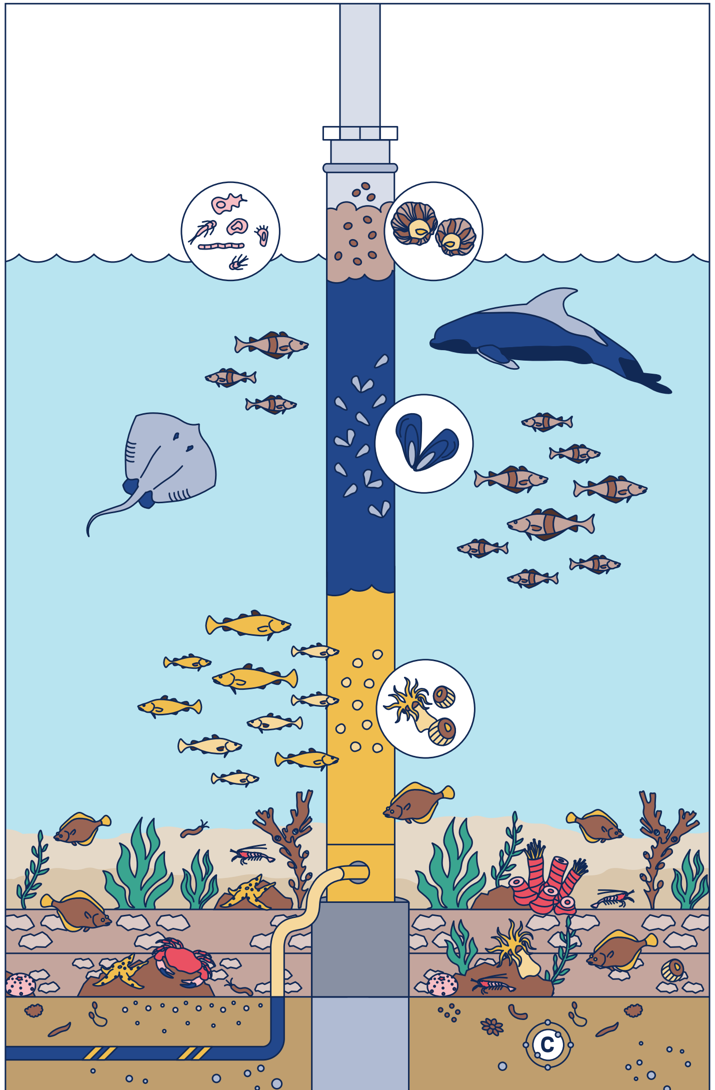
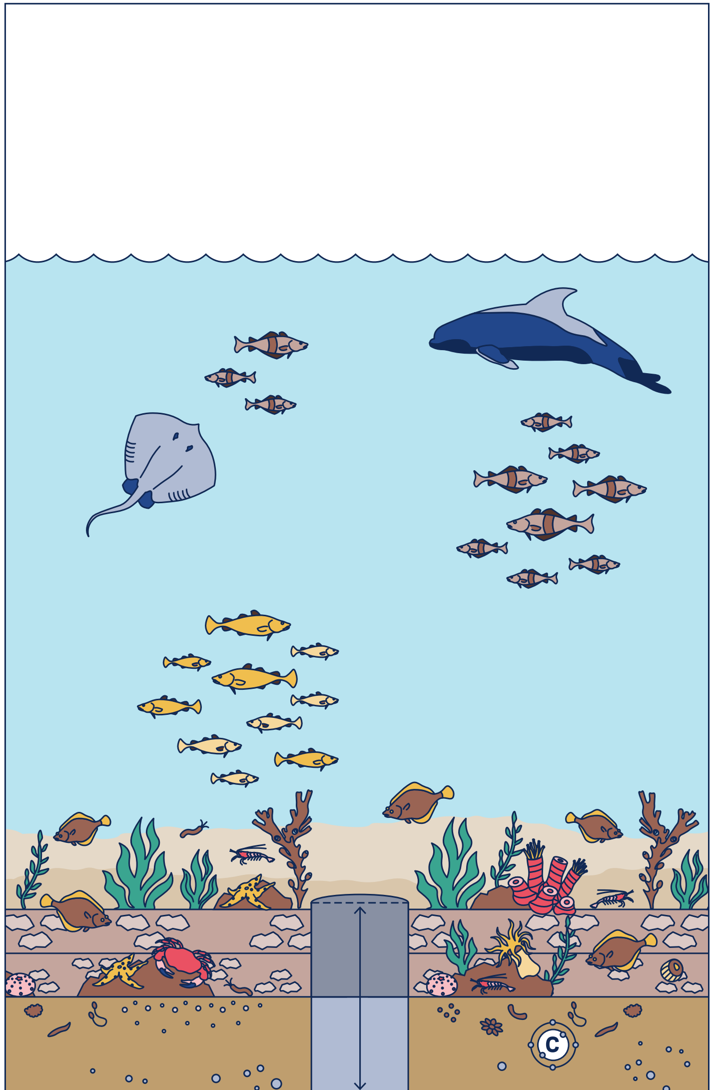
Effects of Decommissioning Offshore Wind & Grid Infrastructure

Scenario-based Environmental Effects

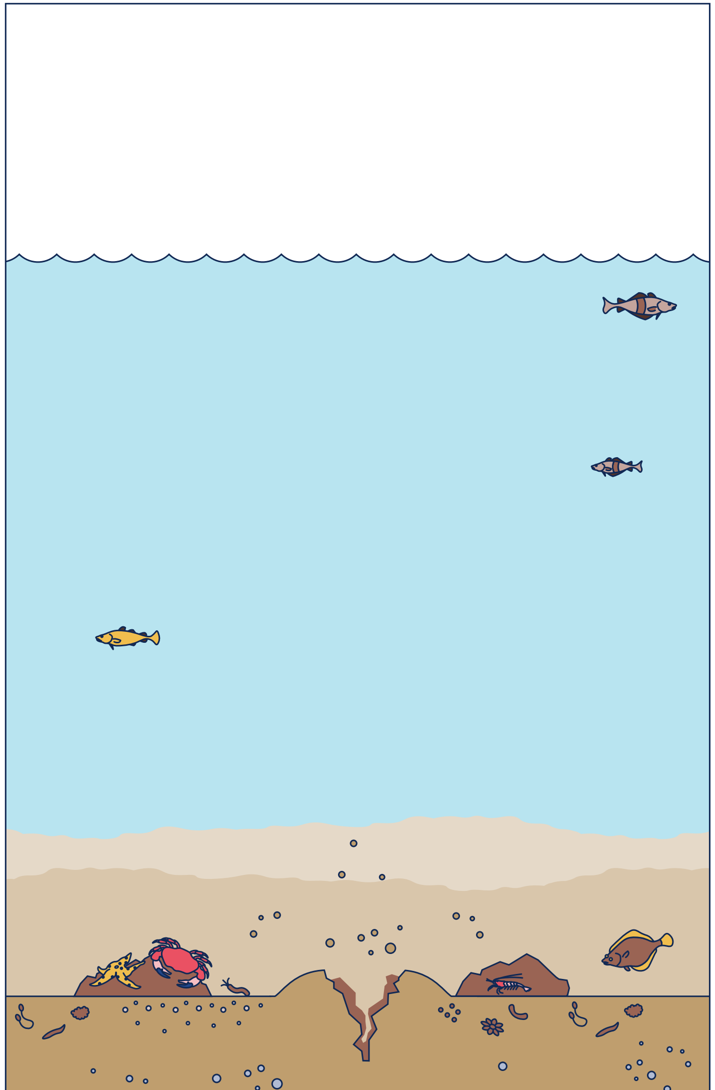
The information provided offers a general overview and is not intended to be exhaustive. The concepts and environmental drivers described will vary depending on local conditions. Therefore, decommissioning decisions should always be made on a case-by-case, site-specific basis and supported by thorough in-situ assessments. Furthermore, the decommissioning scenarios discussed are theoretical options that may currently lack regulatory approval or proven technical feasibility.



Pre-Decommissioning
End-of-Life



Partial Removal
Scenario



Full Removal
Scenario

Illustration & graphic design: Kate Snow Design

Effects of Decommissioning Offshore Wind and Grid Infrastructure

Pre-Decommissioning End-of-Life

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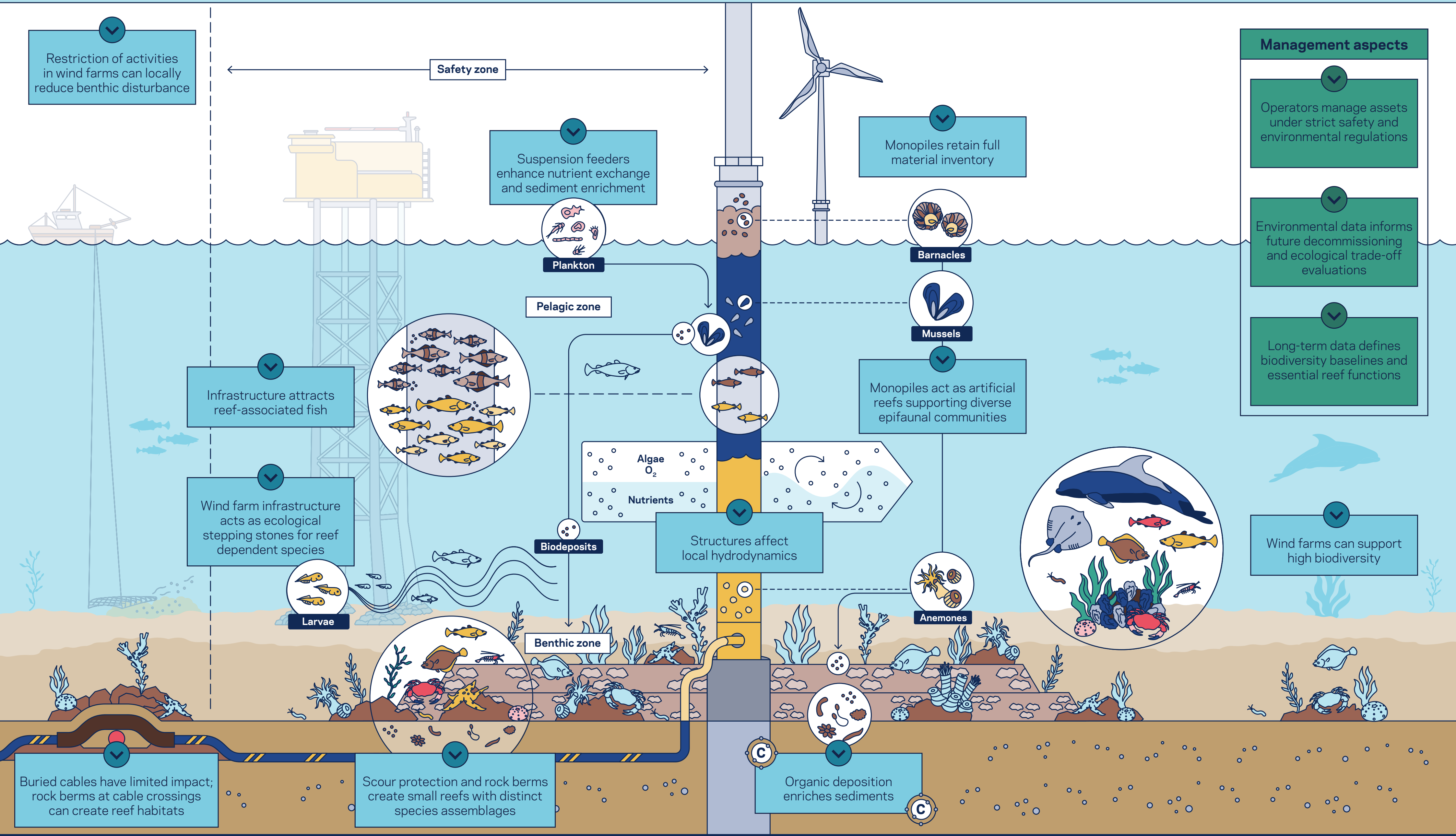

