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Review

Environmental considerations for the decommissioning of subsea cables

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ABSTRACT

Since the first trans-oceanic telegraph cables were laid in the nineteenth century, a subsea network of cables has grown across the global ocean; becoming upgraded with co-axial, and more recently, fibre-optic cable systems. Demands for digital connectivity mean that this network continues to expand, with an estimated >3.5 million km of all types of subsea cable installed to date, and a growing amount of now out-of-service infrastructure requiring decommissioning. While the environmental impacts have been well-documented for installation and operational phases, to date no study has addressed the potential impacts associated with the decommissioning of out-of-service subsea cable systems, which typically have a 20-25-year design life. Here, we address this evidence gap and present a first synthesis of the drivers for, and environmental considerations relevant to, the decommissioning of subsea telecommunications cables. We show that recovery of subsea cables has potential to return commercially valuable materials to the economy with a high degree (>95 %) of recyclability; however, various dynamic environmental conditions and logistical challenges mean that it is not always viable to recover the entire length of a cable system. While cable recovery activities are found to have a localised and short-lived environmental impact, it is important to ensure that any impacts are minimised, particularly in sensitive habitats, or exceptional cases where intense biological colonisation of a cable has occurred. Options for decommissioning out-of-service systems, other than recovery, include in-situ repurposing to make scientific measurements or re-deploying sections of recovered cables elsewhere. Many future opportunities exist for further enhancing the evidence base concerning cable decommissioning and with regards to the gathering of environmental data during cable recovery operations to inform future decision-making and to enhance the wider scientific understanding of shallow to deep sea environments.

1. Introduction

The Blue Economy is growing rapidly to support socio-economic development, energy security and enable the transition to Net-Zero, resulting in an increasingly complex interaction of seafloor infrastructure and users, in an already-pressured marine environment (UNEP-WCMC, 2025). As new infrastructure and developments are installed, older ones have reached, or are rapidly reaching, the end of their operational lives. There is thus a push for the decommissioning and removal of offshore infrastructure, to reduce the complexity of marine spatial planning and conflict for seafloor use; particularly where associated materials can be re-used or repurposed to contribute to a zero-waste economy. However, the benefits of any such recovery and recycling need to be weighed up against any potential adverse effects on

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the marine environment, which requires an evidence base. There has been considerable effort placed on approaches for the decommissioning of offshore energy infrastructure, particularly motivated by legislation such as OSPAR Decision 98/3 in relation to oil and gas installations (e.g. Fowler et al., 2020; Birchenough and Degraer, 2020; Jones et al., 2019; Raitt et al., 2019; Tan et al., 2021). The sheer scale of offshore oil and gas developments in some regions has warranted studies to comparatively appraise the biodiversity benefits (e.g. where they may act as reef-like structures that may foster enhanced biodiversity) and challenges of leaving in-place (e.g. potential for long term pollution) against any implications of removing large structures from the seafloor (e.g. MacIntosh et al., 2022; Sommer et al., 2019; Schroeder and Love, 2004; Ekins et al., 2006; Lemasson et al., 2024; Knights et al., 2024). Similarly, the rapid expansion of offshore wind energy in north-west Europe has motivated a growth in studies that appraise the environmental considerations of wind farm decommissioning (e.g. Dunkley and Solandt, 2022; Hall et al., 2022; Hall et al., 2020; Jalili et al., 2024; Shadman et al., 2021; Smyth et al., 2015; Spielmann et al., 2021; Spielmann et al., 2023a,b; Spielmann et al., 2023b; Topham et al., 2019a,b; Topham and McMillan, 2017). It is therefore surprising that, to date, no study has focused on the decommissioning of a much longer-lived industry, whose assets extend from the shallowest to the deepest parts of the global ocean: subsea cables. This study presents a first assessment of the environmental considerations relevant to the decommissioning of subsea cables, providing a much-needed but currently absent evidence base for decision-making, intended to motivate future studies and collaborations.

1.1. *The global network of subsea cables*

The total estimate of all types of subsea cables installed to date is > 3.5 million km (Appleby and Dawe, 2019, Fig. 1). Telecommunications cables underpin digital communications, carrying almost all digital data traffic worldwide, including the Internet, financial transactions and enabling remote working. The first subsea telegraph cables were laid in the mid-19th century, with an estimated 596,000–714,000 km of telegraph cable installed by 1914 (Appleby and Dawe, 2019; Ash, 2025); forming a network that connected all continents except Antarctica (Clare et al., 2025). Subsequently, coaxial cables provided telephone connectivity from the mid 20th century (469,000 km of coaxial cables is estimated to have been installed), until they were superseded by fibre optic systems from the mid-1980s onwards. Presently, a network of more than 1.8 million km of in-service fibre optic telecommunications cables crosses the world's oceans, carrying >99.9 % of all digital data traffic worldwide, trillions of dollars in financial trading and underpinning the Internet (Carter, 2009; Clare et al., 2023). Between 2023 and 2025 alone, a record number of new cables were under construction, adding about 300,000 km in submarine cable length (Telegeography, 2025). In addition to telecommunications, other types of cables provide important services. Power cables transmit energy, ranging from interconnector cables (designed to balance energy production and demand between countries), export cables (that connect offshore renewable developments to land), inter-array cables (that connect structures such as wind turbines to an export cable) and power distribution cables that provide vital links between island communities. The world's first underwater power cable was installed in 1811 (in Germany's Isar River), whilst the first submarine High Voltage Direct Current (HVDC) cable

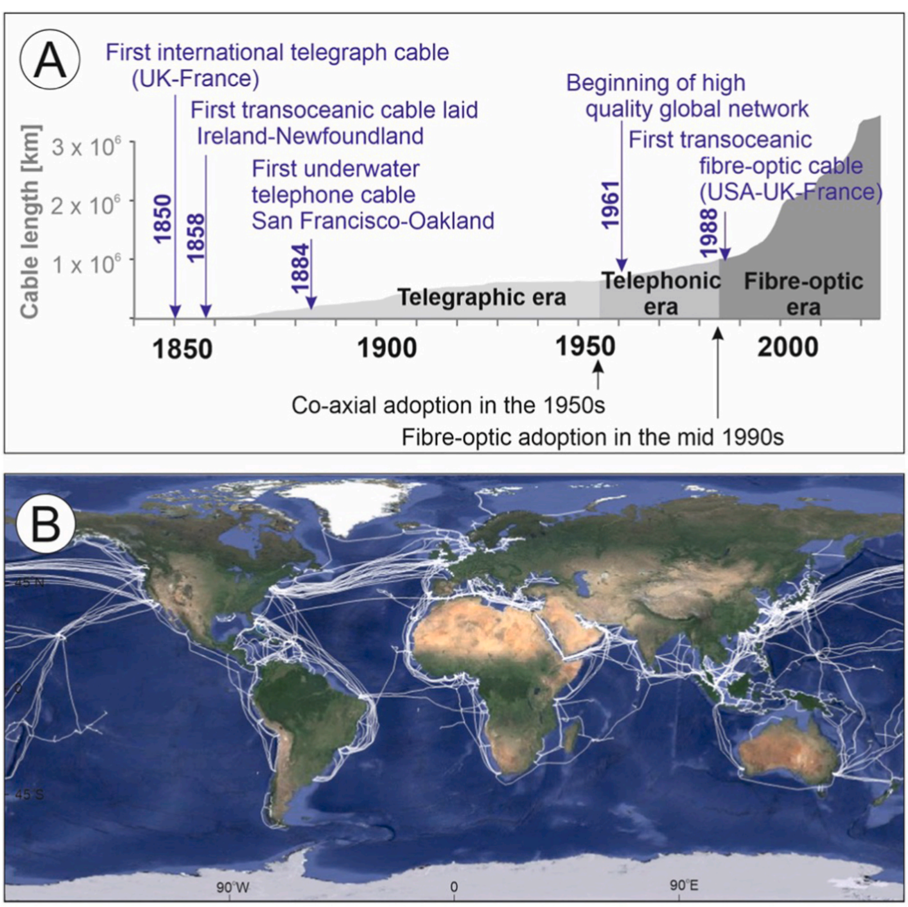

Fig. 1. Cumulative length of subsea fibre-optic telecommunications cables installed to date worldwide (A), shown as a map of in-service fibre-optic systems in (B) courtesy of Global Marine Ltd.

(named Gotland 1) was installed in 1954. In 2015, about 8000 km of HVDC cables existed in the world (Ardelean and Minnebo, 2015), which has recently grown to exceed 10,000 km.

1.2. Growing interest in the recovery of out-of-service subsea cables

Subsea telecommunications cables typically have an average design life of around 25 years, and a growing demand for new, higher capacity systems means that new cables are regularly installed to replace older ones. As a result, around two thirds of the length of subsea telecommunications cable installed to date is out-of-service and the majority left in-situ as it has been considered to generally have only a minor impact on the marine environment (Kraus and Carter, 2018; Carter et al., 2019; Clare et al., 2023; UNEP-WCMC, 2025). There is, however, a growing interest in recovering subsea cables, owing to several reasons that include, but are not limited to the following:

Logistical drivers related to marine spatial planning: As the seafloor becomes increasingly occupied by marine industries, there is less space for laying new cable routes. Removal of old cables can free up the seafloor for new cable systems, particularly where they reduce reliance on geographically congested areas and where new cables can re-use routes that have been historically resilient to threats such as fishing, anchoring and natural hazards such as storms.

Commercial drivers: Various opportunities exist, including recycling of materials recovered from cables that have commercial value, re-use of recovered cables that can be deployed in other settings such as: i) unrepeatered inter-island links providing connectivity between small islands (particularly to less developed regions where the installation of new systems may be financially prohibitive); ii) festoon systems which provide multiple landing points along a coastline or linking a chain of islands, or storage of recovered cable to serve as spare lengths in case of a repair to similar type of system; or iii) re-purposed to make scientific measurements using techniques such as fibre-optic sensing that has applications to tsunami or volcanic hazards early warning, monitoring near-seafloor ocean conditions, detecting climate-driven changes, or observing cetacean activity (UNEP-WCMC, 2025).

Regulatory drivers: The regulatory landscape is constantly changing, with several jurisdictions now mandating the recovery of cables, with requirements typically ranging from territorial waters (up to three or twelve nautical miles) to the limit of the Exclusive Economic Zone (Appleby and Dawe, 2019). As an example, most jurisdictions in Northern Europe mandate recovery (https://www.gov.uk/government/publications/decommissioning-offshore-renewable-energy-installations).

Environmental and social drivers: There is a growing concern about the cumulative impact of human activities on the ocean, with a push to remove human-built structures from the seafloor (also linked to the concept of Marine Net Gain; Hooper et al., 2021). The recovery of cables provides an opportunity to return high quality materials into the product chain, contributing to the circular economy and reducing our reliance on extracting new virgin materials (Allwood, 2014; Jensen et al., 2020; UNEP-WCMC, 2025).

