments.

Robotic manipulation and its automation are required in order to perform active restoration operations that would otherwise be extremely difficult to do manually underwater. These operations could include ploughing the sediment to speed up the adherence process of sessile organisms, performing precise transplanting and/or implanting operations, and sampling some organisms' parts to investigate their physiological status [99]. Accordingly, the following developments in restoration manipulative interventions should be pursued:

(1) Autonomy. Various levels of autonomy in manipulation tasks should be achieved, thereby reducing the need for tele-operated command aboard vessels. The use of artificial intelligence and learning techniques will enable underwater robots to perceive the surrounding environment (i.e., detect, localize, and classify items and obstacles), plan, and execute tasks.

(2) Manipulation control. Once a robot has developed sufficient context awareness and identified its goal, it should be able to execute the task in the best possible way. In this regard, defining a taxonomy as a codified list of recurrent manipulative actions, [100], will allow the implementation of a library of actions from which the robot can choose, according to the information available. A taxonomy of manipulative actions for underwater operations was recently suggested by Mazzeo et al. [40].

(3) Bioinspiration for manipulator designs. Grippers should be tailored to the morphology of the species to be manipulated during the restoration activity. Depending on the specific tasks, different state-of-the-art grippers, including tendons [101] or hydraulically under-actuated soft solutions, can be used. In particular, [41]: ① Soft grippers can passively adapt to different shapes and limit the grasping forces; ② grippers based on micro-spines can collect rocks and porous specimens [102]; ③ suction cups can grasp regular surfaces [103]; and, finally, ④ caging solutions [104] can trap delicate targets with minimal contact.

(4) Integration of advanced manipulation capabilities with different operational specifications on robotic platforms. A manipulation system on a pelagic vehicle such as an AUV [105] or a hybrid ROV [106] will benefit from an aerial perspective of the scene. Regardless, the problem of manipulation from a floating base is complex, and the reaction forces that can be exerted on the environment depend on the power of the thrusters [107]. In comparison, integration of a manipulation system on a benthic robot such as a crawler [90] or ULR [108,109] will benefit from the greater positioning stability and be able to exert higher reaction forces, thanks to the direct contact with the seabed.

4. Integrating sensors into innovative platforms' payloads for the feedback monitoring of marine ecosystem restoration

Measuring the success of restoration efforts in the deep sea will likely require many years, as most deep-sea species are long-lived and slow growing [110]. New data-collection strategies that combine established and innovative biological and environmental sensors are required to monitor the status of reintroduced species over multiple-year timescales. Data acquisition should cover *in situ* intervention areas in a four-dimensional (4D) fashion (i.e., benthopelagic and time intensive), producing advanced management information [111]. The main variables to be monitored from this perspective are the health and survival rate of the reintroduced organisms, as well as the progressing recovery in their demography (i.e., density, distribution, and size/biomass). Moreover, data-collection strategies should be compliant with:

(1) An *ecosystem-based approach* that encompasses all species interacting with the restoration target species, based on previously published results for different ecosystems and involving end-users' (e.g., fishing industry) ecological knowledge.

(2) A *community turnover approach* that makes it possible to track short-term scale-abundance changes in reintroduced species as produced by tidal and intertidal currents (i.e., behavioral activity rhythms affecting species motility and hence presence and abundance in monitoring areas).

(3) A *species growth/reproduction approach* that allows for the tracking of long-term scale-abundance changes produced by seasonal cycles (e.g., demographic fluctuations due to migrations or ontogenetic bathymetric shifts) [112]. This is necessary to distinguish recurrent population dynamic fluctuations (rhythmically varying the detected individuals for certain species in restored areas) from multiannual trends of change in abundance change (as progressive increase or decrease) as a result of

the success (or failure) of restoration strategies.

Information on species density and biomass, behavior, sustaining habitat use (e.g., homing or territoriality, and bioturbation as the Lebensspuren seabed marks), interactions (which disclose hints on the trophic web architecture), and richness and overall biodiversity can currently be obtained via combined data collection by means of different imaging, acoustic, and omics sensors (Table 2). Environmental data are of relevance for the restoration monitoring of benthic habitats [113,114], and any biologically oriented data collection can be accompanied by the synchronous measurement of geochemical and oceanographic variables. Such multiparametric data collection is also necessary in order to acquire relevant information on species tolerance levels to the perceived environmental fluctuations into restored habitats, as described further below.

Table 2
Optical and geochemical sensor approaches to be integrated into advanced payloads in order to improve monitoring progress regarding species density, biodiversity, and organic matter/sediment quality. Sensors have a variable degree of development, as indicated by the technology readiness level (TRL), varying from basic research technology to fully commercialized systems, and footprint at use (related to the impact produced by their functioning).

Sensors	Detection distance ranges	TRL	Actions for sensors integration into restoration-functional payloads	Ecological variables	Relevance of data for restoration	Monitoring footprint
Video-imaging (High-definition (HD), low-light, hyper-spectral, and infrared)	Up to 2–3 m	9	Concomitant imaging of those sensors in a common field of view for taxonomic calibration and expansion in the range of size of monitored species (from bacteria to megafauna)	Megafauna identification, counting, and sizing for the estimation of species abundances*, and biomasses**, leading to the estimation of richness and biodiversity, with behavioral data on activity rhythms, Lebensspuren (bioturbation for remineralization, intra- and inter-specific interactions (as a proxy for food-web structuring)	Recovery of ecosystem functioning aspects related to biodiversity and food-web restructuring, with data on bioturbation and bioengineering, habitat structuring species and bacterial mat	Variable artificial lighting
3D photogrammetry and micro-imaging	Up to centimeters	9		Meio-fauna presence and behavior, coral growth rates, branching/necrosis, polyps (and sponges) filtering rates (opening/closing), epibionts, eggs, and larvae		Artificial light
Multi-beam acoustic imaging	Up to centimeters	9		Megafauna identification (if distinguishable as morpho-species) and counting, biomass and density determination, Lebensspuren (bioturbation and remineralization)		Variable sound frequencies
Synthetic aperture sonar (SAS)	Up to 5 m	9				
Hydrophones, passive acoustic monitoring (PAM)	Up to 2–5 km	9		Megafauna vocalization identification, counting and temporal quantification, as well as tracking of their spatial ecology and geographic connectivity***		None, although telemetry device attachment and retention may cause handling stress and energetic costs to organism
Photo-multiplier tubes (PMTs)	Up to 1 m			Bioluminescence activity, bathymetric movements of deep-scattering layers of organisms as the core of biological components in the oceanic carbon pump		None
3D laser scanning	Up to 5–10 m	9		Characterization, substrate rugosity/fractality, Lebensspuren (bioturbation		High-energy light