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Pre-Decommissioning End-of-Life

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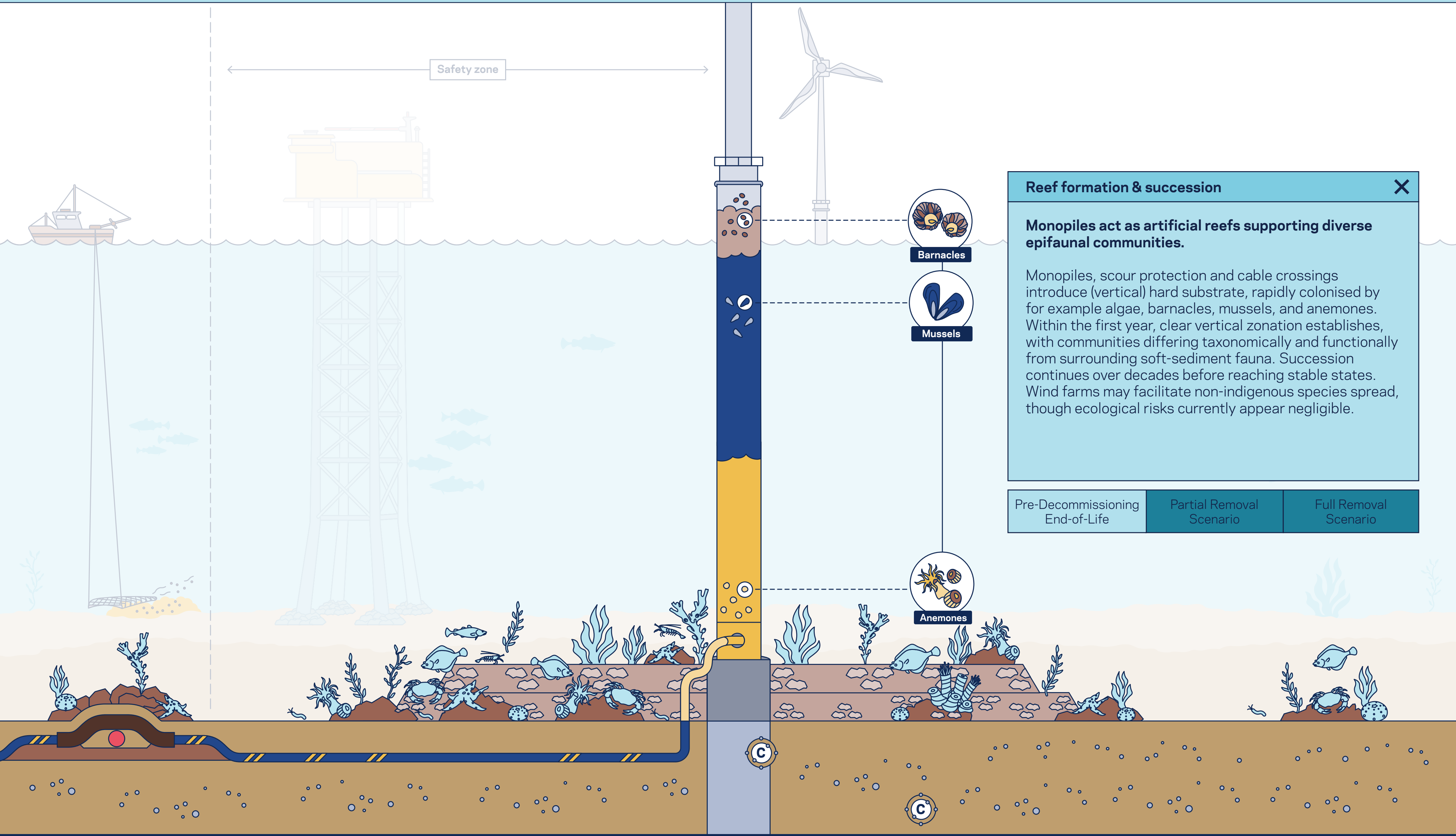

Reef formation & succession

Monopiles act as artificial reefs supporting diverse epifaunal communities.

Monopiles, scour protection and cable crossings introduce (vertical) hard substrate, rapidly colonised by for example algae, barnacles, mussels, and anemones. Within the first year, clear vertical zonation establishes, with communities differing taxonomically and functionally from surrounding soft-sediment fauna. Succession continues over decades before reaching stable states. Wind farms may facilitate non-indigenous species spread, though ecological risks currently appear negligible.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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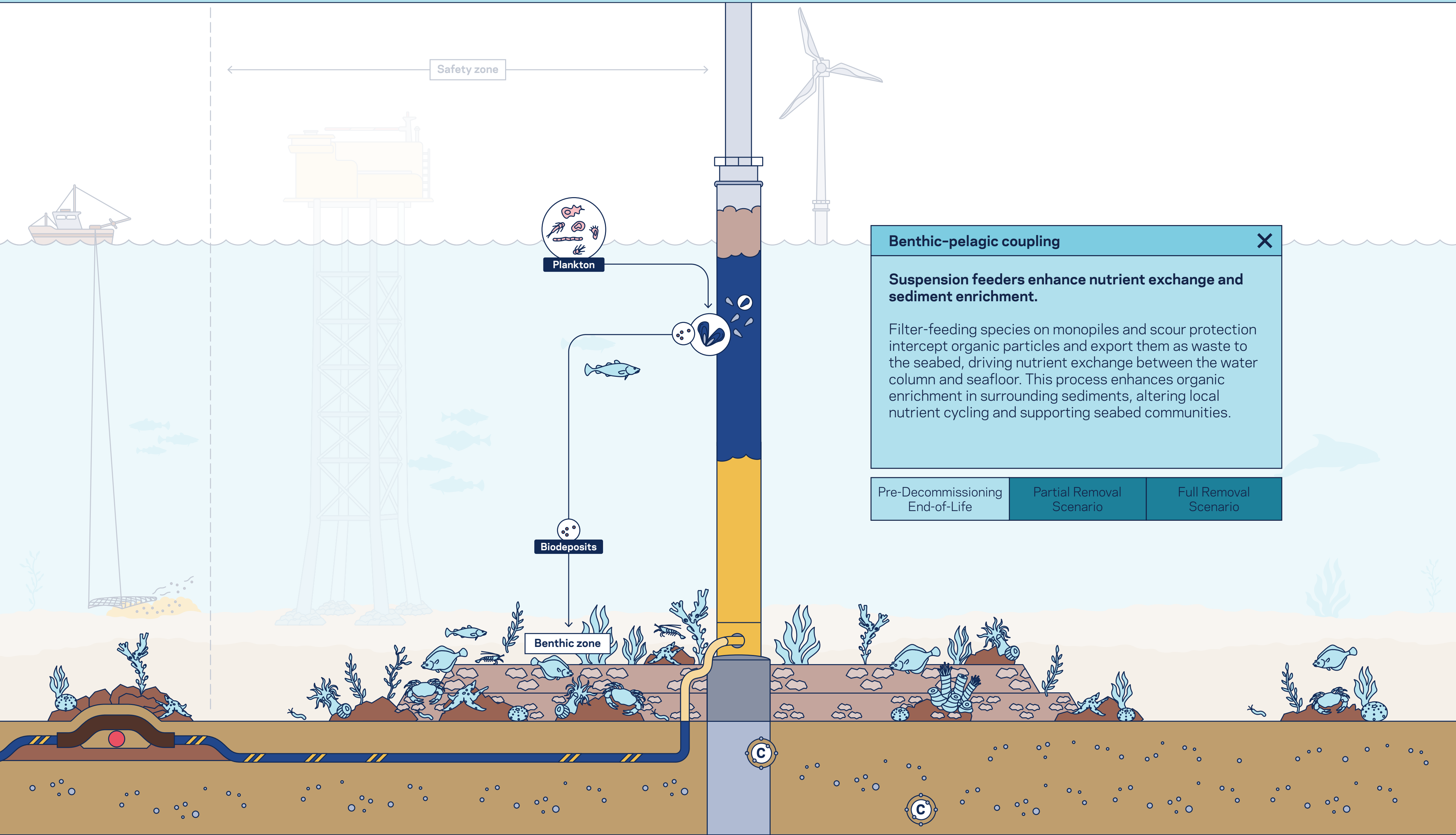

Benthic-pelagic coupling

Suspension feeders enhance nutrient exchange and sediment enrichment.

Filter-feeding species on monopiles and scour protection intercept organic particles and export them as waste to the seabed, driving nutrient exchange between the water column and seafloor. This process enhances organic enrichment in surrounding sediments, altering local nutrient cycling and supporting seabed communities.

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Partial Removal Scenario
Full Removal Scenario

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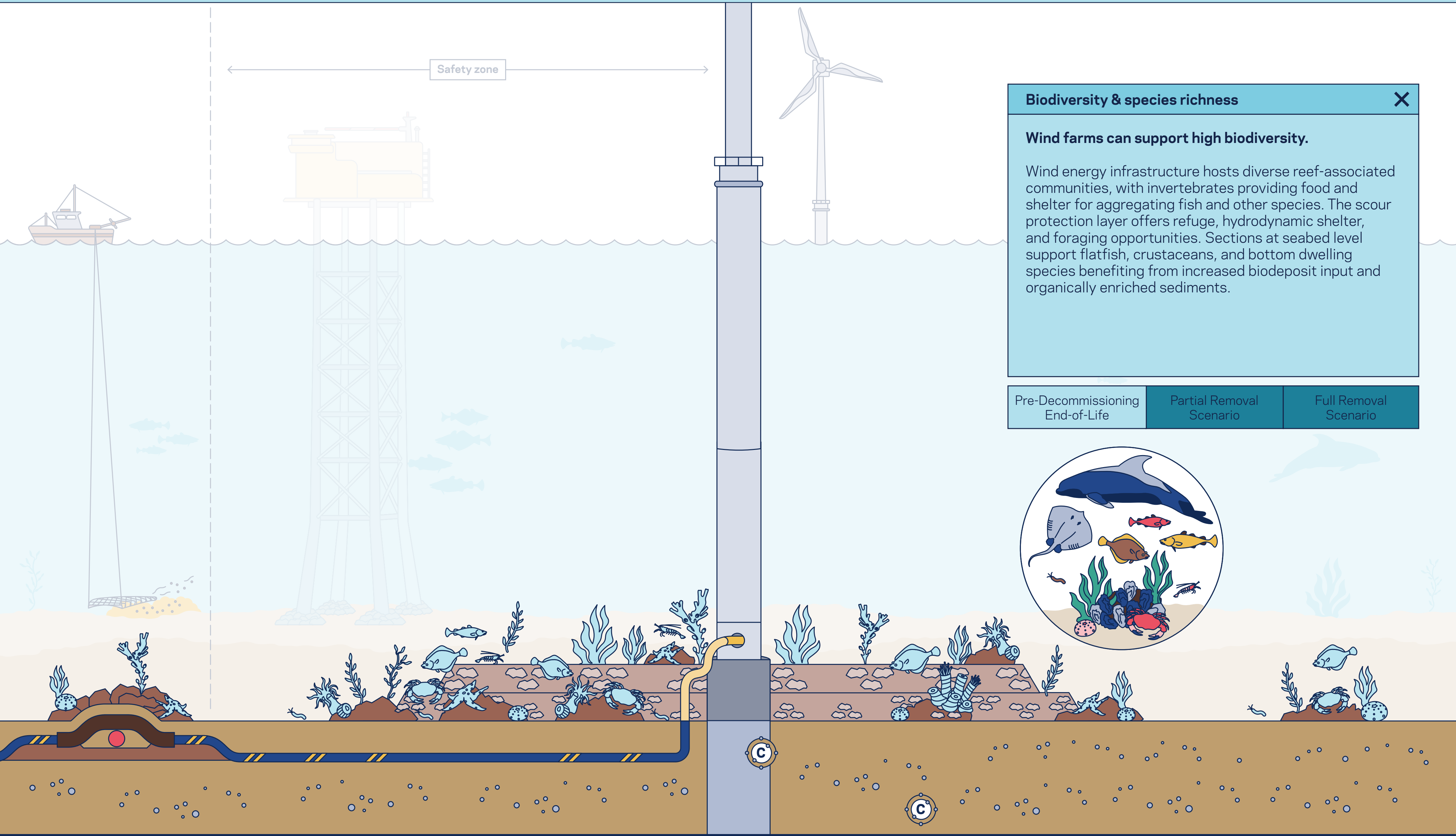

Biodiversity & species richness

Wind farms can support high biodiversity.