However, there remains uncertainty and differences in opinion about whether cables should be left in-situ or recovered owing to a lack of clarity in the potential impacts or merits of recovery. So, despite these many drivers, recovery of cables is not currently the status quo, and any existing approaches are highly geographically- or jurisdictionally-variable. While many scientific studies have addressed the environmental impacts of subsea telecommunications cables in their installation and operational phases (e.g. Andrulewicz et al., 2003; Kogan et al., 2003; Kogan et a., 2006; Carter, 2009; Kuhnz et al., 2011; Barry et al., 2016; Sherwood et al., 2016; Kraus and Carter, 2018; Taormina et al., 2018; Carter et al., 2019; Kuhnz et al., 2020), to date no scientific study has focused on their decommissioning, leaving a key evidence gap (UNEP-WCMC, 2025).

2. Methods

This paper primarily synthesises the current state of knowledge that relates directly or indirectly to recovery and recycling operations for subsea cables. A synthesis of public domain and grey literature underpins the background text on cable design, installation and recovery techniques, and potential impacts based on prior understanding of the identified activities. Our new analysis of original observations from twelve cable recovery reports (shared by cable owners and operators) provide an understanding of the different methods and approaches to cable recovery from various locations offshore from geographic Europe and North America for different segments of the TAT-14 Trans-Atlantic fibre-optic telecommunications cable that was commissioned in 2000 and decommissioned in 2020 (Table 1), and we focussed on success of recovery, the condition of the cable, and types of interactions and disturbance in different environmental settings. From two operations that retrieved 1890 km of cable from offshore Portugal and 1483 km from offshore Eastern Brazil, the condition of recovered cables (like biological colonisation and/or cable degradation) was systematically recorded by the deck crew. Any evidence of colonisation was recorded and is referenced here. Video footage that shows cables being recovered onto the deck of the cable vessel was analysed over a period of five days for the cable offshore Brazil, with any instances of degradation or biological colonisation noted, while photographs of the only noted examples of colonisation were provided for the cable recovered offshore Portugal.

These case studies are focused on recovery projects for which data have been provided by industry partners. It has therefore not been possible to provide examples that represent the full range of conditions that exist in the ocean where cables have been installed, primarily being focused on continental shelf settings with a geographic bias of sites towards locations offshore north-west Europe and north-west USA (which are the locations where reported information is available). While these data are valuable (as such observations have not previously been reported upon in such a manner), future studies should aim to represent a wider range of settings – particularly in deeper waters and specifically looking to include lower latitude, warmer settings. It should be noted that the observations that informed this study are primarily based on those reported in cable recovery reports (Table 1). Those reports were written for industry operational purposes, and hence were not designed *a priori* for scientific purposes. Therefore, quantitative information is not comprehensively available for all of the aspects that would otherwise be desired from a scientific perspective; meaning that we do not always have quantification of the dispersion of any suspended sediment plumes that may be created during cable recovery, of water column turbidity, or of species-level identifications of colonising fauna where observed. However, the qualitative observations remain extremely valuable, as this is the first study of its type, and it is hoped that this catalyses future studies that systematically gather more quantitative data.

3. Cable design, installation and the process of cable recovery

We now provide context for the design and components that make up different types of subsea cables, and that are relevant to their installation and potential for recycling, as well as the activities involved in recovery of out-of-service cables.

3.1. Different types of cable and their material components

Different types of subsea cable serve different purposes and feature different designs. We therefore now summarise these differences, discerning between telecommunications and power cables.

3.1.1. Telecommunications cables

Telecommunications cables are small in diameter – typically modern fibre-optic cables are 17–21 mm in deep water ($>$1000 m), and up to 60

Table 1
Summary of telecommunications cable recovery reports available to and assessed in this study.

Location	Year of recovery	Planned cable length for recovery [km]	Length of cable recovered [km[	Recovery success [% length]	Setting and water depth	Method of recovery	Inform-ation available	Holding and cutting grapnel runs	Segments recovered	Colonisation observed	Comments (where information available)
Offshore NE USA	2021	24.89 km	24.2 km	97 %	Continental shelf to 3 nm of the US coast (<42 m)	Recovery vessel with divers	Full recovery report available	N/A - recovered using divers	1	No	Very shallow burial. Locally muddy seafloor
NW France	2022	0.2 km	0.2 km	100 %	From beach manhole to low water mark	Pulled out by tracked excavator	Full recovery report available	N/A - recovered from shore	1	No	Gravel beach
Netherlands	2021	1.17 km	0.6 km	51 %	From beach manhole to low water mark (<30 m)	Pulled out by tracked excavator	Full recovery report available	N/A - recovered from shore	1	No	Sandy beach
Offshore Cornwall & Devon, UK	2022	4.47 km	3.87 km	88 %	Continental shelf to low water mark (<60 m)	Recovery vessel with grapnel	Full recovery report available	19	2	No	Sandy seafloor
Offshore France	2022	7.56 km	7.56 km	100 %	Continental shelf to low water mark (<50 m)	Recovery vessel with grapnel	Full recovery report available	4	2	No	Sandy seafloor
Offshore France	2021	167.17 km	116.1 km	69 %	Continental shelf to low water mark (<30 m)	Recovery vessel with grapnel	Full recovery report available	38	2	No	Sandy seafloor. In places sand is extremely mobile as cable now locally buried up to 10 m deep (originally buried 0.4–0.6 m), requriing multiple grapnel runs
Offshore Scotland	2022	32.3 km	31.8 km	98 %	Continental shelf to low water mark <100 m)	Recovery vessel with grapnel	Full recovery report available	2	1	No	Firm seabed
Offshore Devon, UK	2022	30 km	30 km	100 %	Continental shelf to low water mark (23–68 m)	Recovery vessel with grapnel	Full recovery report available	2	1	No	Soft sand and gravel - sometimes cable exposed
Offshore Cornwall, UK	2022	55.55 km	55.55 km	100 %	Continental shelf to low water mark (<50 m)	Recovery vessel with grapnel	Full recovery report available	2	1	No	Firm seabed
Offshore Netherlands and Denmark	2021	13.15 km	13.15 km	100 %	Continental shelf to low water mark (<30 m)	Recovery vessel with grapnel	Full recovery report available	29	4	No	Buried
Offshore Netherlands	2021	15.30 km	14.86 km	97 %	Continental shelf to low water mark (<30 m)	Recovery vessel with ROV	Full recovery report available	16	1	No	Sandy seafloor. Only holding grapnel runs performed, as cuts performed by ROV. Multiple cuts required due to cable crossings in the area.
Offshore NE USA	2021	213.7 km	198 km	93 %	From the territorial sea limit to the 25 NM limit of US coast (<45 m)	Recovery vessel with grapnel	Full recovery report available	19	1	No	Locally very mobile sand, requriing multiple grapnel runs to locate and recover cable. More variable and muddy seafloor in other places.
Offshore Portugal, NE Atlantic	2023	1890 km	1890 km	100 %	Continental shelf and slope (up to 5 km water depth)	Recovery vessel with grapnel	Photographs of recovered cable provided	Not reported	1	Along a section approximately 3 m in length (at 4540 m water depth)	Mostly muddy seafloor
Offshore Brazil	2023	1483 km	1483 km	100 %	Continental shelf and slope	Recovery vessel with grapnel	Video of recovered cable provided	Not reported	1	No	Mostly muddy seafloor

mm in shallower water where they may be armoured (Fig. 2C). The components used in subsea cables have evolved since telegraph cables were first laid in the mid-1800s, when they comprised a copper wire, encased in gutta percha (a natural polymer derived from tree latex) insulation, wrapped in brass or jute tape (Fig. 2A; Carter, 2009). Subsequently, this design was strengthened by a sheathing of steel wires that provided protection. The installation of subsea co-axial cables started in the 1950s, when polyethylene was used as the outer insulating material around copper conductors that surround fine-stranded, high-tensile steel wire (Fig. 2B). Modern telecommunications cables rely on the passage of light along 125 μm diameter fibres that are surrounded by stranded steel wires that provide strength, and a metallic conductor (typically copper) for electrical continuity. The fibres in fibre optic cable are housed in a fibre unit, often plastic, which is then encased in steel wire with a copper conductor suaged/welded around the wire unit. This is then encased in polyethylene. A lightweight, deep water cable, is not reinforced with outer armouring. Shallow water cable is armoured to provide protection against external aggression threats such as fishing and anchoring as well as the movement of abrasive sediment in shallow waters. The armour comprises layers of high tensile galvanised steel wires encased in a polypropylene serving, which is then flooded with bitumen. Where telecommunications cables are sufficiently long (typically >300 km), there may be a need to amplify the optical signal strength through use of repeaters that are spaced at intervals along the cable (typically around 80 km). Such repeaters are generally 2–4 m in length and 300 mm in diameter, varying in construction but typically comprise a corrosion-resistant, high-tensile stainless steel or beryllium-copper cylindrical capsule, encased in waterproof polyethylene (Schenk and Waldrick, 1984, Fig. 2F–G). Repeaters in co-axial and early fibre-optic cable systems incorporated surge arrestors that were designed to protect the circuits from any spikes in electrical charge (Gleichmann et al., 1957; Pryor, 1958; Holdaway et al., 1964; Appleby and Dawe, 2019). These comprise sealed units installed in the electronics chassis of the repeaters, which contain a small amount (typically on the order of 3 ng; i.e. three billionths of a gram) of radionuclides, the most active being those including Radium-226 (a Gamma emitter with a half-life of 1600 years; Hosseini et al., 2012; Ahmad et al., 2021; Xu et al., 2022). The radionuclide is included to reduce the statistical delay time for the activation of the surge arrestor (Dance, 1967). In land-based uses, ionising radiation from the sun provided this priming; however, a separate source was required for submarine systems. Such components are no longer used in modern fibre-optic systems.

3.1.2. Power cables

Power cables are larger in diameter than telecommunications cables, varying from 70 to 130 mm diameter for inter-array cables, to 100–300 mm for high voltage export or interconnector systems. Power cables tend to be much shorter than telecommunications cables, with the longest route in Europe currently being the NorNed High Voltage Direct Current (HVDC) interconnector that extends 580 km between Norway and the Netherlands. Power cables have been laid since the early 19th Century, where they used natural rubber to provide electrical insulation, being replaced with synthetic butyl rubber by the mid 20th Century. Modern subsea power cables typically comprise inner conductors of stranded copper or aluminium, surrounded by galvanised steel for armouring, then encased in a polymer such as polyethylene or ethylene propylene rubber for insulation (Fig. 2D). In High Voltage Alternating Current (HVAC) cables, three conductors are generally bunded together (Fig. 2E), whereas for HVDC there may be a single or pair of conductors.

3.2. Installation of subsea cables: surface-lay versus burial

Telecommunications cables are mostly laid directly on the seafloor; the exceptions being where they require protection from potentially harmful human activities such as trawling and anchoring. Burial is generally the norm in water depths of less than 1000 m; however, in some cases burial may occur up to 1500 m water depth where fishing activities extend into deeper waters, e.g. Northeast Atlantic Ocean (Clare et al., 2023). It is estimated that 29 % of the total length of subsea telecommunications cables installed to date lies in water depths shallower than 1500 m (continental shelves and upper parts of the continental slope); hence, the remaining 71 % is a minimum estimate for that which was directly laid on the seafloor, with 62 % lying in abyssal or deeper waters (Clare et al., 2023).