				and remineralization)		
Eco-genomic sensors	Depending on local circulation	4		environmental DNA (eDNA) and environmental RNA (eRNA) (for species presence and broad community analysis)	Recovery of ecosystem functioning aspects related to sediment quality, affecting respiration, remineralization, gravimetric benthopelagic coupling (sedimentation), and carbon sequestration	None
Geo-sonars	Up to 1 m^3	4	Concomitant HD imaging in a common seabed surface and underlying volume to link species and their abundances/biomasses	Quantification of usually "hidden" biodiversity components of the infauna (from meio- to megafauna range of sizes) and its abundance ****, biomass, richness, biodiversity, Lebensspuren (bioturbation)		Variable sound frequencies
Raman spectroscopy	Up to 1–15 cm	9	Gas concentrations (e.g., oxygen) and fluxes, element ratios, suspended/dissolved particles counting	Sediment respiration, geochemical activity, and energy/matter fluxes		High-energy light
Oxygen sensors	1–2 cm	9				None
Fluorescence sensors (turbidity and chlorophyll (Chl-*a*))	Up to 10 cm	9				None
Laser beams (optical backscatter)	Up to 1 m	9				High-energy light
Acoustic current Doppler profile (ADCP)	Up to hundreds of meters	9	Hydrodynamism			Variable sound frequencies

* If standardized for inspected area; ** if a scaling laser or stereo-imaging is available; *** for acoustically tagged animals; **** per unit of sediment volume.

Some monitoring approaches that combine different sensors can provide insights into ecosystem functioning, as metrics of value for the ecological outcome of a restoration. First, time-lapse imaging from fixed sources (e.g., landers; Fig. 3 [115]) or mobile platforms (e.g., crawlers; Fig. 4)—along with multiparametric environmental data acquisition by landers (or nearby cabled observatories; Table 1)—can offer relevant hints on species' ecological niches with a precision not often attained before, by directly relating animals' presence, abundance, and behavior to the fluctuating status of oceanographic and geochemical variables. At these sites, crawlers can monitor ecosystem recovery [53], enabling innovative active restoration approaches. Intervention areas should be equipped with re-deployable benthic and pelagic intervention and monitoring platforms, which can limit costly vessel operations [63,76,116]. To this end, methods from automated precision agriculture, as suggested by Botta et al. [117], for example, can be adopted: While AUVs can take over monitoring tasks from a greater distance, resident robots can apply precise restoration methods on site as well as monitor on a small scale. Then, restoration metric data on seabed communities can be related to the presence of other biological components in the water columns overlying the restored areas, as a proxy for regained habitat quality. This measurement can be achieved by means of the synchronous image-based monitoring of benthic and benthopelagic (i.e., pelagic-descending and seabed-contacting) organisms as constituents of the oceanic biological carbon/energy pump. In fact, rhythmically descending organisms, as diel vertical migrants, can affect the benthic boundary layer with their intermittent presence, eliciting a predator-prey response from benthic communities on shelves and slopes [118,119].