Wind energy infrastructure hosts diverse reef-associated communities, with invertebrates providing food and shelter for aggregating fish and other species. The scour protection layer offers refuge, hydrodynamic shelter, and foraging opportunities. Sections at seabed level support flatfish, crustaceans, and bottom dwelling species benefiting from increased biodeposit input and organically enriched sediments.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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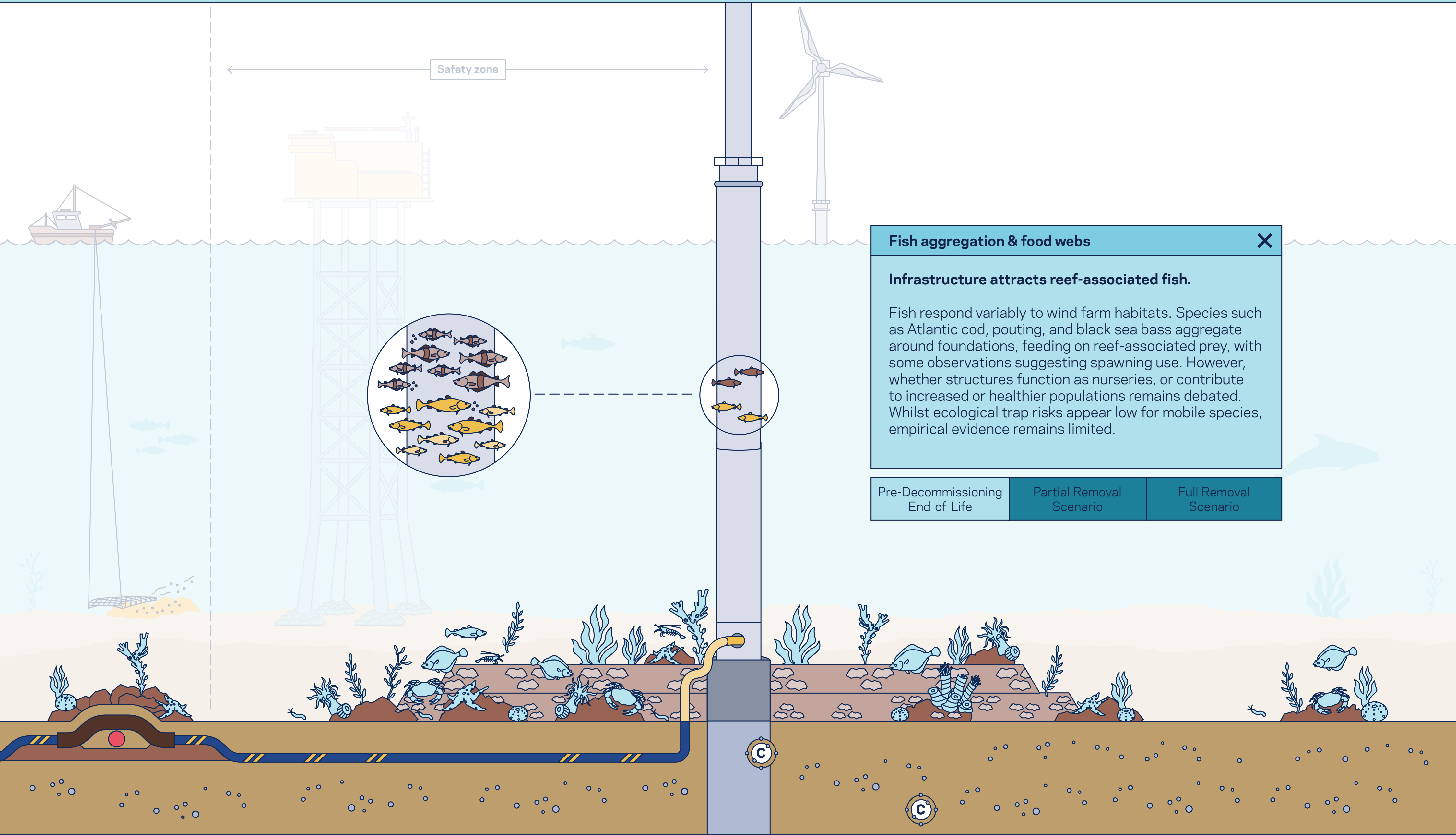

Fish aggregation & food webs

Infrastructure attracts reef-associated fish.

Fish respond variably to wind farm habitats. Species such as Atlantic cod, pouting, and black sea bass aggregate around foundations, feeding on reef-associated prey, with some observations suggesting spawning use. However, whether structures function as nurseries, or contribute to increased or healthier populations remains debated. Whilst ecological trap risks appear low for mobile species, empirical evidence remains limited.

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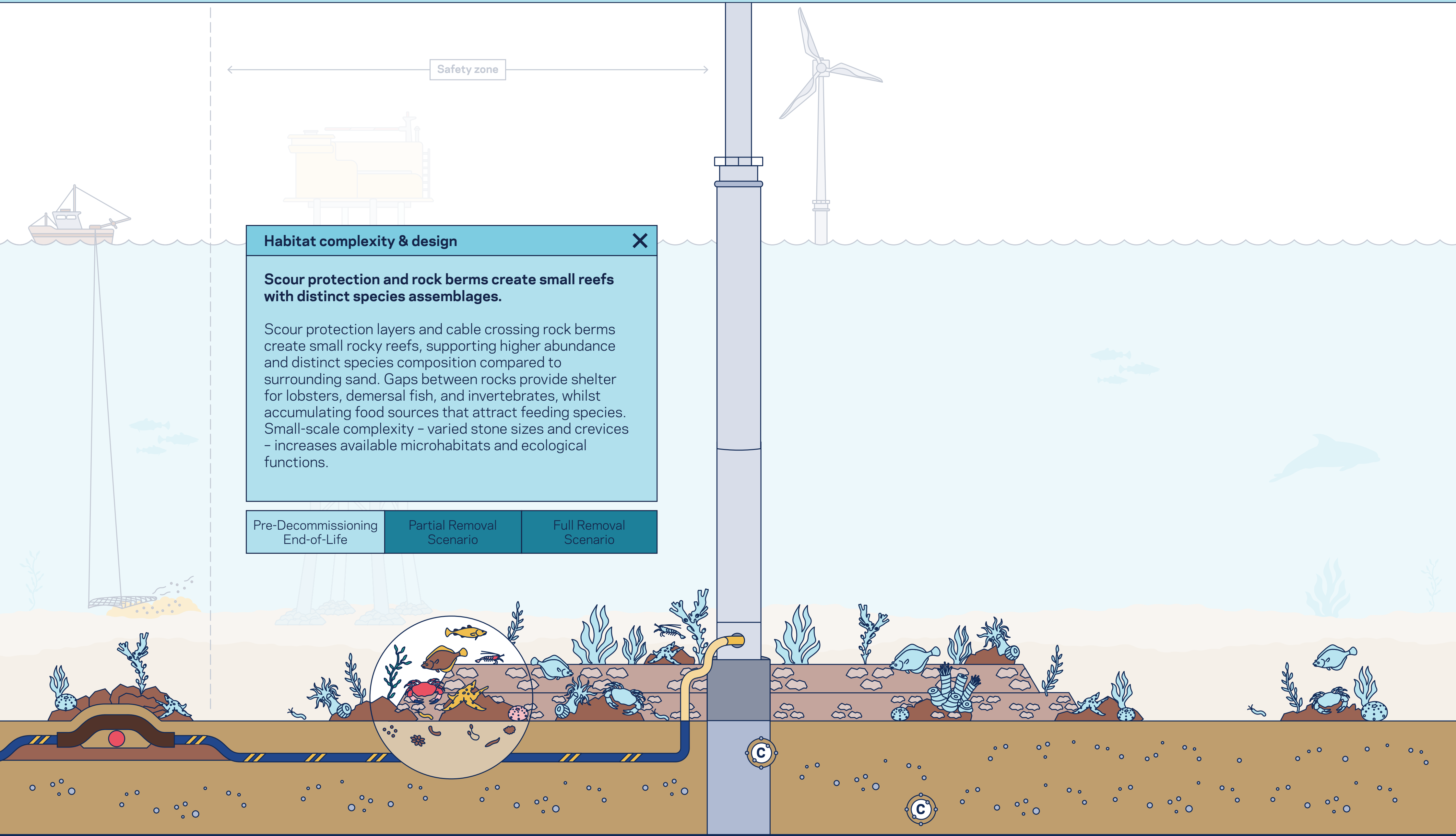

Habitat complexity & design

Scour protection and rock berms create small reefs with distinct species assemblages.

Scour protection layers and cable crossing rock berms create small rocky reefs, supporting higher abundance and distinct species composition compared to surrounding sand. Gaps between rocks provide shelter for lobsters, demersal fish, and invertebrates, whilst accumulating food sources that attract feeding species. Small-scale complexity – varied stone sizes and crevices – increases available microhabitats and ecological functions.

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Partial Removal Scenario
Full Removal Scenario

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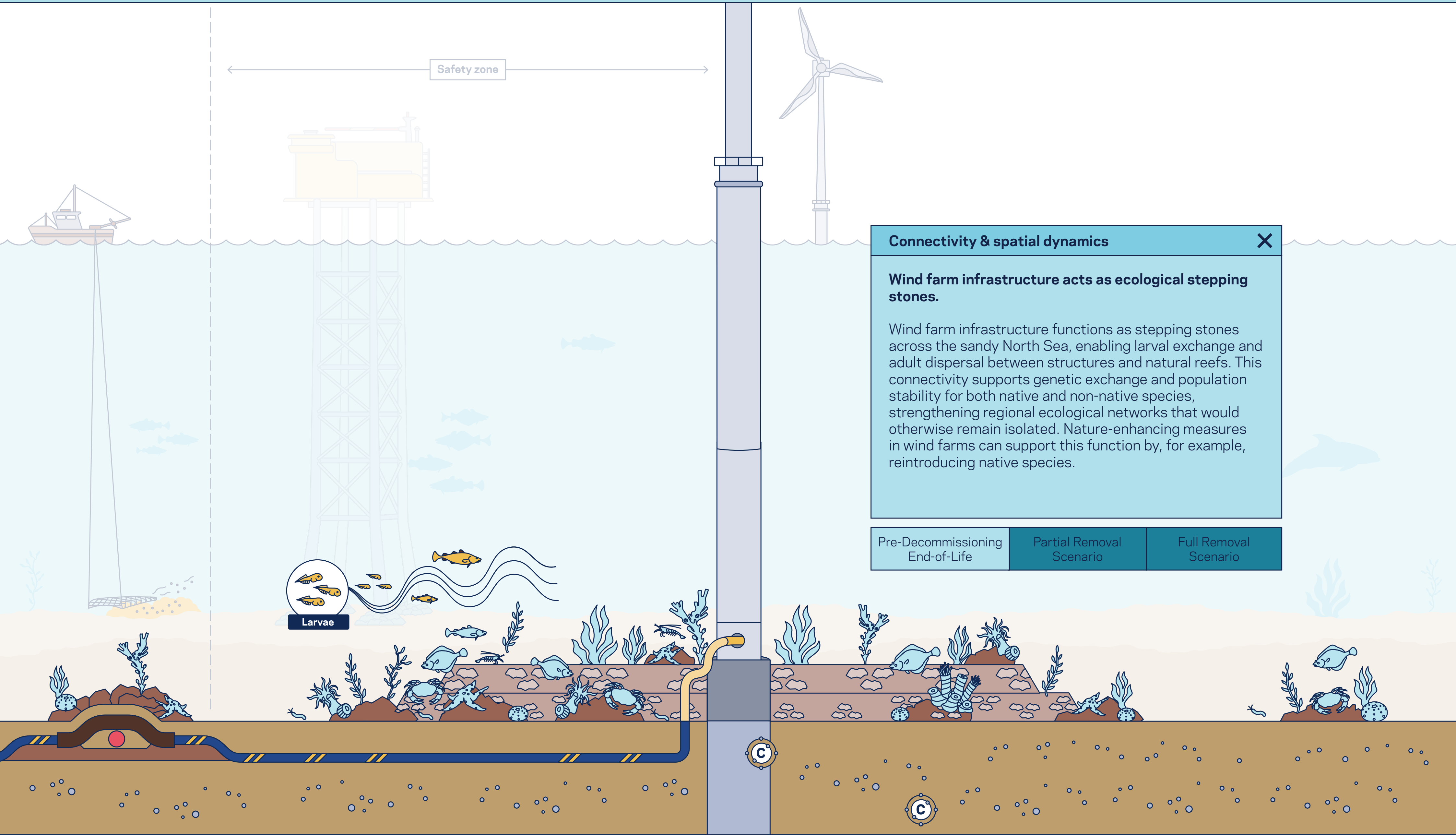

Connectivity & spatial dynamics

Wind farm infrastructure acts as ecological stepping stones.