Power cables typically lie in water depths of less than 100 m, but exceptions exist in deeper water. As a result, most power cables are typically buried to a target depth of 0.5–1.5 m. However deeper burial may be considered to lessen the chance of exposure. For example, in the

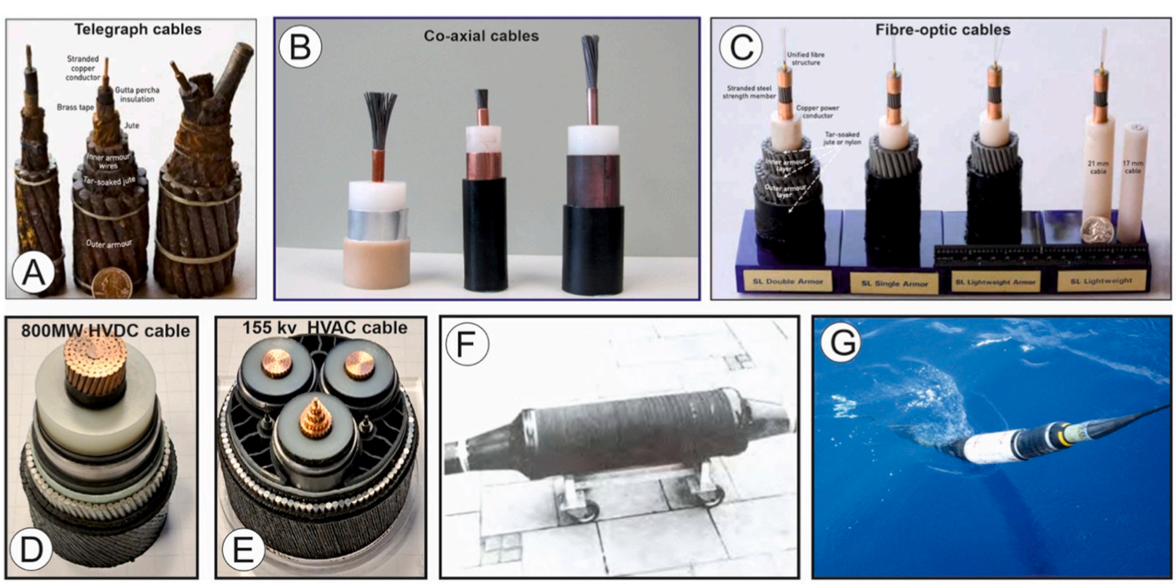

Fig. 2. Examples of different types of subsea cable discussed in this paper, including (A) telegraphic, (B) co-axial and (C) fibre-optic telecommunications cables. Examples of power cables are shown including (D) High Voltage Direct Current and (E) High Voltage Alternating Current systems which are wider diameter than telecommunications cables. A repeater unit for an older co-axial system is shown in (F) which houses electronics used to boost the signal. An example of a more modern fibre-optic repeater is shown in (G).

Netherlands a vertical injector system was used to install power cables up to 8 m, but this is considered atypical and likely to prevent future maintenance/recovery (OSPAR Commission, 2023). Where burial is not achievable, power cables can achieve coverage for greater protection through placement of rock or hard substrates as a physical barrier to human interactions.

The target burial depth for telecommunications cables is typically 0.5–1.5 m, dependent upon the anticipated frequency and magnitude of seafloor disturbance by anchors, trawling and sediment remobilisation by seafloor currents, waves or storms. Burial may be required to a greater depth in certain circumstances, such as in busy commercial shipping lanes and harbours. The deepest burial requirement for telecommunications cables we are aware of is a requirement in Singapore port, to bury cables up to 12 m below seafloor to a depth that can withstand an anchor drop from a Very Large Crude Carrier (IMDA, 2019). Where cables cannot be buried, and there is a need to increase protection in shallow waters, physical measures may be applied. This can include a casing of articulated polyurethane or steel pipe, or localised structures placed along and over the cable, such as scour mats, concrete mattresses and rock berms. The latter are typically reserved for power cables but may be used for telecommunications cables where they cross (or are crossed by) other cables or pipelines to provide physical separation of the infrastructure. The environmental impacts associated with different methods of cable installation are well described by other reports, including OSPAR Commission (2023) and UNEP-WCMC (2025), so are not addressed specifically here.

3.3. Approach for cable recovery

Cable recovery strategies provide important context for potential environmental impacts (Section 4). To first precisely locate the cable, cable charts and route position list (RPL) data are consulted and recommendations of the International Cable Protection Committee (ICPC) are followed, which include 'ICPC Recommendation #1 Management of Decommissioned and Out-of-Service Cables' and 'ICPC Recommendation #2 Recommended Routing and Coordinating Criteria for Submarine

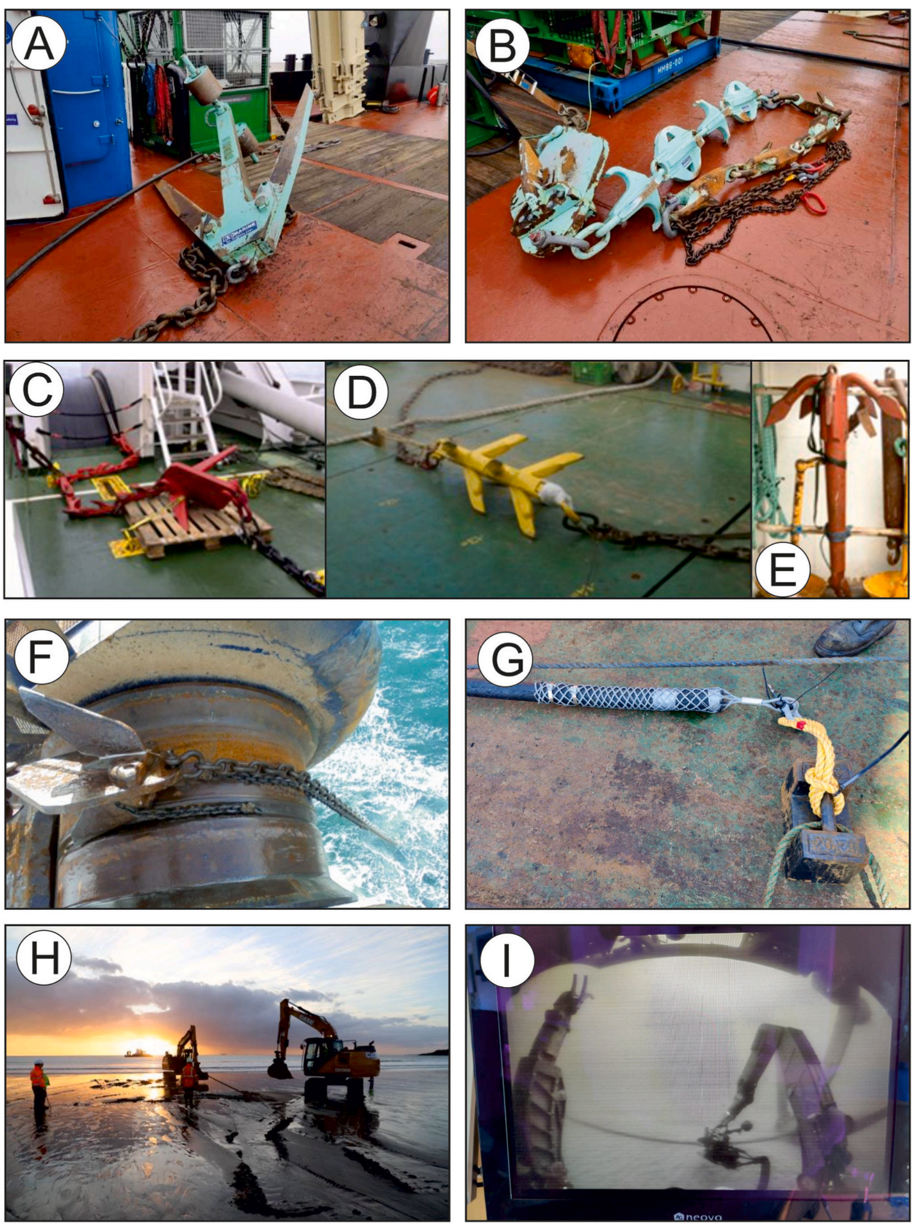

Fig. 3. Devices used for cable recovery, including cutting and holding grapnels (A–F), clump weights that are attached to cut ends of a cable to stop it from moving (G), tracked excavator for recovering shore ends of cables (H) and remotely operated vehicle cutting a cable at seafloor (I).

Telecommunications Cables in Proximity to Other Such Cables'. Significant effort is put into contacting owners of third party seafloor assets prior to decommissioning, and industry notifications of works in specific areas are common.

Recovery operations either require use of a bespoke cable laying or recovery ship, or modification to an existing vessel that has capacity to recover and handle large quantities of cable. For context, a single km of recovered armoured telecommunications cable equates to around 0.7–13 tonnes (depending on diameter and armouring). The physical act of cable recovery typically uses tools called grapnels that cut and hold a cable (Fig. 3A–F). A grapnel train comprises several elements, typically including a hooked cutting blade that is approximately 5 cm thick, and a surface plate that is approximately 50 cm wide, which is connected by flat linked Gifford chains that are approximately 20 cm wide. The cutting grapnel is towed slowly (approximately 1 knot) across the seafloor (where it typically penetrates up to 0.4–0.8 m) until it reaches the cable, which it cuts. A second grapnel run without the blade is performed to hold the cable, allowing it to be winched up to the surface (in the same manner as is routine for cable repair). The Gifford chains are designed to remain on the seafloor and not to penetrate. Grapnels are typically not deployed in areas of hard and irregular seafloor owing to the risk of snagging. Alternatively, an ROV may be used to cut the cable on the seafloor, and to attach a recovery hook. Once the cable end is recovered on deck, a winch is used to pull the remaining cable from the seafloor and up onto the vessel, where it is inspected for condition and any damage, and spooled into cable holding tanks or else cut into specified lengths and placed in containers. The cable is then either recovered by pulling along the cable in the direction of recovery or peeling it back in the opposite direction. In the case of the former approach, it has been possible to pull the vessel along as it retrieves the cable, thus reducing the need for continuously running the ship's engine. A recent example of a project to recover 1200 km of cable from the South Atlantic carried out just one cutting grapnel run, one holding grapnel run and recovered the cable and 97 repeaters. Once the cable was on-board, the main engine was switched off and the cable winch pulled the ship for 1200 km without a break on auxiliary power. For the case of shore-end sections of cable that cannot be recovered at sea because of the shallow waters (typically to the low water spring tide mark), it is often possible to peal the cable from the beach or to remove the cable from any horizontally drilled duct which may have been constructed at installation. This operation often requires mechanical excavation of the beach up to the manhole, which is then reinstated following recovery (Fig. 2H).

Following recovery, it is important that cable recovery reports are provided to the original cable owners such that they can update databases for future marine spatial planning. Once recovered cable sections are brought back to shore, they are either transferred to another location where they can be re-laid, or (more typically) they are mechanically processed to separate out the component copper, polyethylene, steel (and occasionally aluminium) that can be recycled (Fig. 1H,I&J; Appleby and Dawe, 2019).