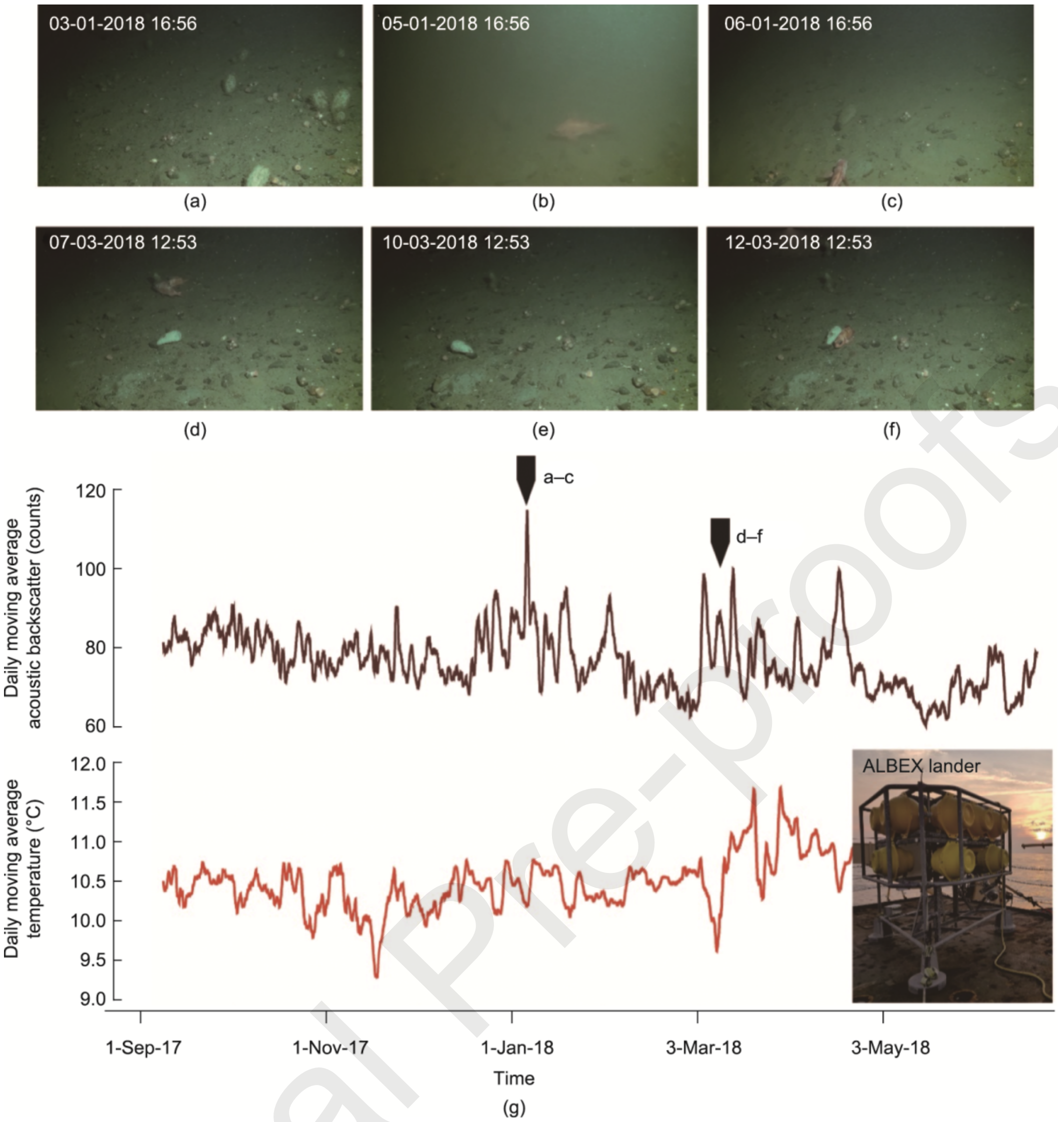


Fig. 3. (a–f) Time-lapse camera images from the Royal Netherlands Institute for Sea Research (NIOZ)-designed ALBEX lander and (g) environmental data (turbidity and temperature) collected during a 10-month deployment in a glass sponge ground (the Sambro Bank sponge conservation area) [115]. The lander system was equipped with an array of sedimentological (sediment trap), physical (acoustic current Doppler profile-ADCP), CTD and biogeochemical (O_2, turbidity, and fluorescence) sensors, plus a video camera system with white lights, collecting a short video clip every 4 h during the deployment. The photographs show the ecosystem dynamics in the sponge ground. (a–c) Benthic storm in winter showing enhanced resuspension in the water column. (d–f) Changes in the orientation of sponges and their interactions with associated fauna (e.g., fish). Time is presented in Coordinated Universal Time (UTC).

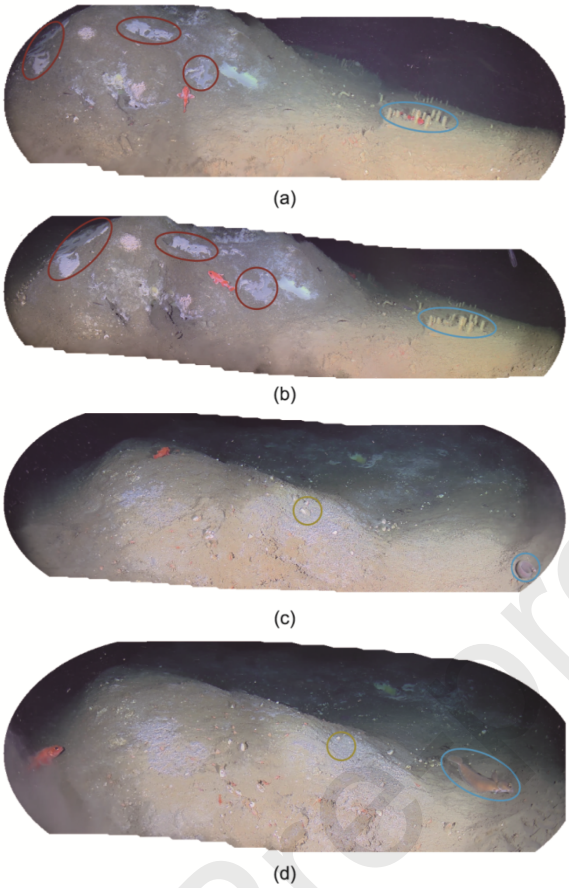


Fig. 4. Examples of the use of photomosaics for habitat and fauna monitoring, as created based on rotating video scans performed with the crawler Wally at the Barkley Canyon Hydrates site of Ocean Networks Canada's NEPTUNE observatory. (a, b) View of the mound with scattered bacterial mats and visible hydrate chunks, adjacent to a field of decaying egg towers deposited by Buccinid snails. Differences in bacterial mat coverage (marked by red ellipses) can indicate changes in circulation intensity that may affect erosion, changes in the methane seepage that provides energy to the chemosynthetic bacterial community, or changes in macro- and megafauna activity (e.g., grazing). (c, d) Views of the flank and ridge of a different mound system. Differences in the distribution of sessile fauna (e.g., chemosynthetic clams, marked by yellow ellipses) can be an expression of activity rhythms in the form of emergence patterns, small-scale displacement, or survival. Note the change in the densities of the small tanner crabs on top of the hydrate mound flank (lower left of mosaics (c) and (d)). (a–d) Differences in the use of space and microhabitat (e.g., egg towers, crawler trail on the seabed, etc.; marked by blue ellipses) by different megafauna species, when monitored over the long term, can indicate time-partitioning and other behavioral aspects of the benthic community. (a–d) Footage to create

was taken on Sept. 21, 24, and 27 and Nov. 4, 2021, respectively.