Wind farm infrastructure functions as stepping stones across the sandy North Sea, enabling larval exchange and adult dispersal between structures and natural reefs. This connectivity supports genetic exchange and population stability for both native and non-native species, strengthening regional ecological networks that would otherwise remain isolated. Nature-enhancing measures in wind farms can support this function by, for example, reintroducing native species.

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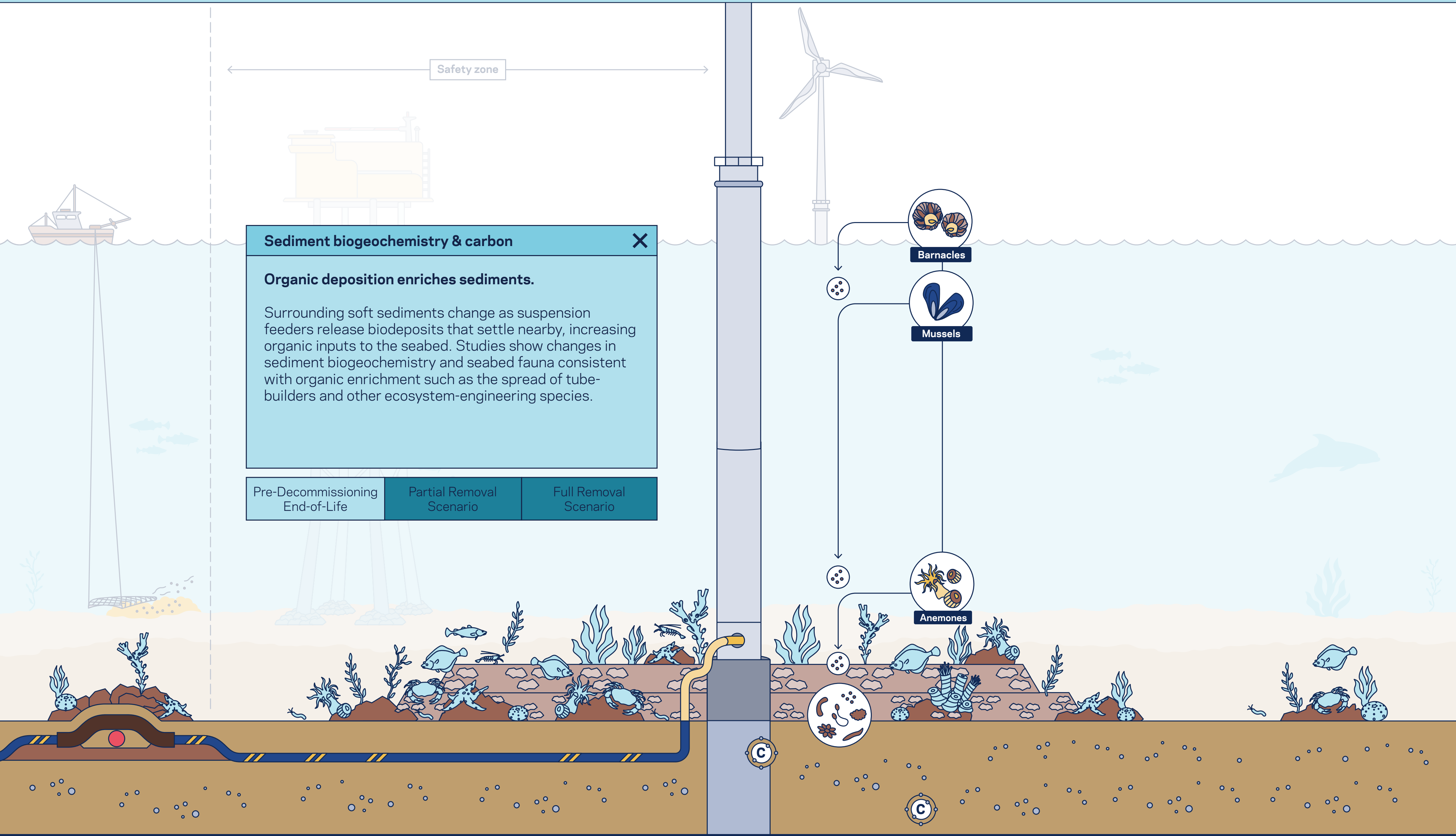

Sediment biogeochemistry & carbon

Organic deposition enriches sediments.

Surrounding soft sediments change as suspension feeders release biodeposits that settle nearby, increasing organic inputs to the seabed. Studies show changes in sediment biogeochemistry and seabed fauna consistent with organic enrichment such as the spread of tube-builders and other ecosystem-engineering species.

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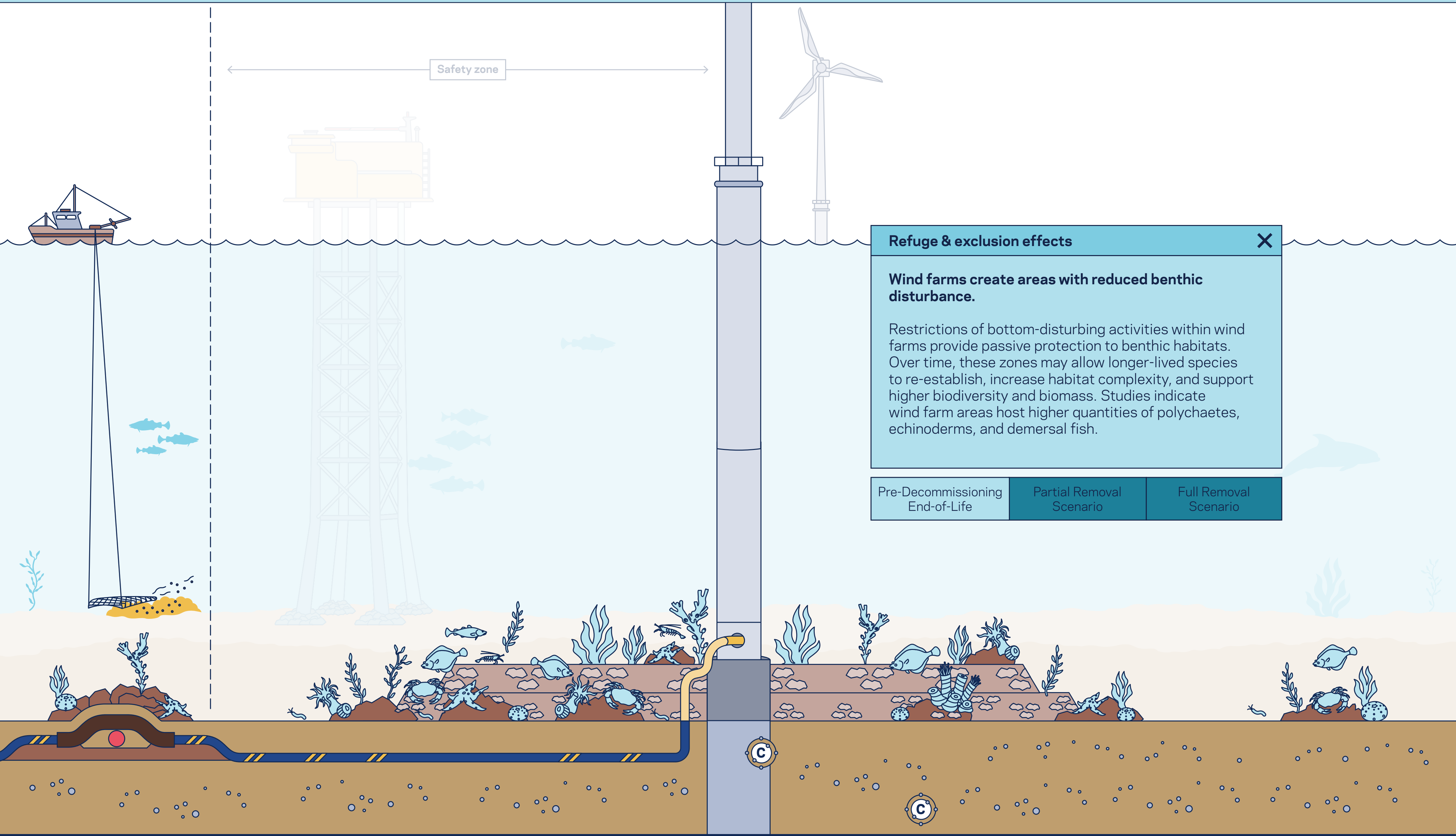

Refuge & exclusion effects

Wind farms create areas with reduced benthic disturbance.

Restrictions of bottom-disturbing activities within wind farms provide passive protection to benthic habitats. Over time, these zones may allow longer-lived species to re-establish, increase habitat complexity, and support higher biodiversity and biomass. Studies indicate wind farm areas host higher quantities of polychaetes, echinoderms, and demersal fish.

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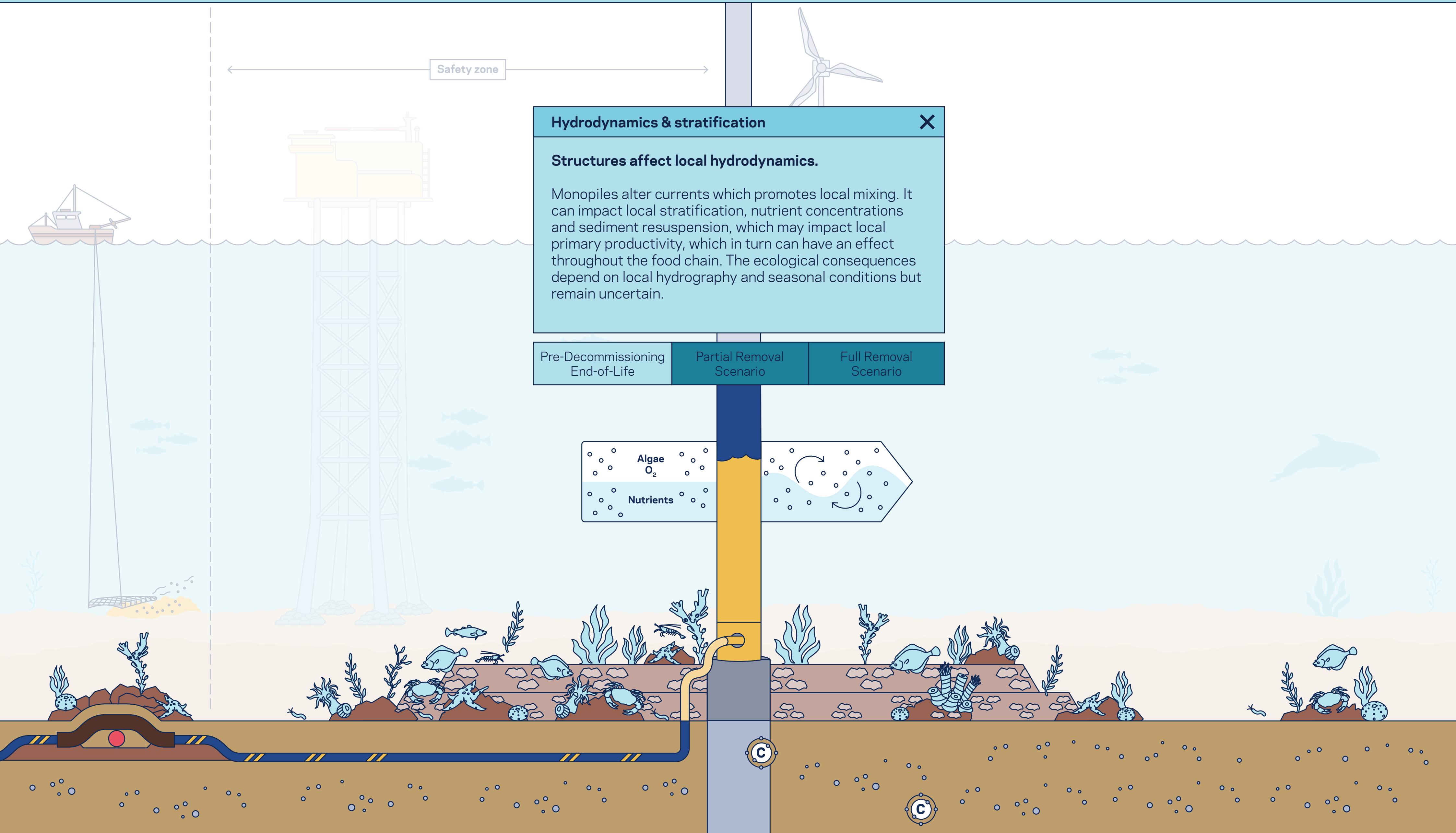