4. Potential environmental impacts of cable recovery activities

We now discuss the effects that cable recovery may have on the marine environment, highlighting potential impacts based on previous studies that have focused on other aspects of cable installation and assessing the degree to which those impacts may be analogous (or not). Specifically, we focus on seafloor disturbance that can arise from: i) the physical impact of grapnel runs on the seafloor that are used to snag the cable; and ii) the cable being extracted from the seafloor or shallow subsurface (in the case of buried cables). We also discuss the extent to which cables may become colonised by epifauna during their lifetime and summarise recent studies that assessed the degradation of cables recovered after several decades in the deep ocean.

4.1. Disturbance created by grapnel runs

Grapnels could cause physical disturbance to marine habitats when recovering cables, but these are highly localised (OSPAR Commission, 2023; UNEP-WCMC, 2025). Grapnels can disturb the seafloor across the width of the surface plate (approximately 0.5 m) and over a distance that depends upon the ease by which a cable can be located; in some cases, a grapnel run for cable recovery can be up to 1 km but may be much shorter. The depth of grapnel penetration will depend on the type and strength of the seafloor substrate (as similarly observed for the penetration of much larger otter boards in bottom trawling and anchors; McHugh et al., 2014; Watson et al., 2022). Grapnel runs for recovery may only involve a single pass at an individual location, unlike pre-lay grapnel runs which are needed along the length of the cable route for route clearance; hence, the spatial extent of any impacts will be far smaller than that involved in installation. However, where charting is inadequate or a cable has become buried, or moved since its installation, it may be necessary to undertake multiple grapnel runs until the cable is secured. In one case offshore north-east USA, 19 grapnel runs were attempted before cable recovery was aborted, because of significant sediment accumulation over the cable, but it should be noted this is an extreme example of repeated grapnel deployments and is far from the norm.

No peer-reviewed study specifically exists for the impacts of grapnel runs, presumably owing to the relatively small and temporary impacts; however, studies have been performed to look at larger impacts during the initial burial of cables via ploughing or jetting operations. Kraus and Carter (2018) reviewed the impacts on seabed and benthic fauna following the burial of twelve subsea cables worldwide, concluding that biological recovery was related to the physical recovery of the seabed that took months in shallow waters with high sediment supply, to >15 years in deeper waters (130–2000 m) where sediment supply was low. All the studies reviewed by Kraus and Carter (2018) concluded that burial of cables had only limited, small-scale effects on benthic biota; hence it is reasonable to infer that any impacts associated with much less-intrusive and smaller-footprint grapnel runs will be far smaller. It is worth noting that appropriate mitigation measures will affect the level of impact. For example, if grapnel runs are through sensitive habitats this could cause significant impacts, albeit at a small scale.

Attempting grapnel runs for cable recovery in sensitive seafloor habitats should ideally be avoided and environmental surveys prior to decommissioning would be beneficial in such cases, particularly in specific settings, to plan how to minimise impact through the decommissioning process. Modern cable routes factor in such environmental constraints as part of their route planning. Indeed, a review by UNEP-WCMC (2025) concluded that the current global network of subsea telecommunications cables does generally avoid such sensitive areas, with less than 1% of the total length of subsea cables worldwide crossing any type of mapped sensitive biogenic habitats (including cold water corals, coral reefs, mangroves, saltmarshes, seagrasses and seamounts). However, sensitive habitats may be crossed by some older out-of-service telegraph or coaxial cables, whose routing did not consider, or had no knowledge of such environmental constraints. Biogenic habitat structures such as biogenic reefs, *maerl* beds, seagrass, coral gardens or sponge aggregations can be regarded as the most sensitive biota or habitats with regards to seafloor disturbance. This sensitivity relates to the long time it takes for these habitats to establish themselves and the slow growth and/or reproduction of the characteristic species, particularly for reef-forming or encrusting species (e.g. Bosence and Wilson, 2003; Lartaud et al., 2014; Morato et al., 2018). A seafloor power cable laid in the Strait of Georgia, British Columbia was observed in some localised cases to have been laid over, or very close to, fragile glass sponges (in 65–108 m water depth); slow recovery of which was observed in some cases (Dunham et al., 2015). However, some types of biogenic reefs can recover relatively fast (e.g. *Sabellaria spinulosa* appear to recover quickly from small scale physical disturbance provided worms are not killed or removed from their tubes; Vorberg, 2000; BIOCONSULT, 2019 and references therein). Seagrass meadows are a sensitive habitat, which can be impacted by the cutting of rhizomes resulting in a direct damage of seagrass plants and loss of connectivity with the seagrass meadow. In the case of cable burial (more disturbing than a grapnel run), the recovery of *Zostera marina* took between 2 and 7 years (Kraus and Carter, 2018 and references therein). However, seagrass recovery is extremely site- and species-specific. While *Zostera marina* may recover quickly, slow-growing species such as *Posidonia oceanica* (found in the Mediterranean) may require more than 100 years to recover from any disturbance (Duarte et al., 2013; Telesca et al., 2015).

4.2. Generation of sediment resuspension during the recovery of buried cables

Sediment resuspension events can adversely affect benthic biota by smothering, displacement and damage of organisms, but the magnitude of the impact depends on local hydrodynamic conditions, resilience and recovery of potential of the affected species/communities, as well as the intensity and duration of the disturbance (e.g. Thrush and Dayton, 2002; Durden et al., 2023). The greatest disturbance associated with subsea cables will be where burial is required for their initial installation in shallow water, as this involves invasive mechanical techniques such as ploughing and jetting that can generate sediment plumes (particularly the case with jetting). The use of controlled flow or mass flow excavation is not always encouraged or permitted as this will have a far more intrusive impact on the seabed environment and cause significant turbidity. Based on post-installation surveys, Kraus and Carter (2018) found that jetting can create sediment plumes that may spread up to 2 km away from the cable where the substrate is fine mud, but that typically sediment plumes were limited to approximately 100 m of the cable. Elevated water turbidity as a result of jetting or ploughing may last for several days, but more often is found to be limited to a few minutes to hours (Taormina et al., 2018). In the case of the Inner Dowsing Wind Farm (offshore UK), 90 % of sediments resuspended during cable laying

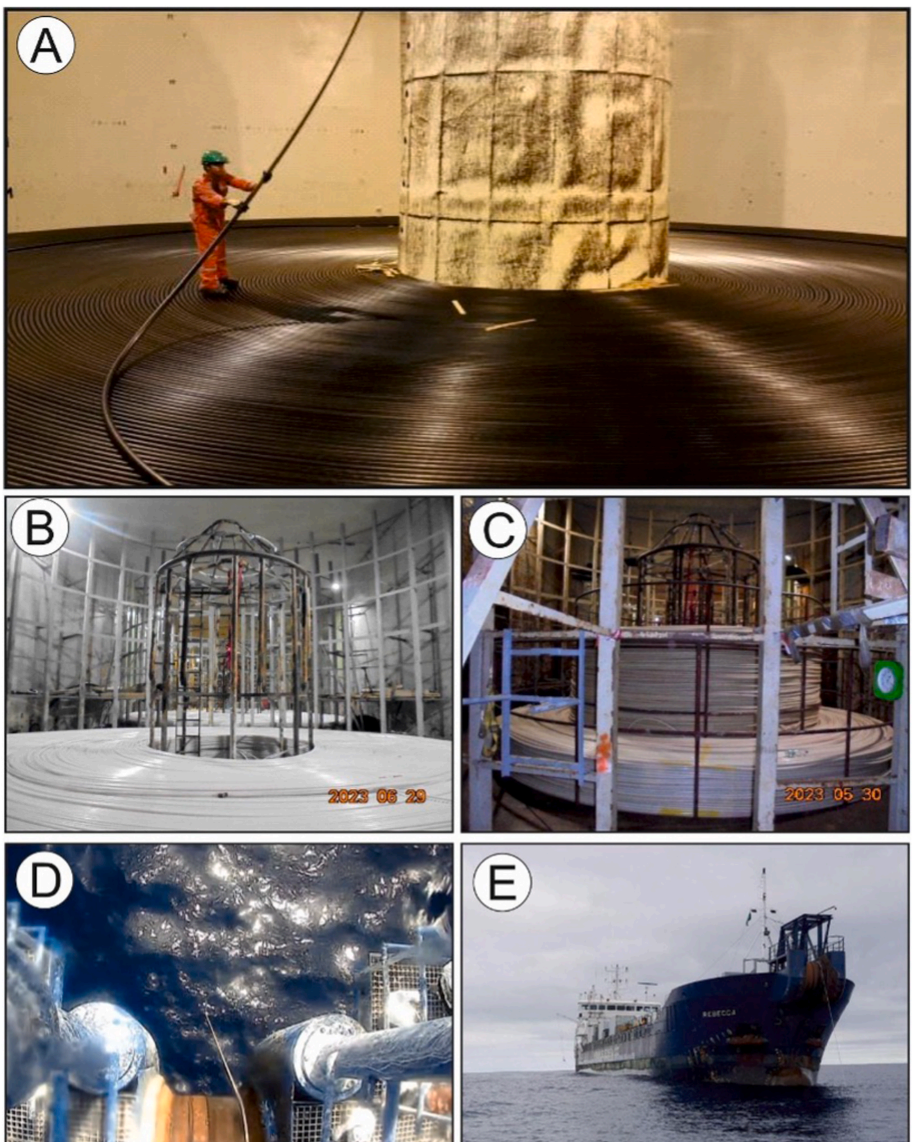

Fig. 4. Cables are typically found to be near-pristine and uncolonized during recovery. (A) A co-axial cable being spooled on-board the recovery vessel after having lain on the seafloor in the central Pacific at almost 5 km water depth since 1974 (from Carter et al., 2019). Fibre-optic cables recovered from offshore Portugal (B&C) and between Hawai'i and Fiji (D; example of cable being brought up onto the deck), that are similarly in excellent condition. Example of dedicated cable recovery vessel during recovery operations (E).

resettled within 1 km of the cable, with the concentration of resuspended material being considered as insignificant when compared with baseline conditions (Baker, 2003).

Permitting constraints placed on recovery operations in shallow inshore settings often restrict recovery operations to location using grapnels, or direct from a beach, and then recovered using a winch. Assessment of ROV video footage acquired during recovery operations of one cable offshore NE USA in this present study did not indicate any apparent plume generated during the retrieval of a seafloor cable. Any sediment plume is therefore likely to be restricted to cases where a buried cable is recovered from below the seafloor and is expected to be only a very localised and short-lived disturbance, with much smaller plumes or sediment disturbance being less than that caused by cable burial activities. Further studies would be beneficial to explore the effects in areas with different types of seafloor substrate.

4.3. Biological colonisation determined from analysis of recovered out-of-service cables

One question around the recovery of cables is whether there could be adverse impacts to biological communities that have settled on the outer surface of the cable. It is well known that many artificial structures, such as pipelines, scour protection devices and oil rigs, can provide a habitat for sessile, epifaunal species (e.g. Gates et al., 2019; McLean et al., 2019). We now discuss to what extent such biological colonisation may be the exception, or the norm for subsea cables.