Geo-sonars may also play a pivotal role in targeting hidden biodiversity components that are relevant to the restoration of ecosystem functioning (i.e., infauna). Geo-sonars are acoustically active (emitting) and passive (hydrophone receiving) devices mounted on lander sediment-penetrating infrastructures, which are capable of the 3D imaging of animals within a volume of sediment. Such information is useful in completing species inventories for the better computing of overall benthic ecosystem biodiversity. Moreover, such infauna richness can be related to recorded burying and burrowing activity, thereby distinguishing this activity from the tracks produced by epifauna [120]. Alternatively, a high-frequency 3D seismic system with 130-kHz acoustic transducers can detect centimeter-scale structures and bioturbation traces in marine mud [121].

To quantify overall respiration and carbon sequestration, the effects of restoration on biological components can be coupled to more deterministic measurements, such as those for sediment quality and remineralization (via Lebensspuren quantification), with high-resolution, multi-beam imaging payloads [122]. This could be done in tandem with benthic respiration chambers (on biogeochemical landers) [73,74] or by means of micro-profilers on crawlers (Table 1). Strategic information on ecosystem functioning can be derived using these monitoring data in association with the organic-matter contents of soft sediments and suspended particulate organic matter [123].

The classical morpho-taxonomic approach for the assessment of diversity in the restoration of deep-sea habitats can be very time consuming and may require sample collection over broad spatial and temporal scales. Moreover, there is a need for high-level taxonomic expertise. To address these issues, environmental DNA (eDNA) may be a practical solution, as it can reveal biodiversity across all taxonomic groups (i.e., from prokaryotes to whales) [124]. Significant advances in molecular methodology and bioinformatics, accompanied by a steady increase in computational power, have made “omics” technologies and data increasingly accessible [124,125]. Once a water or sediment sample is collected, the extracted eDNA can be analyzed either by using “universal” markers targeting whole communities (from microbes to megafauna) by means of metabarcoding [126,127] or by targeted species-specific assays, usually performed via real-time quantitative polymerase chain reaction (qPCR) or digital PCR (dPCR) [128].

The adoption of sediment eDNA metabarcoding as a tool for biodiversity and quality assessment is rapidly becoming more widespread, driven by advantages in terms of time and cost-effectiveness [124,129]. This approach still suffers from technical and operational challenges, such as the inability of some commonly used gene regions to reliably separate taxa to the species level, incomplete reference databases for marine benthic organisms, and errors that can occur in reference data [130,131]. However, it allows the parallel analysis of hundreds of samples [132] and the co-detection of a broad range of species [133], and thus has great potential for the biomonitoring of deep-sea ecological restoration.

At the same time, the use of cutting-edge technology for *in situ* sample collection without the need to deploy and lift equipment from the surface to the seabed for each individual sample could further improve eDNA biomonitoring in the restoration of deep-sea ecosystems, especially for large-scale long-term assessments. In this regard, *in situ* fully automated procedures for eDNA (from sampling to sequencing) coupled with imaging and passive acoustic monitoring (PAM) for the cross-validation of taxa have been proposed [134], although less sequencing and markers comparison are available for deep-sea species [135]. The most recent application of lab-on-a-chip (LOC) [136,137] technologies to marine research involved the use of the third-generation Environmental Sample Processor (3G-ESP) [138], which, coupled to an AUV, was employed for the quantification of eDNA across a broad range of taxa at sea [139]. DNA sequencing technology is also evolving, thanks to the nanofabrication of highly performing microfluidic chips comprising modules for DNA extraction, libraries preparation using protocols integrated with magnetic particles (e.g., VolTRAX by Oxford Nanopore Technologies (ONT)), and single-channel-structure nanopores for sequencing (e.g., MinION; ONT). These advances make feasible the installation of next-generation eco-genomic sensors on platforms monitoring deep-sea restoration *in situ*.

Finally, the *in situ* tracking of species behavior may provide useful insights into restoration outcomes by taking individuals’ permanence and activity within restored areas as an additional indication of regained environmental quality. In this type of monitoring, arrays of moored PAM arrays may play a key role in monitoring whether acoustically tagged individuals in restored areas follow similar behavior patterns to natural populations in spatially fixed survey areas [140] (Fig. [141]).