Hydrodynamics & stratification

Structures affect local hydrodynamics.

Monopiles alter currents which promotes local mixing. It can impact local stratification, nutrient concentrations and sediment resuspension, which may impact local primary productivity, which in turn can have an effect throughout the food chain. The ecological consequences depend on local hydrography and seasonal conditions but remain uncertain.

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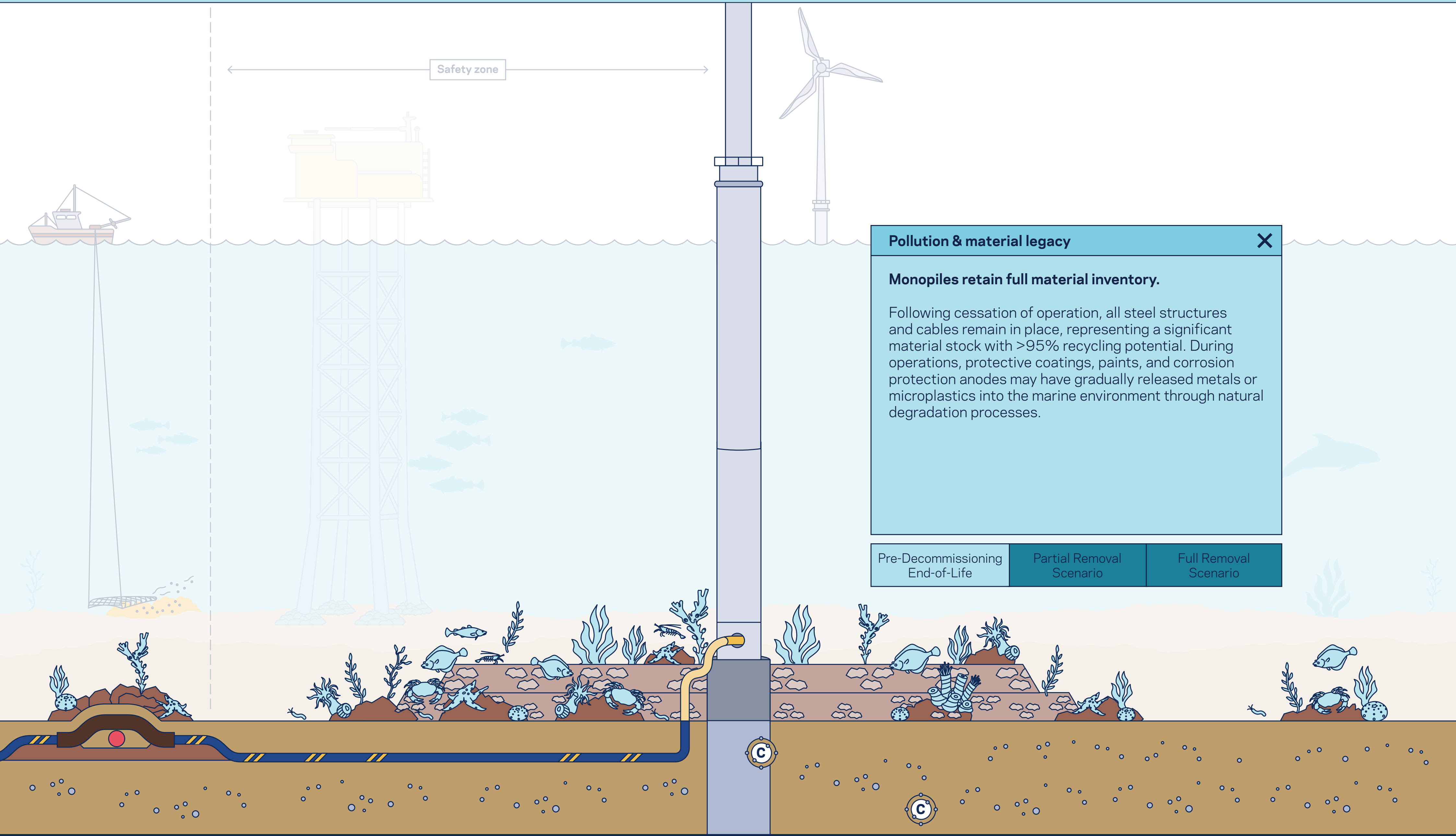

Pollution & material legacy

Monopiles retain full material inventory.

Following cessation of operation, all steel structures and cables remain in place, representing a significant material stock with >95% recycling potential. During operations, protective coatings, paints, and corrosion protection anodes may have gradually released metals or microplastics into the marine environment through natural degradation processes.

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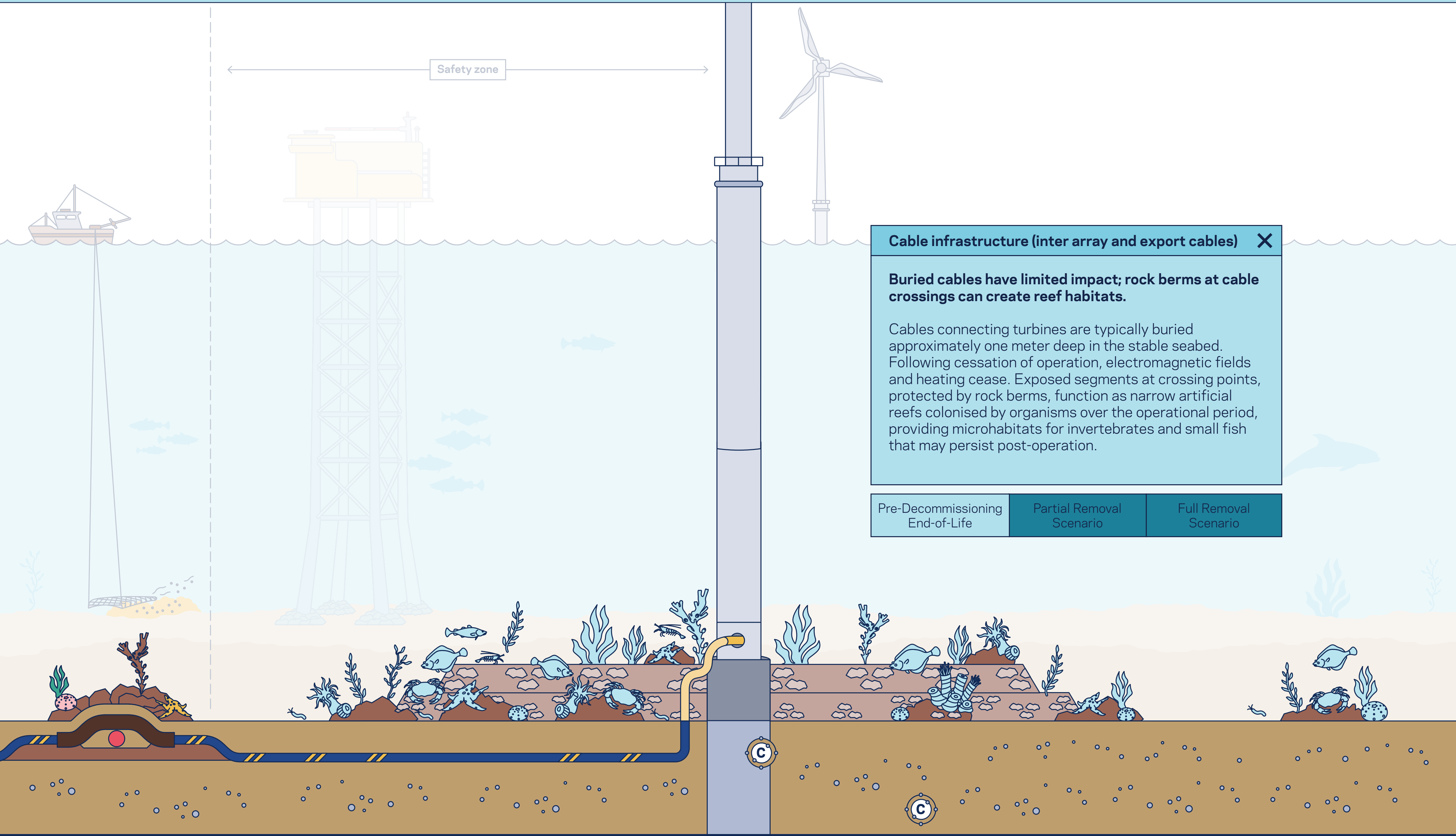

Cable infrastructure (inter array and export cables)

Buried cables have limited impact; rock berms at cable crossings can create reef habitats.

Cables connecting turbines are typically buried approximately one meter deep in the stable seabed. Following cessation of operation, electromagnetic fields and heating cease. Exposed segments at crossing points, protected by rock berms, function as narrow artificial reefs colonised by organisms over the operational period, providing microhabitats for invertebrates and small fish that may persist post-operation.