Seafloor cables recovered from the central Pacific, North Atlantic and Mediterranean Sea after 38–44 years were found to be well-preserved and physically intact with clean outer sheaths with no visible trace of biological encrustation (Fig. 4A,B&C); on this point, it is worth noting that cables are not coated with antifouling agents (Carter et al., 2019). In a recent recovery from offshore Portugal, North-eastern Atlantic, the deck crew kept a continuous record of cable condition during recovery. The 30 mm-diameter telecommunications cable was in near-pristine condition with no signs of degradation apparent along its entirety. Of the total 1890 km length of cable that was recovered in that operation, only one instance of visible biological colonisation was observed, limited to a cable length of less than 3 m where sponges, anemones and hydroids were attached (Fig. 5). The same operation was repeated for another telecommunications cable recovered from offshore eastern Brazil. Along the total of 1483 km of cable recovered, no instances of any degradation nor biological colonisation were noted from visual observations. Analysis of video footage recorded over five days of telecommunications cable recovery in the Pacific Ocean between Hawai'i and Fiji similarly revealed near-pristine cable recovered on deck with no visible evidence of any colonisation along a total recovered length of 1500 km (Fig. 3D). For the eleven different cable recovery reports analysed in this study, no comments were made about biological colonisation. A localised example from a section of cable recovered from shallow water in the Mediterranean Sea showed more extreme colonisation (Fig. 6G); hence, colonisation can occur but appears to be far from the norm, and instead is likely restricted to very specific settings and locations.

When one of the first trans-Atlantic cables was pulled up to the sea surface for repairs, it was locally encrusted with corals, clams and other life (Nature, 1882). This came as a surprise as, at the time, it was thought that the ocean could not sustain life below 600 m; yet this cable was recovered at around 3000 m water depth. Similarly, observations of colonisation of a section of telegraph cable recovered in 1876 after 6 years by *Desmophyllum pertusum* was reported from 1000 m depth off

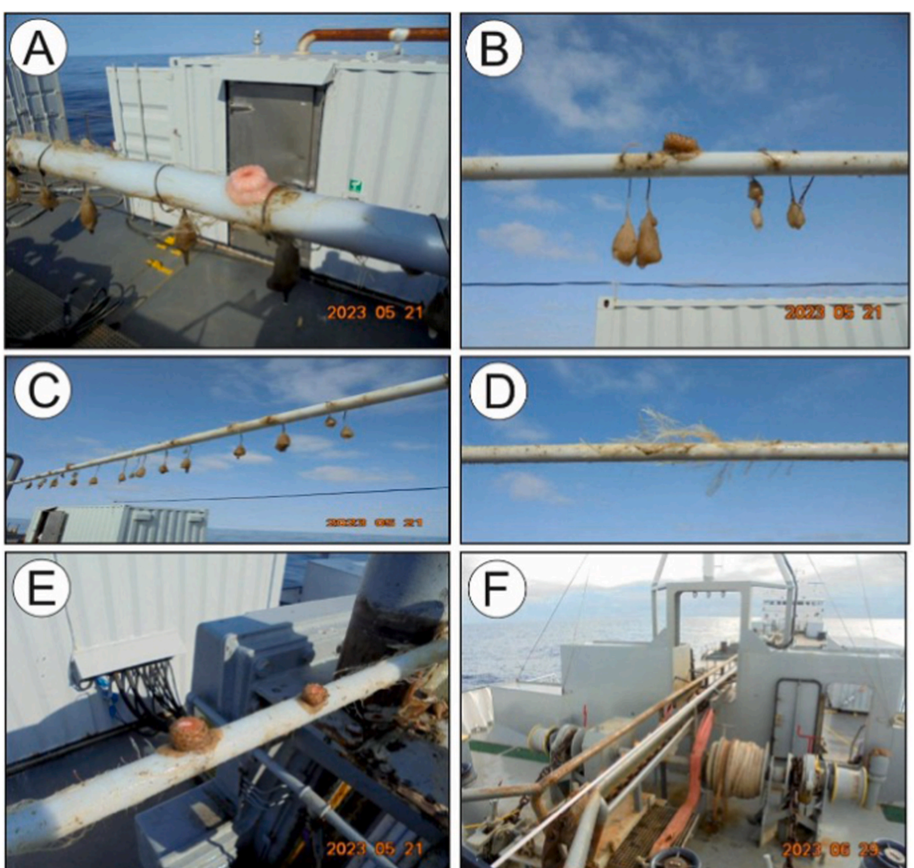

Fig. 5. The only examples of visible biological colonisation along 1890 km of recovered length of cable (30 mm diameter) offshore Portugal. Photographs along an approximately 3 m section show (A–C) sponges and anemones, (D) hydroids), and (E) only anemones. The cable was continuously monitored as it came on board (F).

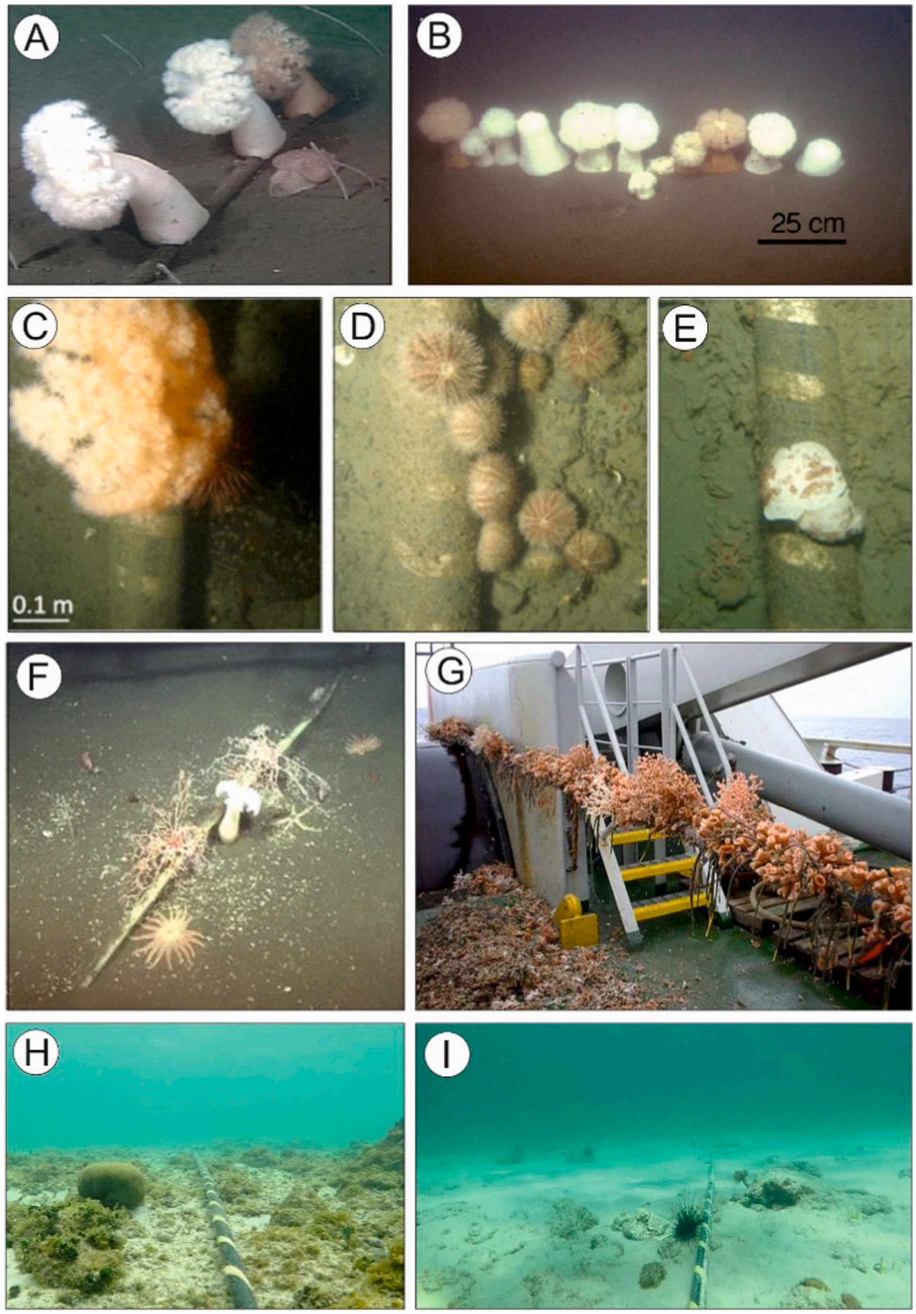

Fig. 6. Examples of localised biological colonisation that is reported in relatively shallow and well-oxygenated waters, including anemones, echinoderms, sea pens and molluscs on hybrid power-communications cables offshore California (A-B; modified from Carter, 2009; Kogan et al., 2006). Sessile and mobile biota observed on a subsea cable in the Strait of Georgia, Canada, including (C) *Metridium* sp. and *Mesocentrotus franciscanus*, (D) Strongylocentrotus droebachiensis, and (E) Nudibranchia. (F) Colonisation of partially exposed section of cable from Half Moon Bay in northern California (from Carter, 2009). Rare instance of extreme colonisation by coral on an armoured cable in the Mediterranean Sea (G). Examples of other surface laid cables in the Caribbean Sea, that are not colonised, but are in close contact with organisms (H–I).

NW Spain (Duncan, 1877). A further record from 800 m depth in the Bay of Biscay revealed colonisation by much larger coral colonies between laying in 1930 and repair in 1968. A total length of 460 m of cable was reportedly encrusted in coral. Such observations and the known duration of cable deployment allowed estimates of the growth rate of these slow-growing cold water corals (Wilson, 1979). Other telegraph cables repaired in the late 1800s revealed specimens of blanket sponges from the Bay of Biscay and heavy encrustation by corals offshore Singapore. It was noted that where the outer protective sheath of old telegraph cables remained intact that there was no evidence of colonisation, which only occurred where the inner iron wires were exposed (Nature, 1882).

Co-axial cables have also been reported to locally support various epifauna and epiflora (e.g. Ralph and Squires, 1962; Levings and McDaniel, 1974), although relatively sparse information is available for such systems. Based on analysis of 42 h of video footage of the seafloor, Kogan et al. (2003, 2006) observed no statistical difference between the abundance and distribution of fauna on the seabed within 1 m and 100 m of the ATOC scientific co-axial cable offshore California. The cable locally provided a hard substrate for anemones (*Metridium farcimen*) where the cable crossed soft, cohesive seafloor sediments, that would otherwise be unsuitable for them (Kogan et al., 2006). However, this and other cables offshore California were more typically buried by the natural sedimentation, with no seafloor expression of the cable after only a few months or years and this surface became unavailable for colonisation (Kraus and Carter, 2018).