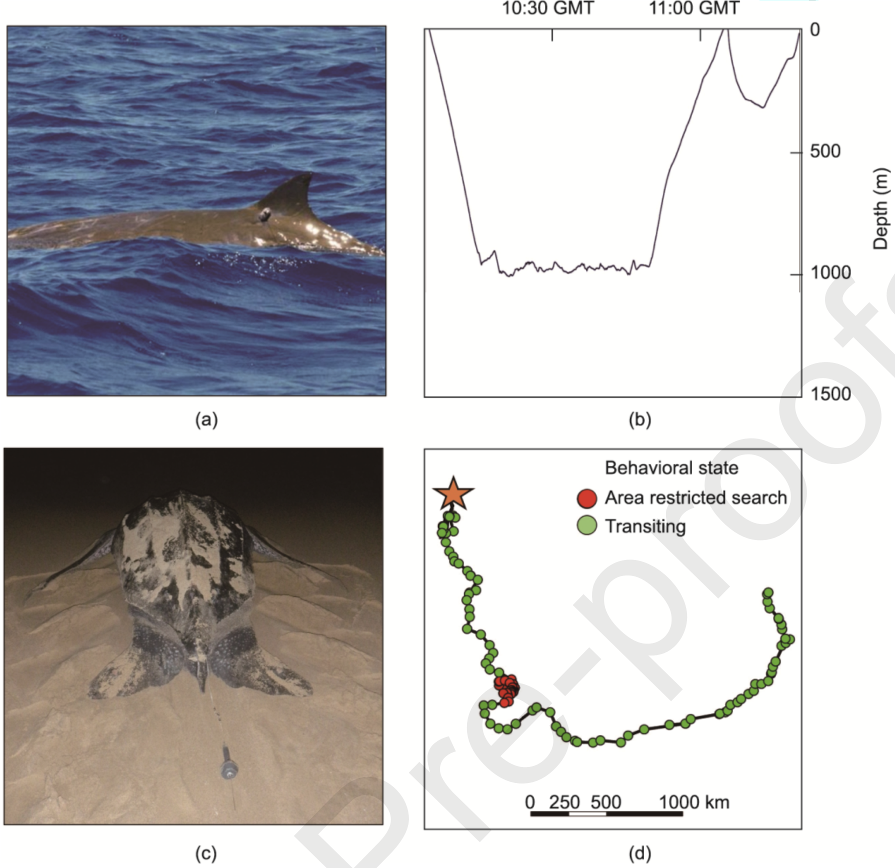


Fig. 5. (a) Blainville's beaked whale (*Mesoplodon densirostris*) with a biologger visible just below the dorsal fin (photo credit: NOAA Fisheries). (b) Dive profile of a bottom-feeding Blainville's beaked whale. (c) A leatherback sea turtle (*Dermochelys coriacea*) with a tethered satellite transmitter. (Photo credit: N.J. Robinson). (d) Telemetry-generated daily locations from a post-nesting leatherback turtle indicating areas of transiting in green and area-restricted search (ARS) behavior that is typically indicative of feeding bouts (recreated using data from Robinson et al. [141]).

It should also be noted that the use of PAM arrays for monitoring restored species may provide opportunistic insights into transient species that have been tagged with acoustic devices outside the restored area, hence providing relevant information on connectivity levels among the chosen intervention sites. For example, trends in the presence and abundance of apex predators such as sharks or beaked whales can provide valuable information on ecosystem functioning [142]. Data on the movement patterns of such large, deep-diving apex predators obtained from other methods, such as animal-borne biologgers or satellite transmitters (Fig. 5), can also provide information on prey availability over areas spanning entire ocean basins [143]. Apex predators can also be equipped with a range of other sensors for measuring depth and temperature and even cameras, to opportunistically obtain data over similarly large habitats [144].

The geographic ranges of deep-sea species dispersal are still poorly known, and this factor could deeply affect restoration outcomes, based on the reintroduction of motile species. Data-logging technologies can be used to assess connectivity in restored areas, by tracking adults' and juveniles' movements across, into, and out of restored areas, thereby providing relevant data on factors that contribute to the remediation of ecosystem services (e.g., animal export across areas contributes to breeding and enhances the genetic diversity of stock).

5. Pilot restoration actions: Case studies of robotic intervention and monitoring

The value of using robotic platforms (see Table 1) for the spatial scaling of active restoration and its monitoring has not yet been reviewed in the scientific literature, and some relevant operational factors related to the ecology of the reintroduced species should be carefully evaluated. Below, we present different cases of active restoration centered on the reintroduction of bioengineering species to increase local biodiversity. Sessile bioengineers accelerate the restoration of seabed quality (e.g., sediment capture and the increase of overall surface fractality), assisting in the arrival of motile species with different levels of dependency upon the substrate. In particular, crawlers (e.g., gastropods and echinoderms) and walkers (e.g., crustacean decapods) are more dependent on the substrate than swimmers (e.g., fishes and cephalopods). It should be noted that these examples focus on individual iconic species; however, their combination into diversified pools of reintroduced organisms may further enhance the restoration approach. Such species are currently the object of intense restoration-oriented research, and their combined reintroduction depends on the fine tuning of protocols.

To provide examples of how robotic platforms can aid active restoration and monitoring in deep-sea habitats, we present three case studies: ① reef-building cold-water corals (CWCs; e.g., *Desmophyllum pertusum*, also previously known as *Lophelia pertusa*) [145]; ② soft-bottom bamboo corals (e.g., *Funiculina quadrangularis* (*F. quadrangularis*) or *Isidella elongata*)—a case study that is also applicable to other organisms such as sponges (e.g., *Suberites* spp.), sea pens (Pennatualceans), and even sea cucumbers (*Holothuroidea*); and ③ soft-bottom fishery resources such as the Norway lobster (*Nephrops norvegicus*). While *Nephrops* is a commercial target species that would be immediately marketed, the other (sessile) species are considered bycatch (with the exception of sea cucumbers, depending on the location and hence societal appreciation of their use as a commercially valuable resource). In any case, the recollection and preservation for transference of bycatch or commercially targeted species would be necessary for restoration purposes.

*5.1. Restoration of reef-building cold-water corals (*Desmophyllum pertusum*)*

The restoration of reef-forming CWCs has already been carried out in several areas of the Atlantic Ocean, such as the Koster-Väderö Fjord of Southwest Sweden [146], where the remains of reefs of the scleractinian coral *Desmophyllum pertusum* are present, albeit widely degraded. These corals require elevated and sediment-free surfaces, and their larvae prefer small crevices and complex surface textures, which facilitate settlement [147]. Therefore, artificial reefs have been developed with a surface composition and shapes that facilitated larval settlement [148,149]. The aim is to design biocompatible 3D-printed artificial reefs that can be mass produced and to restore the habitat in the fjord on a large scale by providing new settling grounds for sessile structuring fauna. If successful, this restoration should lead to an increase in fish and other fauna that thrive in the reef habitat [150,151]. Such eco-structures can be composed of natural volcanic aggregates without any synthetic or toxic substances, with a moderately alkaline pH of 8.5–9.0 that is ideal for calcifying organisms. Other recolonizing assets include 3D-printed eco-reef modules [152] designed to mimic three different orientations to attract larvae.