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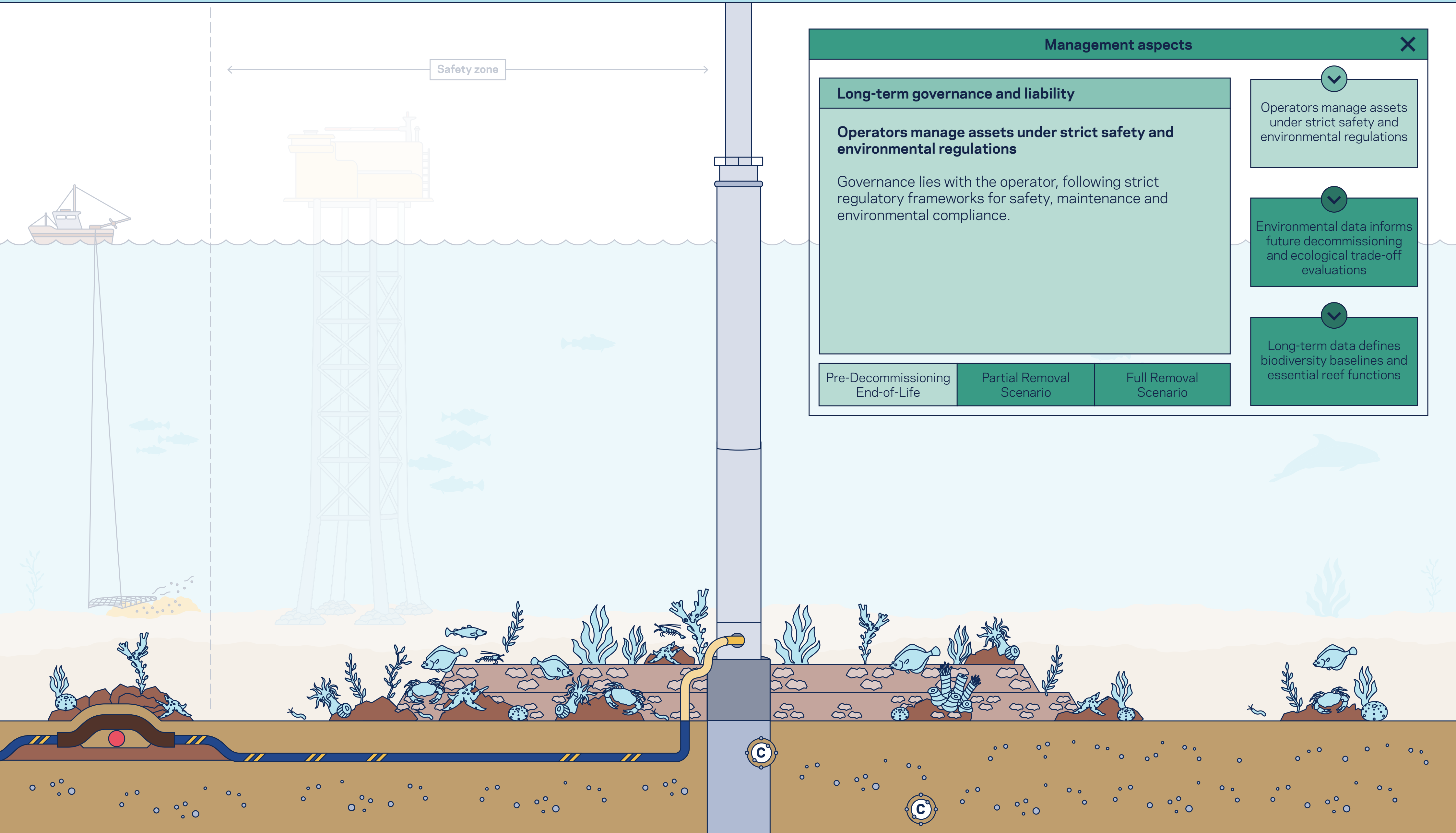

Management aspects

Long-term governance and liability

Operators manage assets under strict safety and environmental regulations

Governance lies with the operator, following strict regulatory frameworks for safety, maintenance and environmental compliance.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

- Operators manage assets under strict safety and environmental regulations
- Environmental data informs future decommissioning and ecological trade-off evaluations
- Long-term data defines biodiversity baselines and essential reef functions

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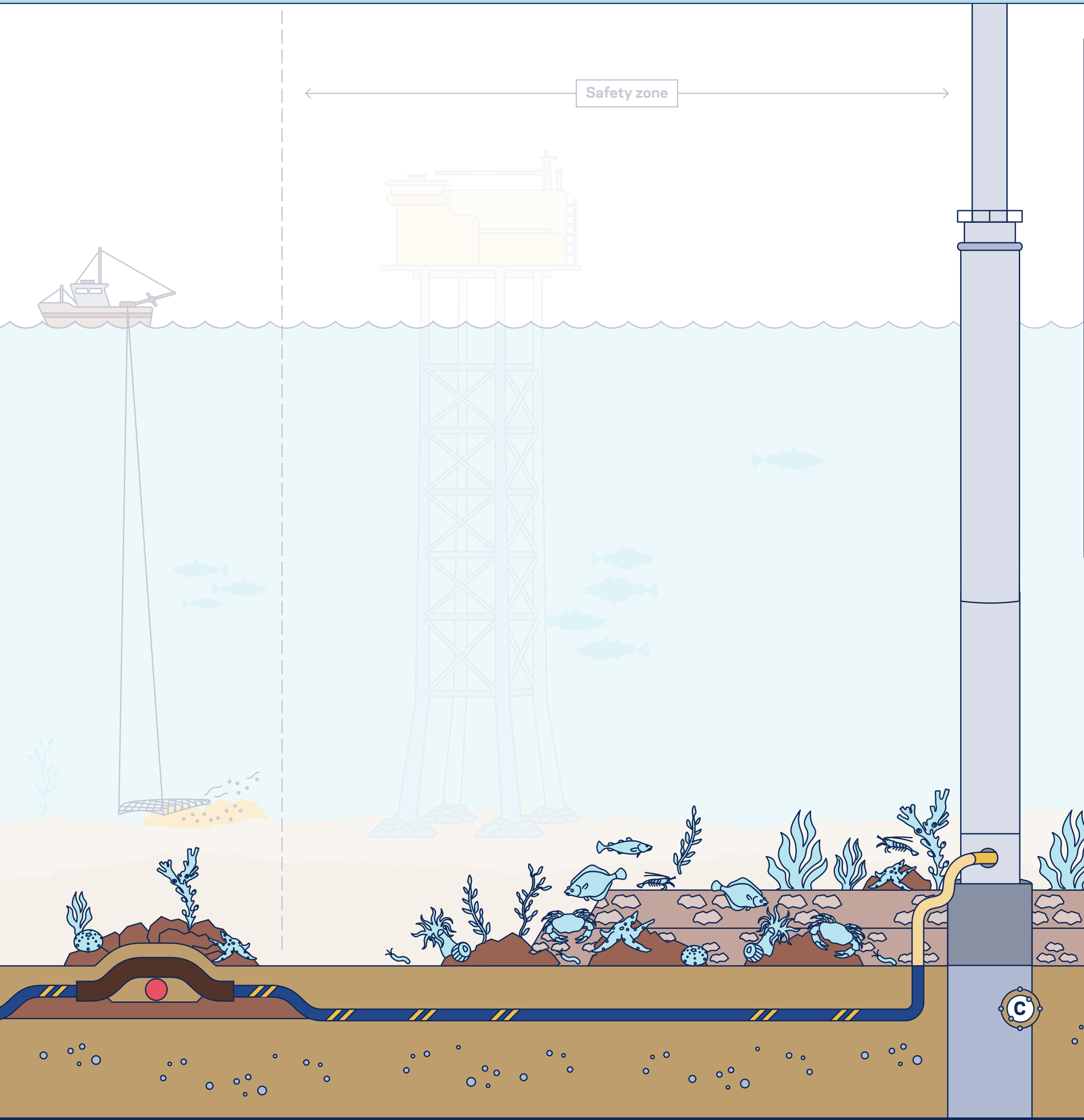

Management aspects

Decision-making framework

Environmental data informs future decommissioning and ecological trade-off evaluations.

Decision-making is largely guided by regulatory frameworks and operator responsibilities focused on safety, maintenance, and environmental performance. During this phase, data from monitoring programs and studies can inform end-of-life planning and may help define potential ecological trade-offs between full and partial removal.

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Partial Removal Scenario
Full Removal Scenario

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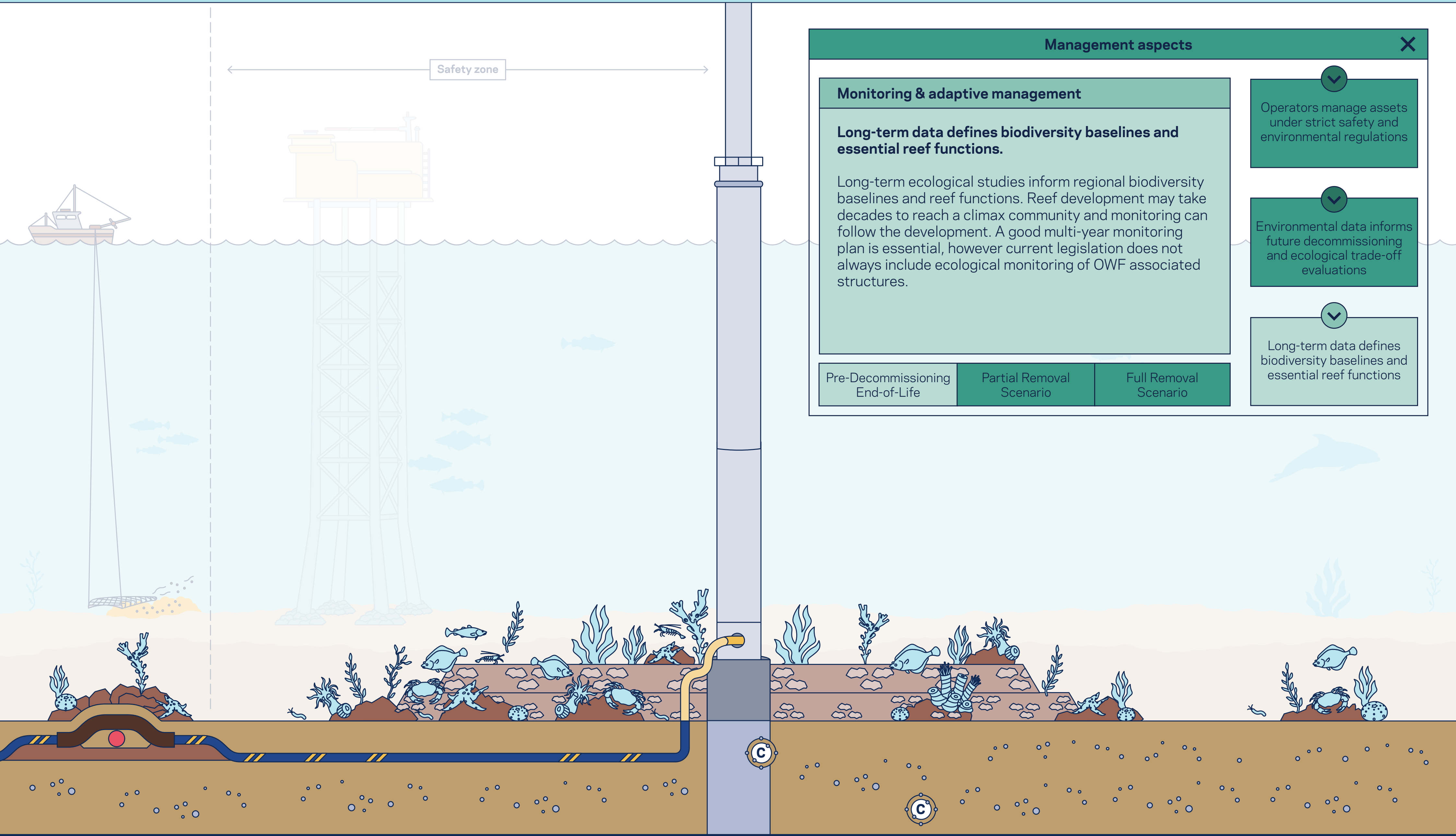

Management aspects

Monitoring & adaptive management

Long-term data defines biodiversity baselines and essential reef functions.