Very localised biological colonisation was noted on a power cable in the Strait of Georgia, British Columbia at Galiano Ridge (Dunham et al., 2015). Sessile and mobile biota were observed on the cable, including anemones (*Metridium sp.*), sea urchins (*Mesocentrotus franciscanus, Strongylocentrotus droebachiensis*, and nudibranchs (Dunham et al., 2015). Partial colonisation of four in-field power cables that connect between floating wind turbines was reported offshore Scotland at the Hywind Scotland Pilot Park, being dominated by barnacles (Balanoidea), and with three possible young colonies of deep-water coral (*Desmophyllum pertusum*), on one cable (Karlsson et al., 2022). It is worth noting, however, that these cables were suspended in the water column, and are thus not necessarily a like-for-like comparison for cables laid on the seafloor.

While colonisation of cables has been reported in several locations, the limited physical footprint of subsea cables (particularly in deep water where they are 17–21 mm diameter) means they cannot support high habitat complexity (OSPAR Commission, 2023). Instead, colonisation and associated increases in species diversity and abundance are more prone on larger-area structures that may be installed to provide protection for cables where they cannot be buried (e.g. rocky seafloors). Such structures may include concrete mattresses or rock placement, and are more typically used to protect power cables and less frequently used for telecommunications cables, except when crossing third part assets (e.g. pipeline crossings). In rare cases, metal protection may be used (e.g. steel half shells clamped around a cable). A concrete mattress at the Hywind site was found colonised over 40 % of its surface by polychaetes (*Sabillaria spinuolsa*) and hydroids (*Ectopleura larynx, Nevskia ramosa, Tubularia indivisa* and *Urticina* spp.) (Karlsson et al., 2022). Rock mattresses used to stabilise a cable connecting a tidal turbine site offshore France experienced heavy colonisation by megafauna including lobsters (*Homarus gammarus*; Taormina et al., 2018). Where a hybrid power and telecommunications cable could not be buried (due to outcropping bedrock) in parts of Bass Strait, south-east Australia, it was locally protected in shallow water by a metal shell (not a routine practice for cable protection). Sherwood et al. (2016) noted that the shell had a benthic community similar to that of the surrounding area within three years, having become entirely colonised. For sections of the same cable system that were buried, some epifaunal colonisation was noted on the cable and fragments of consolidated sediment exposed in the trench; however, this had disappeared as the trench infilled with natural sediment and the seabed returned to its normal state over the course of one to two years (Kraus and Carter, 2018).

5. Summarising the state-of-the-art understanding and recommendations for the future

5.1. Recovery of subsea cables returns commercially valuable materials to the economy

The limited degradation of subsea telecommunications cables in the marine environment means that their components are typically of high grade and offer a high degree of re-use or recyclability (Fig. 7). This statement is based on previous studies that analysed sections of recovered subsea cable that had laid on the seafloor for several decades, as well as laboratory experiments that subjected sections of new and old cable to corrosion by seafloor. Further information is detailed in those studies and summaries (Collins and Mudge, 2008; USA Navy, 2014; Carter et al., 2019; OSPAR Commission, 2023). Analysis of sections of recovered telecommunications cables from the central Pacific, North Atlantic and Mediterranean Sea that had lain on the seafloor for a period of 38–44 years revealed that their plastic outer sheaths were intact, apart from a few patches of scuffing that occurred during recovery operations (Fig. 4A; Carter et al., 2019). No degradation of the inner conductors was apparent, and the stranded steel that provides the strength to the cable was free of corrosion. Laboratory studies that subjected new and recovered cable sections to a range of simulated environmental conditions, including corrosion by seawater, confirmed that lightweight cables (the unarmoured type that is laid in international waters, which accounts for >85 % of the ocean and cable length, and that has an outside diameter of 17–21 mm and a mass around 0.7 kg/m; OSPAR Commission, 2023) are chemically inert (Collins and Mudge, 2008; USA Navy, 2014). Laboratory analysis of cables with protective metallic armour (the type installed in water depths ~<1000m) temporarily released very low concentrations of zinc, primarily on intentionally damaged sections of cables. Zinc naturally occurs in seawater, largely being introduced from the atmosphere and rivers (17,000–66,000 tonnes per year; Weber et al., 2018). The very low concentrations observed (<11 parts per million) recorded in the small, contained experiment would be significantly further diluted within the open ocean, particularly with the action of currents that sweep across the seafloor. Therefore, the limited degradation of subsea telecommunications cables in the deep sea (which ensures that they provide compelling targets for recovery and recycling) may also provide justification for leaving them in situ, owing to their neutral to benign impacts following installation (International Cable Protection Committee, 2016). The literature base is less well developed for subsea power cables, although studies have addressed factors affecting cable life, including abrasion and corrosion, which could lead to degradation of cable integrity, potentially providing challenges to recovery (e.g. Tang et al., 2018; Dinmohammadi et al., 2019; Wang et al., 2021; Ahmad et al., 2024).

Where recovered cables can be re-deployed elsewhere, this would

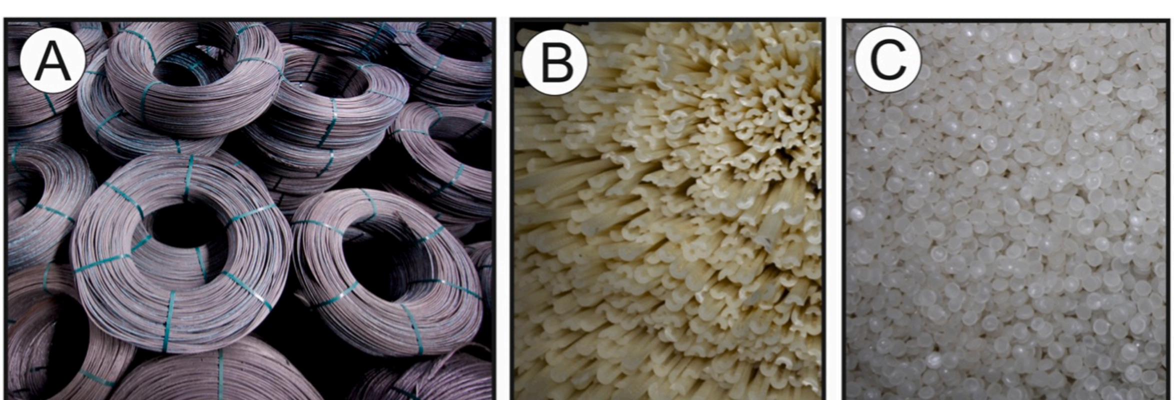

Fig. 7. Components from subsea cables can be recovered for recycling, including the stranded steel (A) and plastic sheathing (B), which is pelletised for re-use (C).

represent a truly circular economy. For example, two analogue cables recovered in 1988 were re-deployed as a 27 km-long cable system between Cuba and the USA, while in 2007 an out-of-service fibre-optic cable was recovered from offshore USA and re-laid to provide a new connection in Bermuda. In the case of recycling of cables, in most cases close to 100 % of the materials they comprise (copper, polyethylene and steel) can be re-introduced to the global supply chain, reducing the need for further exploitation of virgin materials and CO_2 emissions (Appleby and Dawe, 2019). Some repeater units from older fibre-optic and co-axial cable systems contain cathode tubes that were primed with a small amount of radioactive material (typically Radium-226) that cannot presently be recycled cost-effectively (due to the trace amounts used in surge arrestors); however, recyclability of the repeaters and equalisers still remains high (95 % by weight is not uncommon for older systems that contain such components). The level of radioactivity of these small (around 3 ng) Radium-226 sources is low and they are classified as Category 5 Radioactive Material (i.e. cannot cause permanent injury and are classified as UN2911 Exempted Packages. In many cases there is no residual activity because the isotope used has completely decayed. The International Maritime Organization classifies these as Class 7 materials. Their housing within the repeater serves as a Type B Equivalent Transport Container (i.e. designed to safely transport radioactive materials), which means that activity beyond that housing does not exceed background levels during both the operational life of a subsea cable and any recovery operations; hence, they can be recovered safely but it is essential that the extraction and disposal is undertaken by licenced radiation remediation specialists (Appleby and Dawe, 2019). Most repeater types have up to four to five layers of protection outside of the electronics chassis, which are usually located within a brass tube, that is then housed inside a plastic tube sat inside the sea housing. Removal of the sources from the electronics chassis is a relatively straightforward procedure, but one which must be dealt with by certified radiation remediation specialists, following all requisite environmental management and monitoring protocols. All sources are then transported to licensed processing facilities where the radioactive materials are extracted and then stored appropriately according to prevailing national requirements and International Atomic Energy Agency (IAEA) guidelines.

5.2. Cable recovery has a localised environmental impact and biological colonisation by megafauna is the exception rather than the norm

Consideration should be given to the marine environment (whose designation may have changed since a cable system was installed) on a case-by-case basis, particularly to ascertain the sensitivity of any habitats and the method of recovery. However, recovery of subsea cables appears to only have a very very localised environmental impact; being primarily related to short grapnel runs and localised disturbance from pulling up shallow-buried cables. Any disturbances will therefore be far smaller than those that relate to cable installation, unless there were to be a requirement to retrieve deeply-buried cables, which would warrant use of mechanical trenching, plough or jetting tools, or remove any physical protective structures. Cable recovery also plays a key role in removing out-of-service infrastructure to enable the installation of new cable systems along previously-used routes, reducing the need to route through previously undisturbed or more sensitive areas of seafloor.

On the basis of the studies performed to date, and observations from recovery operations assessed in this present study, biological colonisation of subsea cables by larger visible organisms (megafauna) appears to be the exception rather than the norm and is more likely on older telegraph cables than co-axial or fibre-optic cables, or else is more reserved to protective structures than cables themselves. Indeed, were cables to consistently be extensively colonized, the removal of encrusted or attached species would complicate recovery operations, with adverse commercial implications. It would be scientifically valuable to systematically record any instances of colonisation along subsea cables where it does occur, ideally sampling the different species encountered and also recording information in relation to water depth, seafloor substrate and other environmental conditions. Such an approach was advocated for as far back as when early telegraph cables were first repaired. An article in 1882, commented: "*Cable operations have been of great assistance to the geographer, and the soundings taken in order to ascertain the nature of the sea-bottom, where a cable route is projected, have enriched our charts quite as much as special voyages. There is, however, another way in which these operations could be made subservient to the cause of natural science; but it is a way which has not been sufficiently taken advantage of. Besides the specimens of stones, mud, and sand, which the sounding-lead brings up from the deep, the cable itself, when hauled up for repairs, after a period of submergence, is frequently swarming with the live inhabitants of the sea-floor crabs, corals, snakes, molluscs, and fifty other species-as well as overgrown with the weeds and mosses of the Bottom. Some valuable information might be gained if the electricians of repairing ships in these eastern waters would only make some simple observations. Curiously enough, so long as the outermost layer of tar keeps entire, very few shells collect upon the cable, but when the iron wires are laid bare, the incrustation speedily begins, perhaps because a better foothold is afforded*" (Nature, 1882). This message is still pertinent, and technology has changed since then, enabling many more approaches that have been used to record information during cable recovery operations, such as using Remotely Operated Vehicles (e.g. Fig. 3I), from direct sampling of specimens, or by use of Environmental DNA (Rees et al., 2014; Jones et al., 2019). Where colonisation does occur, analysis of recovered cables sections may provide insights into deep sea ecology that would otherwise go unknown (UNEP-WCMC, 2025). Cables may provide a very localised so-called 'reef effect' where they provide a localised hard substratum for sessile, epifaunal species, thus increasing species richness with a potential positive ecological effect; however, the small surface area of a cable does not support high habitat complexity and the reef effect is only considered to apply to larger surfaces of hard substrate, such as concrete mattresses or rock placement at cable crossings which may be up to 150 m^2 in area (OSPAR Commission, 2023).