The innovative combination of two main approaches for CWC restoration can be envisaged to enable the spatial scaling of operations: ① Fragments of the corals are collected (either *in situ* or recovered from fisheries bycatch), attached onto a suitable substrate, and returned to benthic environments using the "Badminton" technique or an ROV [153]; and ② CWCs are recruited *in situ* on artificial substrates and transplanted at the target site.

In the "Badminton" technique, the bases of corals (i.e., stalk-like fleshy structures with a contracting capacity, used by organisms to remain attached to soft sediments) are attached to cobbles and deployed via overboard throwing. This technique has been successfully used at depts up to 80–90 m [154]. At greater depths, to avoid current drift and damage, organisms must be deployed by the same technique but from a reduced height above the seabed by means of cylindrical Bio-Liberators (BiLi) [152−155].

A method based on the deployment of artificial infrastructures consists of using several small colonization chips instead of a few larger artificial reefs (that are usually deployed by vessels) (see ARMS, below). The manipulation capability of benthic robots such as crawlers could be very well suited in this case. The robots' manipulation of the recolonization chip distribution should be compliant with the spatial arrangement of the species in question, which will influence the survival of the reintroduced organisms [152]. The operational steps leading to active intervention and monitoring by a network of autonomous benthic and pelagic robotic platforms, with a crawler to perform substrate manipulation, are listed below (Fig. 6):

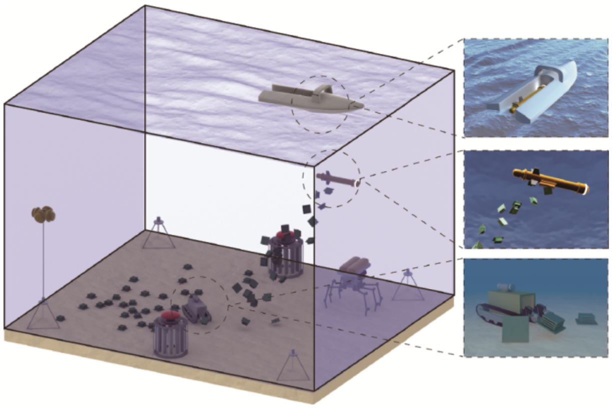


Fig. 6. Restoration scenario for CWC reef areas and ecotones of transition with open mud plains. Landers (triangular-shaped tripods) for monitoring and cylindrical fuel cells (with several vertical gas cylinders) for mobile platform recharging, delimit the restoration intervention by crawlers endowed with a robotic manipulation arm, which can spatially order recolonization chips dropped by an AUV. All acquired information can be transmitted via acoustic modems (on top of fuel cells as circular-shaped) to ASVs with different forms of compression/data sub-sampling. Acoustic release of some chips can be provoked for laboratory physiological analyses.

(1) Site exploration/characterization prior to the intervention. Seabed transects by means of AUVs will allow the high-precision mapping of the biological and geomorphological components of the seabed with different resolutions. Dead reckoning is necessary for the precise geo-positioning of landers in between the reefs to delimit a polygonal intervention area, as well as for the identification of the best spots to drop recolonization chips. At the same time, ROVs, AUVs, or dropped cameras (Table 1) could be used to expand the exploration at spatial scales beyond that of the network itself.

(2) Network deployment. One central lander with data-exchange capability and including optoacoustic imaging plus geochemical/oceanographic sensors, should be positioned in relation to the variable number of satellite landers. The nodes' reciprocal distances could span from tens to hundreds of meters, depending on local constraints. Platform lifespans could be increased by the deployment of fuel cells for battery recharging [90]. The network data-exchange and mission-reprogramming capability would be ensured by a central station moored projection (Section 2) bearing an acoustic modem that can exchange information across the water column with ASVs (Table 1).

(3) Deployment of colonization infrastructures. Instead of using vessel-dependent releasing devices or from-deck dropping strategies, AUVs could be used to hoover in between CWC reefs, precisely delivering recolonization chips to previously identified seabed areas [156]. These chips could be similar to (but lighter than) autonomous reef-monitoring structures (ARMS) [157].

(4) Manipulative interventions. Lander-docked crawlers [87] with a manipulator arm and gripper could be used to redistribute dropped recolonization chips, according to criteria for maximizing recolonization and survival. Those crawlers could activate the acoustic release of some chips to enable their recovery for laboratory analyses.

(5) The monitoring of interventions. Once the network has been deployed and interventions have been made, monitoring could be enforced by means of synchronous biological and environmental data collection. The temporal dynamics of the intervention and their effects on the local area should be based on edge-computing capabilities [42], with the onboard processing of image navigation data to decide on stopping and focusing on specific sites or changing the monitoring transect depending upon obstacles. AUVs and slow-moving, stepping-stone advancing crawlers (i.e., to mitigate sediment resuspension by tracked wheels; see Section 1.4) should also cross restoration area borders, within adjacent zones, in order to evaluate the effect of recovery in terms of, for example, modified sediment and organic matter fluxes, biomass spill-over, and bioturbation as proxy of infauna recolonization. Monitoring the restoration intervention also makes it possible to identify the progress made and/or the need for further interventions to ensure the full success of the restoration.

5.2. Restoration of soft-bottom bamboo corals (e.g., F. quadrangularis *or* Isidella elongata*) and sponge grounds*

The restoration of soft-bottom corals and sponges is pursued, as these species increase sediment capture and accelerate seabed quality recovery in heavily fished areas [158,159]. The type of distribution and density of sessile organisms that should be achieved at reintroduction may influence the decision to use "planting" by mobile platforms. Achievable distribution is of relevance, since filter feeding success is influenced by current-shadowing, substrate rugosity, and overall colony density [160,161].