Long-term ecological studies inform regional biodiversity baselines and reef functions. Reef development may take decades to reach a climax community and monitoring can follow the development. A good multi-year monitoring plan is essential, however current legislation does not always include ecological monitoring of OWF associated structures.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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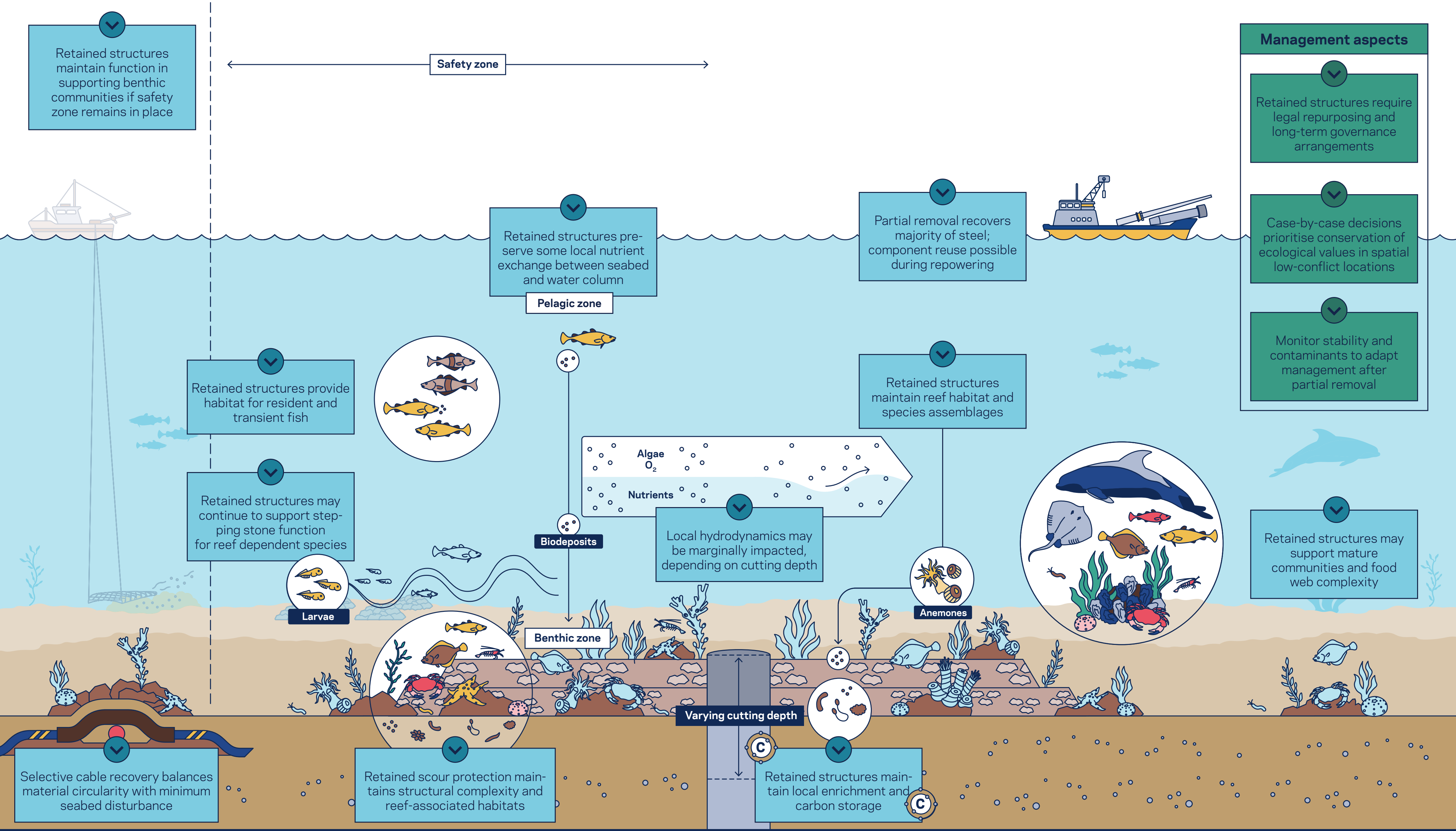
Effects of Decommissioning Offshore Wind and Grid Infrastructure

Partial Removal Scenario

The wind farm is no longer operational. Blades, turbine, tower and most of the monopile foundation are removed and transported to shore. Scour protection and (part of) sub-seabed foundations remain in place to (partially) preserve biodiversity and minimise disturbance. **Monopile cutting depth (below, at, or above seabed) affects habitat disturbance levels.** This approach retains some structural complexity and connectivity for reef-associated species, though removing monopile communities disrupts nutrient cycling. Selective cable recovery balances material circularity with ecological impact.



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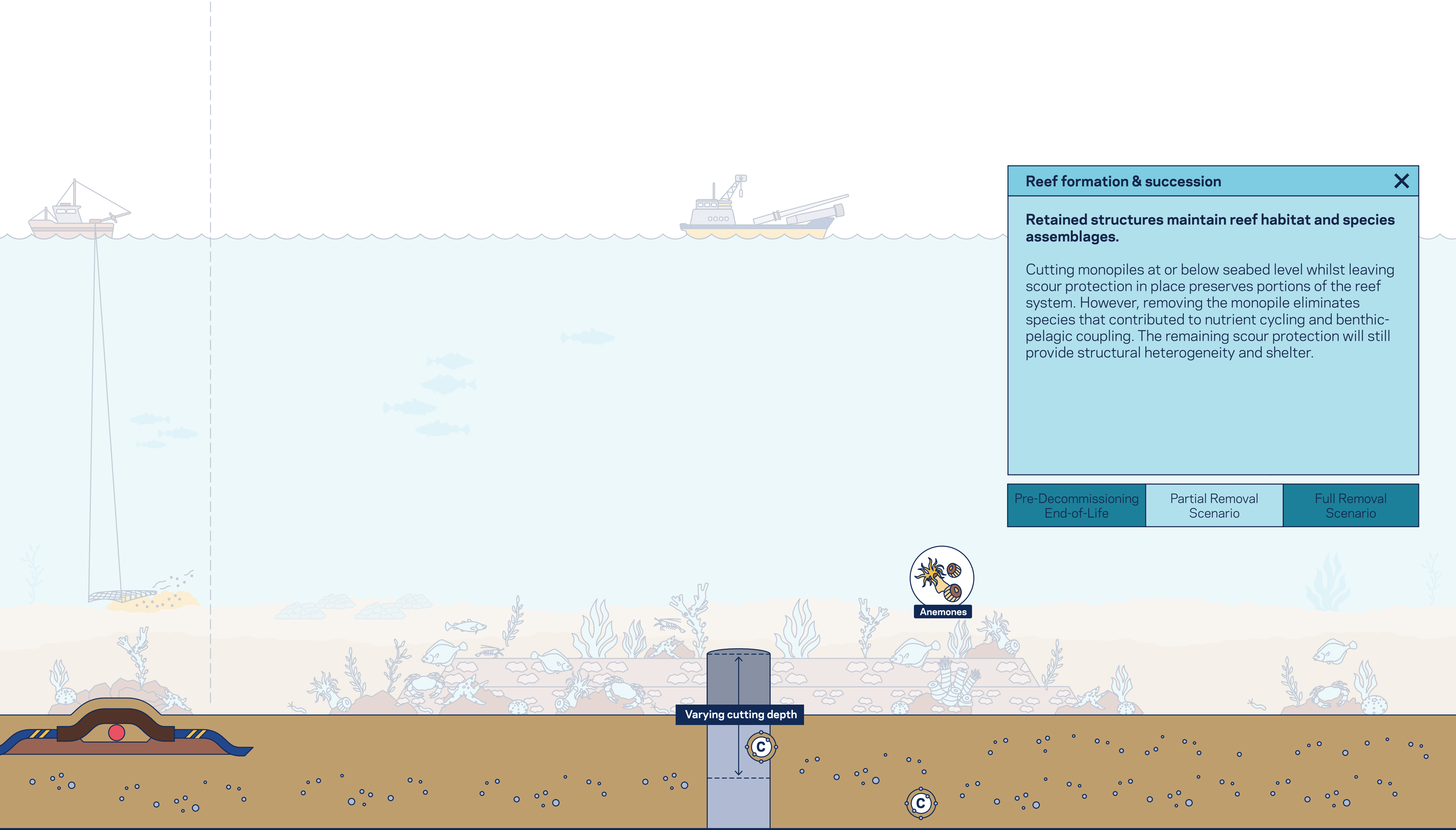

Reef formation & succession

Retained structures maintain reef habitat and species assemblages.

Cutting monopiles at or below seabed level whilst leaving scour protection in place preserves portions of the reef system. However, removing the monopile eliminates species that contributed to nutrient cycling and benthic-pelagic coupling. The remaining scour protection will still provide structural heterogeneity and shelter.

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Partial Removal Scenario
Full Removal Scenario

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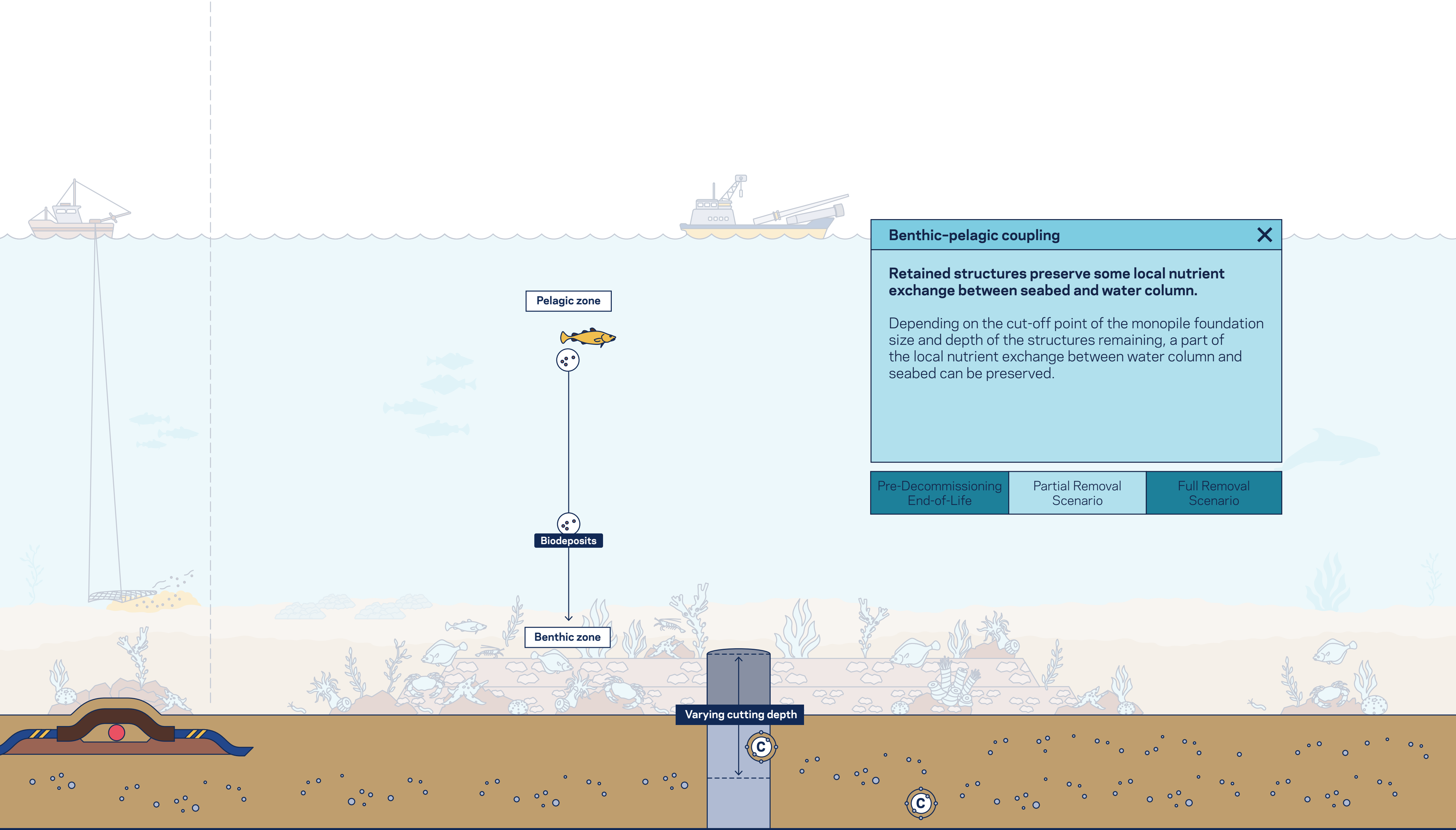

Benthic-pelagic coupling

Retained structures preserve some local nutrient exchange between seabed and water column.

Depending on the cut-off point of the monopile foundation size and depth of the structures remaining, a part of the local nutrient exchange between water column and seabed can be preserved.