Future studies could involve more detailed seafloor surveys (e.g. using Autonomous Underwater Vehicles and Remotely Operated Vehicles) and sampling of a range of biotic components (e.g. megafauna, macrofauna, meiofauna) in the vicinity of the cables throughout their life (including control conditions) and following recovery to establish ecological succession, timescale for seafloor and environmental recovery after any potential disturbance (or lack thereof). Scientific cabled observatories may provide ideal opportunities as example sites for such study. To ensure the most useful scientific data are acquired, information should be systematically recorded during recovery operations in a standardised manner. This should include taxonomic identification of any colonising species, their extent and links to environmental variables (e.g. depth of burial, cable age and type, seafloor substrate etc).

5.3. It is not always possible to recover all lengths of subsea cables

A recovery operation will aim to retrieve as much cable as possible; however, the cable recovery reports that we analysed (Table 1) revealed that the total recovered length did not always match that which was desired. For the case study examples in this paper, the success of recovered length varied from 51 % to 100 %, with an average of 92 %. We now discuss some of those reasons, which explain why mandating full recovery of an entire subsea cable system may not be sensible or feasible in all cases.

5.3.1. Excess burial

The burial of cables on the beach is generally readily achieved to 2 m depth, and in limited cases this may continue along the shore end burial, but recovery is readily dealt with by use of an excavator or by pulling on the shore end. The main issue with recovering a buried cable offshore is being able to locate the cable. Cables are typically buried offshore for protection in water depths of up to 1000–1500 m, to target depths of 0.5–1.5 m below seafloor; however, while up to 1.5 m burial may be desired, burial is challenging in submerged settings, and a shallower burial depth is more normally the case. De-trenching grapnels that can penetrate 1 m depth are manageable, and therefore most cable lengths are typically recoverable. Larger grapnels are extremely cumbersome to operate, but in shallow waters (i.e. less than around 1000 m water depth), once a section of cable has been accessed, it is still possible to recover sections that are buried up to around 1.2 m by peeling the target (i.e. pulling up cable that is buried). Experience of recovering double armoured cable (with a maximum breaking tension of 75 MT) has shown that this can work, but the cable parted where it was buried >2 m. Any burial below this depth requires controlled flow excavation and more invasive methods, which are more environmentally impactful and for which obtaining permits are often challenging.

Post-burial sediment movement can pose a significant challenge, making cables that would otherwise be accessible, inaccessible. Analysis of cable recovery reports offshore France and USA revealed it was not generally possible to recover some cables where they were buried more than 0.8 m below seafloor. In one instance offshore France, a cable section had become excessively buried by the migration of sand waves, meaning that 51 km of a total of 167 km of cable could not be recovered and was left in situ. In another case offshore north-east USA, while 24.2 km was recovered, 688 m cable length could not be recovered because the maximum working tension was reached on the recovery winch, which should be capable of a 15 MT pull. Soundings from the recovery vessel showed that water depths were noted to have shallowed to 22–25 m, compared to the water depths of 26–27 m at installation.

Deep water cable is not mechanically buried during installation, but may subsequently become buried locally by natural processes (e.g. abyssal currents, turbidity currents in deep-sea canyons, and other natural hydrodynamic events), but experience has shown that this is typically recoverable. Exceptions may exist where burial has occurred as a result of catastrophic natural processes, such as underwater landslides or volcanic eruptions where cables can become buried by tens of metres of material, transported down to several thousand metres of water depth and along courses up to several thousand kilometres long (e.g. Clare et al., 2023; Talling et al., 2022).

Shallow water is the most challenging for recovery from burial because this is where the cable is most deeply buried and where active sedimentation can be evident. Locating the buried cable in shallow water is the biggest challenge and tensions experienced are higher when compared with deep water. On average tensions of 12 MT are achievable, with peaks of up to 20 MT, based on the mechanical limitations of chartered, shallow draft vessels for such operations. These chartered vessels are mostly ‘MultiCat’ (multipurpose) vessels, which have significantly greater pulling capacities than deep water recovery vessels. Deep water tensions depend on the cable type and the depth of water involved, with tensions of up to 10 MT within the working mechanical limitations of the ship’s equipment.

In exceptional cases, deep burial can be intentionally undertaken for a specific reason, such as high levels of human activity in a particular area, or due to dynamic seabed conditions that risk cable exposure or suspension, which can more commonly be the case for power cables in European waters (Bricheno et al., 2024). There are areas of the world where there are examples of extreme intentional deep burial to a depth of 10 m below seafloor for telecommunications cables. This has been required as a permitting/consenting condition; notably within Singapore port limits and the Traffic Separation Scheme (TSS), and also in Hong Kong. It is highly unlikely that these sections would be possible to recover (IMDA, 2019). In order to recover deeply buried cables, specialist de-burial or de-trenching equipment or mass flow excavators may be required that have more significant environmental impacts than typical cable recovery peel back techniques that are currently used, and are thus more typically left in situ.

5.3.2. *Constraints caused by existing infrastructure*

Out-of-service cables may be crossed by later-installed submarine telecommunications cables, power transmission cables, and pipelines, in which case an out-of-service cable cannot be recovered without potential damage to other infrastructure. Therefore, even when cables are recovered, there will necessarily be some sections that are not recoverable. Where a live cable crosses one that is targeted for recovery, it is necessary to cut around that crossing location, leaving part of the recovered cable fixed to the seafloor with clump weights (Fig. 3G). Where cables cross at 45–90°, a cut is made either side of the crossing at a distance of three to five times the water depth from the live cable; however, where cables cross at smaller incidences or in parallel, if there is separation distance of less three times the water depth, then recovery is not attempted. The presence of concrete mattresses, rock protection or other physical protective structures will locally limit the ability to recover cables.

5.3.3. *Regulatory or permitting restrictions*

Governments may decline to provide removal permits for cables on the perceived grounds that removal would cause more disturbance to the marine environment (e.g. disturbance of seafloor sediment and generation of turbidity in the water column and extraction of buried cables) or to marine cultural heritage (Flatman et al., 2009) than leaving an out-of-service cable in situ. This may be particularly true for cables buried in Marine Protected Areas, where there could be designated features of more vulnerable ecosystems that are protected within the site and they wish to avoid disturbance. In most cases where cable removal is proposed, it is for marine spatial planning purposes rather than environmental reasons. The benthic impacts of recovery are likely to be negligible but still higher than leaving in situ - therefore the drivers from governments or regulators are generally in relation to freeing up seafloor, reusing existing routes, or leasing the seabed for other activities.

Within regulatory processes, it should not be assumed that cables can or should be recovered in all circumstances; however, barriers to recovery should be assessed and eased where appropriate. When permits, concessions, or seabed leases are granted, there can be requirements for infrastructure to be removed at end of service from areas within national jurisdiction. In addition, at the time of installation, permits can be conditional on deep burial to avoid interaction with other seabed users or damage to the cable. This can create policy tensions, as deep burial can render it impossible to recover cables, and some sections of cable may not be recoverable even when installed using typical methods due to dynamic seabed movement, sedimentary remobilisation, or assets being installed over the top.

There is no consistent, harmonised approach for the policy and governance in relation to recovery of subsea cables internationally, which inhibits certainty for planning and decision-making by governments, regulators and industry as a whole. Decisions are currently made on a case-by-case basis, often requiring consent or licenses or as a result of the consenting conditions. Many regulators now request a decommissioning plan that evaluates both options (i.e. leave cable in situ or to be recovered). As an example, there is wide diversity in the regulatory approaches that are taken across geographic Europe. Under the MSP Directive (2014/89/EU), European Union member states are obliged to have had marine spatial plans in place by 2021; however, there are different approaches taken by those members states to the management of legacy seafloor assets – and some member states have not yet fully implemented the MSP Directive. The Netherlands and France both have consent conditions that presume full removal of at the end of life for the entirety of a subsea cable system, which does not take into consideration the conditions under which it will not be possible to recover a subsea cable (e.g. at crossings of in-service cables, due to excess burial etc). This lack of nuance leads to a lack of certainty for industry at the outset of a project. This is in contrast with Denmark, where a streamlined and straightforward approvals process considers recovery on a case-by-case basis, providing greater regulatory incentives that still allows governance and oversight.

Under the United Nations Convention on Law of the Sea (UNCLOS), while there is no requirement for a licence to install or repair a subsea telecommunications cable within the Exclusive Economic Zone (EEZ) of the United Kingdom, there is for cable recovery. Within UK waters there is a contractual requirement and economic incentive for modern cable to be removed, once they are out of service; however, the permitting process does not easily facilitate this, often extending the period of time an out of service cable remains in situ and increasing the associated costs. There is also no mechanism for the recovery of older out of service cables, which fall under an old regime but still require a Marine License to recover. In the UK, for cables installed in the last couple of decades, wayleave is charged on a cable, be it in or out of service. This approach is based on contractual commitments imposed in UK waters on cable owners. For the TAT14 system, for example, there was an economic incentive to recover the cable in UK waters in order to remove these charges. All new cables in UK waters also require a decommissioning plan with relevant funds put aside for these works. This situation creates a regulatory disincentive to recover out of service cables from UK Territorial Waters or EEZ, which is compounded by a lack of a regulatory vehicle by which owners could be obliged to recover cables. This issue could be addressed providing an exemption for licencing to harmonise it with installation and repair activities, or through self-service licensing (e.g. as administered by the Marine Management Organisation in the UK; MMO (2025)).

Similar divergence in approaches exist elsewhere worldwide, and even within individual national jurisdictions, as exemplified by regulations varying by State within the United States EEZ (e.g. California imposes more prescriptive conditions than for East Coast states) with some states specifying recovery as a requirement. Works within the US territorial sea must be undertaken by a US-flagged and US-crewed vessel (relating to the Jones Act; US Customs and Border Protection, 2024). Beyond three nautical miles, foreign flagged vessels can be used, provided they do not call at any US port. Permitting is generally associated with the US Army Corps of Engineers and the relevant Environmental Protection Agency. Local Authorities are involved where land-based cable is to be cleared from beaches or ducts. Other jurisdictions have regimes in place that can make cable recovery activities challenging, such as in the cases of Indonesia and India where only flagged vessels of these two nations, crewed by their own citizens, are allowed access to work in their waters respectively; this is the case for both installation and recovery works, which may make cable recovery much less likely. Some countries, such as New Zealand, have a self-certification procedure which is a paper-based application for recovery within their EEZ (despite being an exempted activity). It is hoped that this present paper provides a basis to support greater harmonisation of approaches between different jurisdictions, and to stimulate discussions around a more generic globally-applicable solution.