Single seafloor robots with specific insertion baskets can be used to plant sessile fauna such as sea pens and sponges in a spatially ordered and distributed manner. The insertion basket or tray consists of mechanical parts that allow the placement of individual organisms, either in parallel or along a biodegradable rope. With these capabilities, crawlers could insert up to several hundreds of organisms per hectare within 48 h (for comparison, four divers and two months are needed for a similar task (e.g., eelgrass) in shallow waters; see Section 1). Alternatively, crawlers may assist in the active reintroduction of organisms imported into targeted areas by other moving platforms with their monitoring capability, as per the scheme of action presented in Fig. 7:

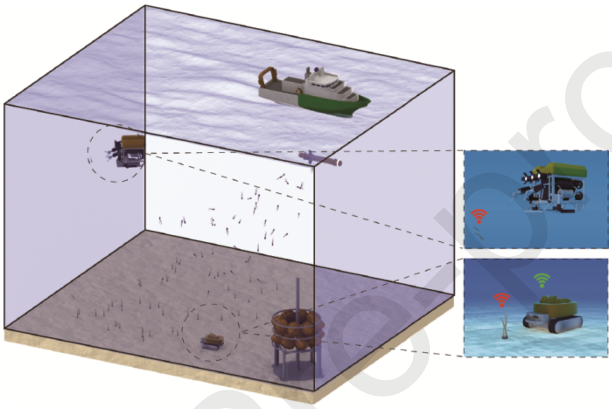


Fig. 7. Restoration scenario of soft-bodied CWCs in open-slope mud plains. Once the AUV drops a batch of individuals (via the "badminton" technique), their location can be identified by the vessel-deployed MANSIO-VIATOR system via SLAM for up to a week of full autonomous operation. Data are stored on the crawler for later download upon recovery. CWC surface ejection (for posterior laboratory analysis) can be elicited by acoustic releasing.

(1) An accurate optical and acoustical reconnaissance of the area, including mapping of its biological and geomorphological characteristics by ROV/AUV/crawlers, is required as a preliminary step to identify key spots for intervention.

(2) Batches of sessile organisms should be precisely deployed into intervention areas by AUVs, ROVs, and crawlers (Table 1) using the Badminton technique. Acoustically emitting sources could also be delivered within such a batch to allow the identification of the organisms' positioning (see below). The Badminton technique would need to be modified for *F. quadrangularis*, as this species has a peduncle that remains embedded on the seafloor. Most likely, a conic weighted biodegradable wedge would be used to allow the penetration of the peduncle into the sediment.

(3) A simplified monitoring approach could be used: Vessel-deployed crawlers with limited operational autonomy (up to one week; Table 1), such as the MANSIO-VIATOR system [87,90,162], could be used to reach sessile organisms via SLAM guidance, activating video acquisition along the reaching transect and specifically onsite.

*5.3. Restoration of soft-bottom fishery resources such as the Norway lobster (*Nephrops norvegicus*)*

The persistence of benthic animals reintroduced into restoration areas may depend upon their different lifestyles in relation to motility. *N. norvegicus* is one of the most important commercially fished crustaceans within the European community [163]. However, it is showing signs of population decline, and its muddy seafloor habitats have been heavily impacted by trawl fishery in recent decades [42]. Restoration of this species can primarily be performed via its repopulation into Fishery No-Take zones [140]; however, more knowledge is required on behavioral aspects related to burrowing and territoriality. In fact, reintroduced animals may displace to unknown distances in order to find suitable conditions (e.g., low density of conspecifics), even abandoning restoration areas.

Based on the reintroduction of *Nephrops*, networks of robotic platforms may be relevant for restoration strategies, as they can track animals' displacement after release in relation to habitat use and biomass export [140]. Accordingly, the operational aspects of active repopulation intervention are as follows (Fig. 8 [140]):

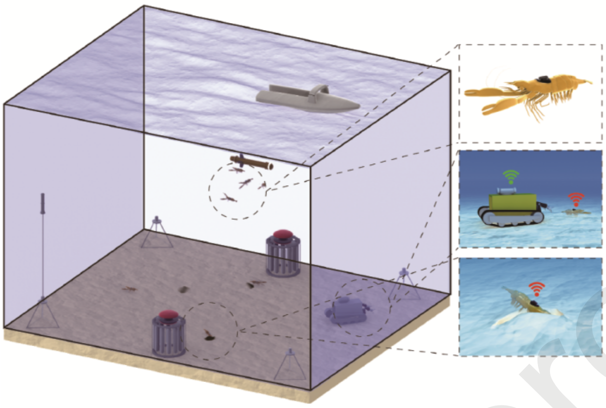


Fig. 8. Repopulation of fishery resources (i.e., *N. norvegicus*) within a dwelling area delimited by a network of monitoring landers (triangular-shaped tripods) and cylindrical fuel cells (with several vertical gas cylinders) for mobile platform recharging. All landers can receive the pings of acoustically tagged individuals (delivered onsite by an AUV), triangulating their position in near real time via moored hydrophones [140]. Crawlers could precisely track and pursue the animals leaving the restored areas if also equipped with hydrophones, allowing simultaneous temporally intensive (mobile) video-monitoring of their burrowing activity. All acquired information can be transmitted via acoustic modems to ASVs with different forms of compression/data sub-sampling.

(1) The deployment of a network of fixed and mobile platforms delimiting the intervention area (Fig. 6) would be relevant; landers would bear both opto-acoustic imaging and water-column-moored PAM devices to portray the behavior of animals (i.e., in terms of burrowing activity) at release.

(2) Batches of acoustically tagged individuals [140] should be released at the center of the network area to provide data on space use by reintroduced species. A new class of emitting bidirectional acoustic tags [155] that are capable of communication should be used to permit spatial tracking (see below).

(3) Untethered crawlers [91] should be endowed with PAM sensing capabilities and could be used to track and video-record the presence and movement of acoustically tagged animals wandering across or leaving repopulation areas. The burrowing behavior of animals within the intervention area should be monitored with low-motion, stepping-stone missions (i.e., limiting the sediment resuspension impact and potentiating their monitoring capacity as movable observatories) [42]. Then, animals' displacement tracking by an autonomous crawler should be enforced to operate over a kilometer scale, from the center of restored areas across and beyond their borders, thereby surpassing AUV tracking functionalities based on increased functional autonomy.

5.4. Life-cycle assessment of active restoration for the evaluation of economic revenue

The outcomes of current robotic-mediated restoration strategies should be evaluated through life-cycle assessment (LCA) analysis centered on, for example, the required patch densities of restored organisms in relation to the capability of platforms to make a good implantation, the trends in the biomass gains of exploited services (i.e., stocks), and the stored CO_2 from energy/matter measured fluxes, versus the energy consumption and structure degradation of platforms and sensors, vessel costs from operations, and money investment in scientific personnel.

In particular, the LCA technology-oriented analysis should include environmental gains from employing autonomous solutions and *in situ* monitoring and data collection from innovative sensors and vehicles, in conjunction with remote control and mission planning. Suitable performance indicators can be identified in order to clearly measure the improvements made (e.g., the size and persistence of patches or reintroduced organisms). Such analysis will be performed though a life-cycle cost (LCC) assessment of the platforms and sensor technologies used, which will consider the costs and benefits throughout their life-cycle phases (i.e., design, construction, operation and maintenance, and decommissioning). The target would be to minimize the cost of machine-based restoration and monitoring before, during, and after the intervention's activities. A cost-benefit ratio of the proposed technological solutions should be higher than 1; that is, the net present value (NPV) of the proposed technological solutions should be higher than that of alternative (existing) solutions (e.g., crawlers for seeding/planting and monitoring vs. vessel-assisted Badminton releasing and ROV surveying).

Finally, a natural capital accounting framework could be applied to monitor and evaluate the ecosystem services and benefit values generated for society before and after restoration activities. Natural capital accounting is an integrated statistic framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, and linking this information to measures of economic and human activity [164]. It provides a structured approach for assessing the dependence and impacts of economic and human activity on the environment. Based on this framework, a database of the identified deep-sea ecosystem services' benefit values from past research can be established to be used in the creation of natural capital accounts and cost-benefit analysis.

Inquiry persists regarding what party should be responsible for funding these actions. Multiple studies have indicated that the financial feasibility of deep-sea restoration through conventional ship-based activities is exceedingly challenging, with costs ranging from over 1 million to 100 million EUR per hectare [165]. However, the implementation of robotic interventions, which adhere to precise restoration measures, as outlined earlier, has the potential to significantly reduce these expenses by several orders of magnitude.

The implementation of innovative funding schemes, such as public-private partnerships, which incorporate crowdfunding campaigns, alongside the utilization of social cost-benefit analysis (SCBA), as proposed by Chen et al. [166], as well as the enforcement of the "polluter pays" principle, as advocated by Laffoley et al. [167], are recommended.

6. Conclusions

Although marine robotics make the achievement of high levels of platform development and consequent commercialization possible, there is still a long way to go before these technologies will be able to autonomously operate active restoration interventions in the deep sea. Future implementations will include the integration of control protocols to simultaneously coordinate the missions of various underwater platforms and to potentiate the capability for *in situ* autonomous restoration intervention. In contrast, automation in ecological monitoring is achieved by means of permanently instrumented areas where networks of benthic and pelagic platforms already exist in perpetuity (e.g., cabled observatories and neutrino telescopes from the European Multidisciplinary Seafloor and Water Column Observatories (EMSO), the Ocean Network Canada (ONC), and the US Ocean Observatory Initiative (OOI)). Those fixed assets (that host docked crawlers, in some cases) may provide suitable control fields for the operational evaluation of platforms' performance in restoration intervention and monitoring tasks.

The development of robotic-mediated active restoration will benefit from autonomy and remote control in restoration operations, in order to consistently reduce the costs of vessels operations. Nevertheless, the development roadmap is still long in relation to both the technological aspect and the operational know-how needed to capture, preserve, and maintain reintroduced species, each of which has its own ecological role and specific effect on the whole restoration dynamic. Single-species approaches will be progressively substituted by multi-species approaches to introduce ecological interactions through ecosystem engineers, as an accelerant factor for biodiversity recovery. This task will not be an easy one; ecosystem restoration requires a knowledge of ecosystem structure (i.e., species' functions in relation to the food web architecture and overall carbon input fluxes) that is not always available, depending on the case. Such ecological know-how can be gained through ongoing multiparametric monitoring approaches that combine synchronous biological and environmental data acquisition for the largest number of species possible. This knowledge should act as feedback for structuring the technological requirements of autonomous platforms—not only in relation to their mission planning but also in the form of specifications for the robotic manipulation and movement tracking of organisms.

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Compliance with ethics guidelines

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Highlights

1. Marine deep-sea restoration should be based on landers with docked crawlers and AUVs, allowing *in-situ* autonomous interventions, battery recharging, and remote data transmission
2. Crawlers with robotic arms should be used for active restoration
3. Innovative combinations of HD, multi-beam imaging, active acoustics, omics and environmental (oceanographic and biogeochemical) sensors should be used to enable restoration monitoring
4. We describe three potential case-studies for robotic-mediated restoration in deep-sea iconic environments.