5.3.4. *Re-purposing of cables for scientific and other applications*

Advances in technology now enable the optical fibres at the core of modern telecommunications cables to be used as distributed sensors that can make fine-scale measurements of strain, temperature and ambient noise that have been shown to have potentially broad utility in ocean science. Such applications include the use of fibre-optic sensing as an early warning system for tsunamis, to detect and characterise earthquakes and volcanic eruptions, to monitor ocean bottom temperatures and currents, and even to detect biophonic noise generated by cetaceans and other marine life (e.g. Lindsey et al., 2019; Matias et al., 2021; Nishimura et al., 2021; Bouffaut et al., 2025; Landrø et al., 2022; Marra et al., 2022; Rørstadbotnen et al., 2023; Spingys et al., 2024). There are few locations in the deep ocean that benefit from sustained monitoring and in most cases, such monitoring is far from real-time (Levin et al., 2019). Fibre optic sensing along cables provides a potentially valuable opportunity for relay of information across long distances without reliance on sea-going vessels. In some cases, out-of-service cables have been repurposed for such scientific applications and may thus remain in use, albeit for a different purpose to that for which they were initially commissioned. Therefore, governments or regulators should not always plan for cables to be recovered after their approximately 25-year lifetime if there can be further scientific and conservation value in such repurposing (UNEP-WCMC, 2025).

5.3.5. *Considerations around marine net gain*

In order to address long-lasting impacts of human activities on biodiversity in the ocean, corporate organisations and governments are starting to commit to policies of nature improvement and restoration that ensure any biodiversity impacts are compensated for, such that the result is a healthier environment than beforehand (termed 'Marine Net Gain'). Marine Net Gain principles ensure that all development activities are accompanied by further biodiversity improvements. It is increasingly recognised that certain physical structures may enhance endemic biodiversity through colonisation, and hence can play a role in Marine Net Gain such as through biodiversity offset calculations (e.g. Bas et al., 2016; Weissgerber et al., 2019). Smyth et al. (2015) found that endemic epibenthic communities had started to become established locally on rock armouring on the Wave Hub power cable offshore Cornwall (UK) within five years of its installation. As decommissioning is not planned until after 2037, it has been suggested that colonisation will be highly productive and that removal of such protective structures would effectively remove the habitat and the ecosystems services provided, undoing any biodiversity enhancement (Sheehan et al., 2020). In the case of renewables developments, it has been proposed that partial decommissioning is most appropriate for the conservation of benthic biodiversity; wherein foundation structures are cut at or below the seafloor and removed, while buried cables (that would require excavation) and any protective structures are left in place, because of the ecosystem services they provide and the disturbance that would arise from their retrieval (Drew, 2011; Sheehan et al., 2020; Spielmann et al., 2023a,b).

Ambiguity in ownership of old cable systems: This may arise due to an inability to locate or verify the legal owner of older cables due to records being lost or data not stored online; particularly those dating back from the 1970s to the telegraph era, which can complicate or prevent full recovery, even when technically feasible. This underscores the importance of public archives (e.g. https://pkporthcurno.com/collections/our-archive/) and improved ownership records, regulatory clarity, and collaboration with telecom providers to grant permissions for cable retrieval. Without such measures, cables that could be recovered and recycled potentially remain on the seafloor.

5.4. *Suggestions for the future*

There may be benefits in a more strategic approach to cable recovery in future. Some of the possible enhancements that have potential environmental benefits may include.

- Reduced repeat seafloor disturbance: A single-activity longer-length recovery operation would minimise repeated interactions with the seabed, replacing multiple, smaller route clearance efforts over time as development increases with lesser frequency, longer length recovery process.
- Addressing legacy challenges: The retrieval of out-of-service cables from areas designated for future marine developments or new cable routes could mitigate potential spatial conflicts and ensure more efficient use of seabed resources. In addition, it means fewer sections of cable would remain due to a more strategic approach to recovery.
- Regulatory and policy: The suggestions above rely upon reduced regulatory barriers that exist in some jurisdictions and rely upon an innovative approach to policies relating to compensation or marine net gain. Active engagement between governments, industry and stakeholders is needed to identify and enable these opportunities.

- Consideration of whether removal of out-of-service infrastructure can be considered as a compensation option, or as a marine net gain measure, can support streamlining and reduced barriers in consenting for other sectors (e.g. offshore renewable development).

As the issue of decommissioning marine infrastructure is relatively new, it is apparent that there is a lack of consistent approaches for end-of-life management of subsea cables. Different approaches are sometimes taken in different jurisdictions, and different considerations are made, even within the same regulatory organisation due to varying foci of departments. For example, a focus on natural capital may lean decision-making towards leaving cables in situ to minimise any seafloor disturbance, a lens on the circular economy would steer towards recovery and recycling being preferable, while a focus on strategic marine spatial planning could advise removal of old cables to free up space for new assets or suggest to limit recovery so as not to jeopardise existing infrastructure. It is therefore clear that there is a need for a more holistic approach, and the gathering of appropriate evidence, ensuring that multiple stakeholders and sectors are engaged to inform responsible decision-making.

It is hoped that this study motivates further work, particularly field-based studies to strengthen the evidence base in relation to environmental considerations for the decommissioning of subsea cables, and to inform decision-making. Engagement should continue between the subsea cable industry, governments, policymakers, and scientific research community to share data (particularly via open-access scientific databases) and provide access to and understanding of the latest evidence base. Such information can feed into regional best practices, such as via the OSPAR Commission, which should be updated as the evidence base develops. The new insights gained from such engagement and data sharing will likely have wider environmental scientific value in addition to informing decision-making around decommissioning. Ideally, this will inform a more harmonised approach to such decision making, with sharing of lessons learned between jurisdictions that can be enabled through various fora, such as the OSPAR Commission and United Nations Environmental Programme. Non Governmental Organisations (NGOs) can play a key role in bringing together key stakeholders and in promotion of approaches, such as the International Cable Protection Committee and European Subsea Cables Association, who have working groups focused on decommissioning and cable materials. Cross-sectoral organisations are particularly useful in this regard as they also ensure that multiple industry sectors can share knowledge, understand potential conflicts, and navigate solutions. An example is the Seabed User and Developer Group in the UK, which brings together maritime industries across many sectors, government, its agencies and other stakeholders, such as environmental NGOs, to co-develop strategies for regulation and marine management, ensuring benefits to both business and environment, which is critical for effective development and implementation of new approaches. This issue becomes increasingly timely as seafloor use becomes increasingly under competition with the expansion of offshore industries such as offshore wind, in light of the emergence of biodiversity or marine net gain, and due to increasing requirements for new and geographically diverse subsea cable routes for power transmission, communications, financial trading, and digital data traffic.

Innovative data acquisition (e.g. eDNA) during cable recovery operations has the potential to provide complementary new scientific insights in areas that are sometimes poorly characterised or surveyed. The collation of cable recovery reports and monitoring of cable condition that cover a greater geographic range would also be extremely valuable. The majority of case studies that we focussed on in this contribution are in proximity to geographic Europe and North America; hence, further studies that include offshore Asia, Africa, America and the Pacific Ocean would extend the commentary in this paper.

More systematic recording of cable condition and biological colonisation during recovery operations would be beneficial to enhance the current evidence base. Ideally such recording should characterise all lengths of a cable, rather than just sections that are deemed ‘interesting’ to provide a complete picture. There is also value in gaining a greater understanding of the value played by localised artificial structures that used to physically protect a cable, and their potential for biodiversity enhancement. Future studies could include assessment of potential chemical and microbiological drivers for colonisation dynamics on these structures compared with the cables, e.g. biofilm formation. We suggest that key variables should be recorded to maximise the value of future studies, including but not necessarily be limited to the following information: i) environmental context (water depth, location reported as coordinates, seafloor sediment type); ii) the state of the cable (burial depth (including as-installed depth and depth observed at recovery), age of cable, cable type (e.g. lightweight, armoured etc), condition of recovered cable (i.e. intact and pristine versus degraded); iii) recovery operations (e.g. recovery success (i.e. length of cable recovered versus left in situ), number of grapnel runs and their footprint (i.e. length and width)); and iv) biological observations (extent of any colonisation and its location, species-level identification of colonising species).

6. Conclusions

Out-of-service subsea cables account for around two-thirds of the >3.5 million km of subsea telecommunications cables that have been installed since the 1850s, which include telegraph, coaxial and modern fibre-optic systems. There is growing interest and demand for the recovery of these systems, arising from evolving regulatory requirements, logistical drivers to free up areas of seafloor for new routes, and to recover materials to contribute to a more circular economy. In this paper, we synthesised a first of its kind evidence base, summarising the current state of understanding with regards to the materials that make up different types of subsea cable and assessment of the potential impacts of those activities on marine biodiversity. The main impacts primarily relate to the interaction of grapnels with the seafloor and extraction of shallow buried cables, which are all highly localised and short-lived (i.e. during the recovery operation itself) in nature, equivalent to, or less than, impacts that occur during installation. Evidence from recovery of cables has shown that, while surface laid cables can locally become colonised with fauna, this is the exception and is far from the norm. With this in mind, consideration of local environmental conditions should be factored into decision-making for decommissioning of subsea cables, to ensure that any impacts are minimised for sensitive seafloor ecosystems. Recovery of all lengths of subsea cables is not always possible; however, with sections that are excessively buried or crossing in-service infrastructure typically left in situ. Decommissioning can also include repurposing of subsea cables for scientific monitoring that has wide potential for enhancing understanding of deep-sea processes.

This is a first of its kind study, but it is hoped that this forms the basis of focused future studies that take a systematic approach to recording environmental information to fill key evidence gaps. This should include, but not be limited to, ensuring field studies are performed across the breadth of natural environmental settings in which cables are laid, to record the type and condition of cable, its burial state, the extent of any colonisation and associated taxonomic identification, and link that to environmental variables such as substrate type, water depth. Many future opportunities exist to further enhance the evidence base concerning cable decommissioning, with regards to the sharing and gathering of ecological data, monitoring of cables in-situ and during recovery, through enhanced knowledge sharing between a diversity of industry, policy-related and academic stakeholders, and to develop consistent forward-looking strategies for decommissioning requirements of subsea cables worldwide.

CRediT authorship contribution statement

M.A. Clare: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **A.R. Gates:** Writing – review & editing, Validation. **D.O.B. Jones:** Writing – review & editing, Validation. **I.A. Yeo:** Writing – review & editing, Methodology. **A. Hilario:** Writing – review & editing, Conceptualization. **K.J.J. Van Landeghem:** Writing – review & editing. **L. Harris:** Writing – review & editing. **L. Carter:** Writing – review & editing. **S. Appleby:** Writing – review & editing, Methodology, Investigation, Data curation. **P. Appleby:** Writing – review & editing. **A. du Plessis:** Writing – review & editing, Data curation. **M. Logan:** Writing – review & editing, Methodology, Data curation. **R. Melville:** Writing – review & editing. **Q. Nguyen:** Writing – review & editing. **E. Calhoun:** Writing – review & editing, Conceptualization. **R. Fletcher:** Writing – review & editing, Conceptualization. **J. Wrottesley:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Michael Clare reports financial support was provided by the International Cable Protection Committee that enabled aspects of this research. Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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