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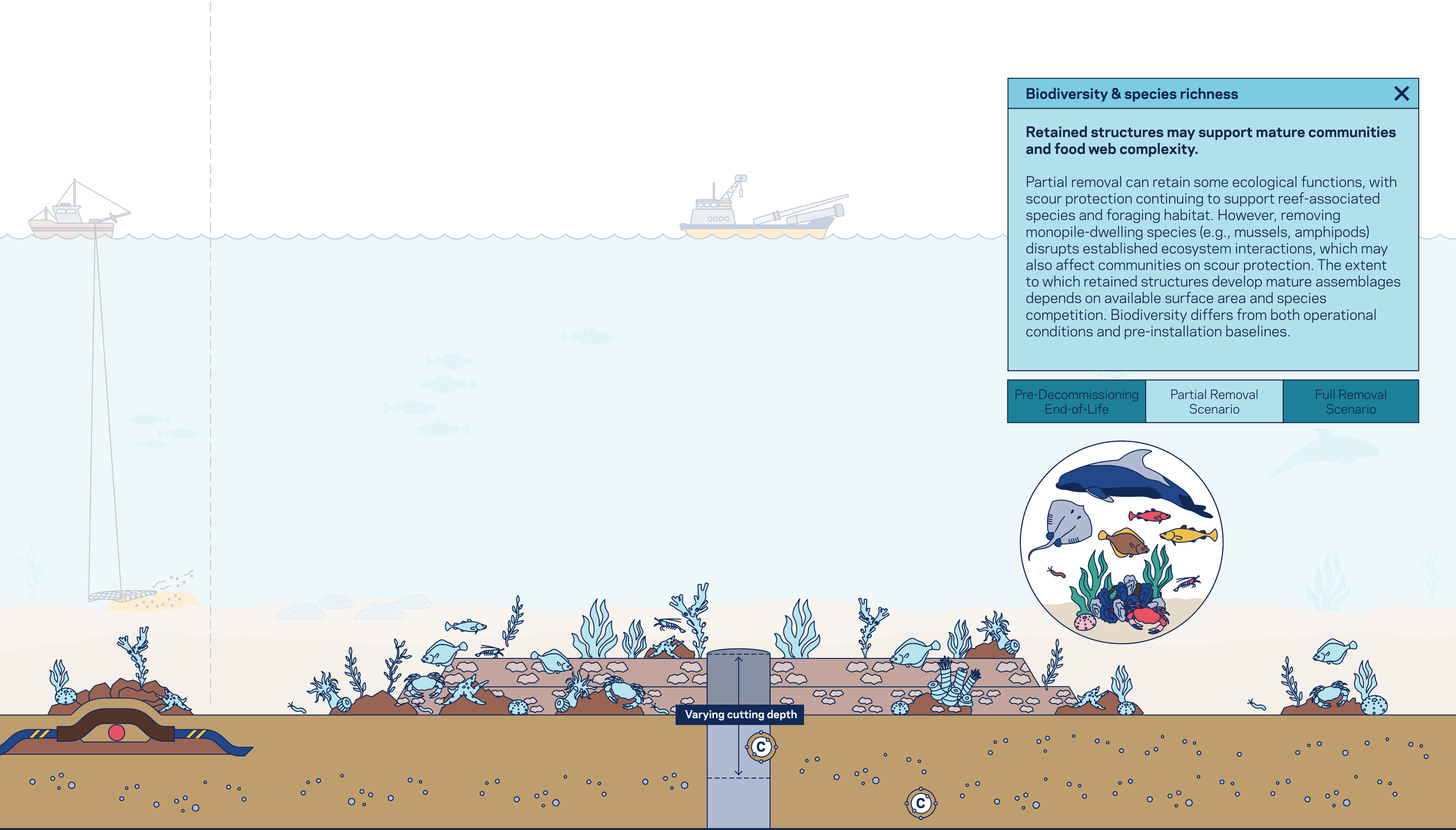

Biodiversity & species richness

Retained structures may support mature communities and food web complexity.

Partial removal can retain some ecological functions, with scour protection continuing to support reef-associated species and foraging habitat. However, removing monopile-dwelling species (e.g., mussels, amphipods) disrupts established ecosystem interactions, which may also affect communities on scour protection. The extent to which retained structures develop mature assemblages depends on available surface area and species competition. Biodiversity differs from both operational conditions and pre-installation baselines.

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Partial Removal Scenario
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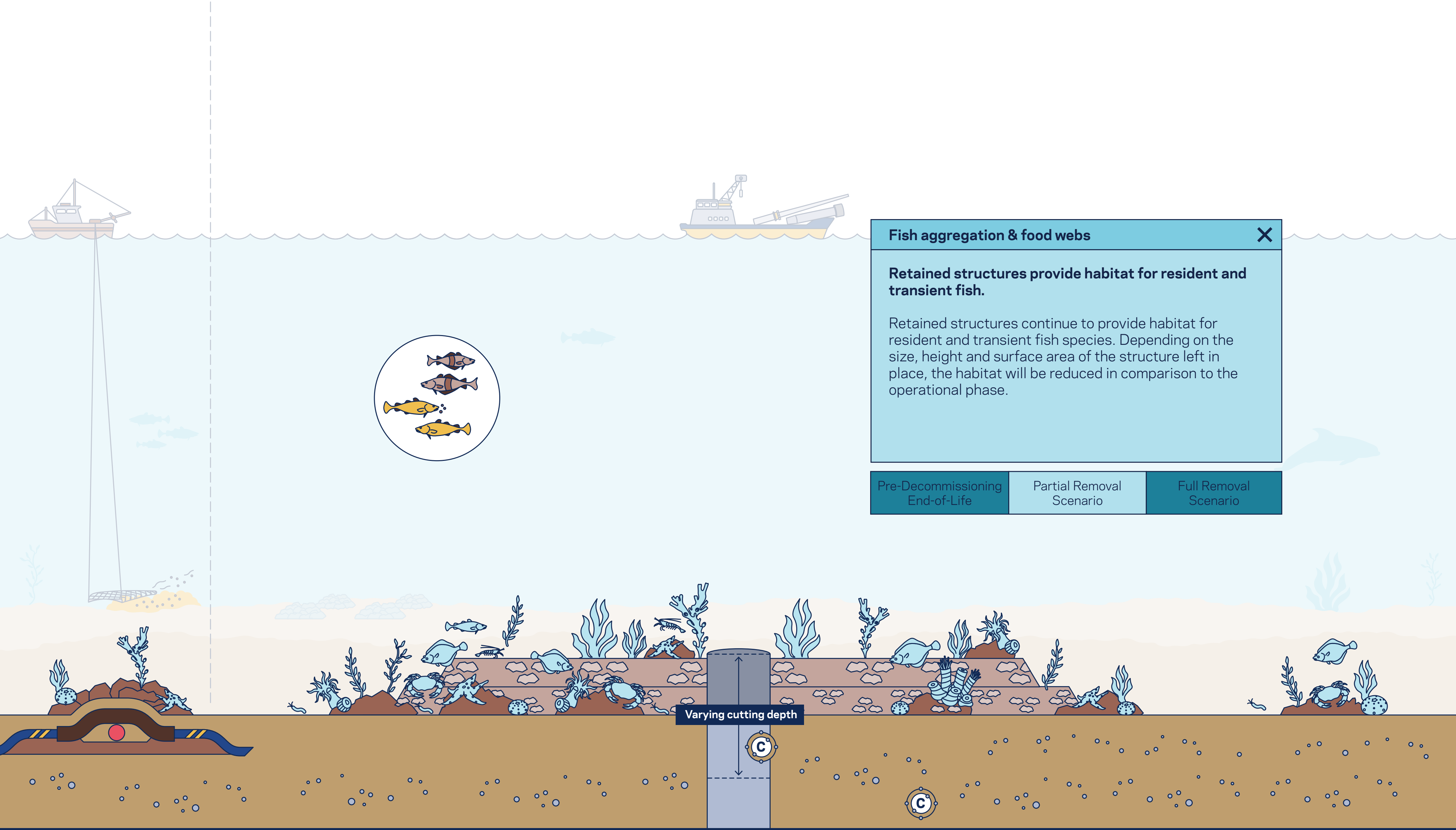

Fish aggregation & food webs

Retained structures provide habitat for resident and transient fish.

Retained structures continue to provide habitat for resident and transient fish species. Depending on the size, height and surface area of the structure left in place, the habitat will be reduced in comparison to the operational phase.

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Habitat complexity & design

Retained scour protection maintains structural complexity and reef-associated habitats.

Retained scour protection continues to provide structural complexity and small rocky reef habitats. Gaps between rocks maintain shelter for lobsters, demersal fish, and invertebrates, whilst accumulating food sources. Small-scale complexity from varied stone sizes and crevices supports available microhabitats and ecological functions, though reduced compared to operational conditions because of reduced benthic-pelagic coupling.

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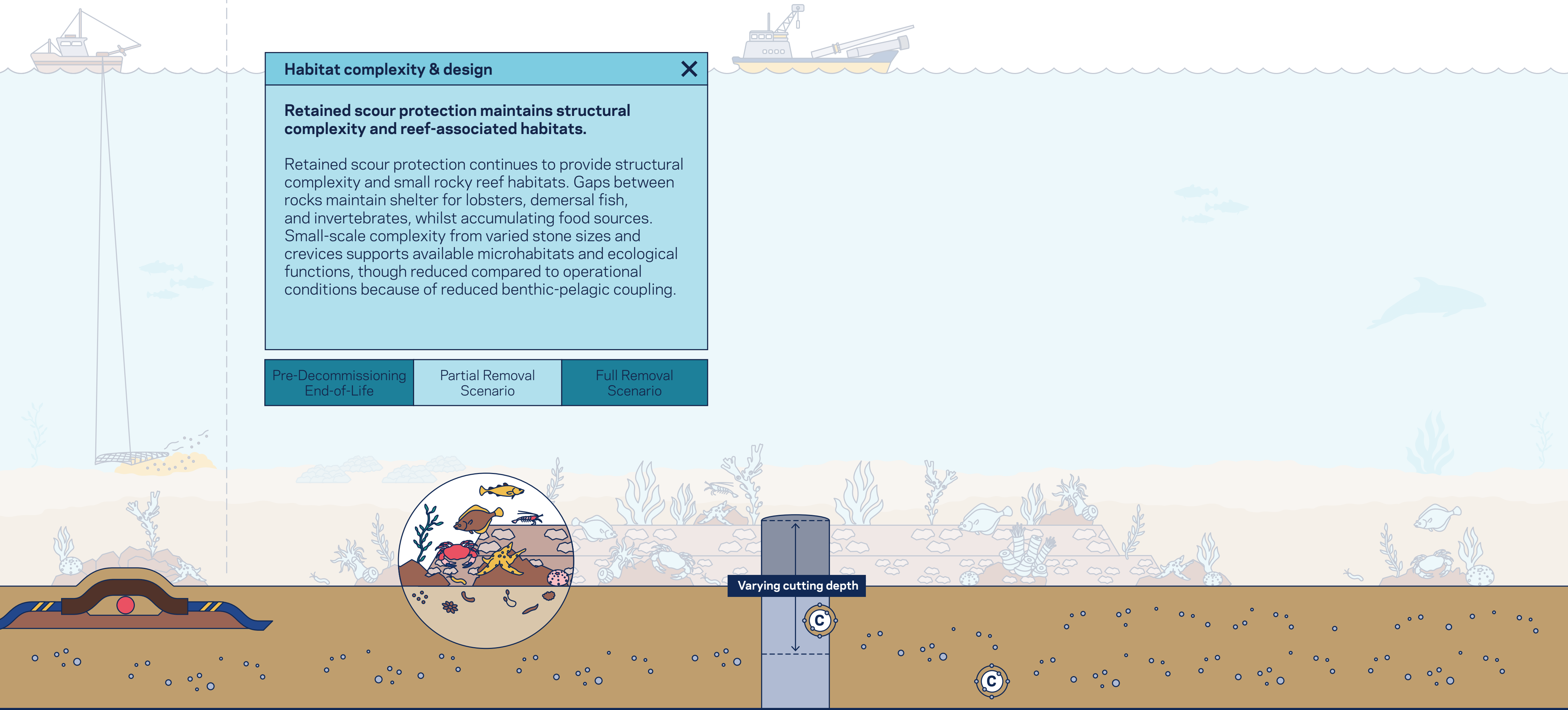

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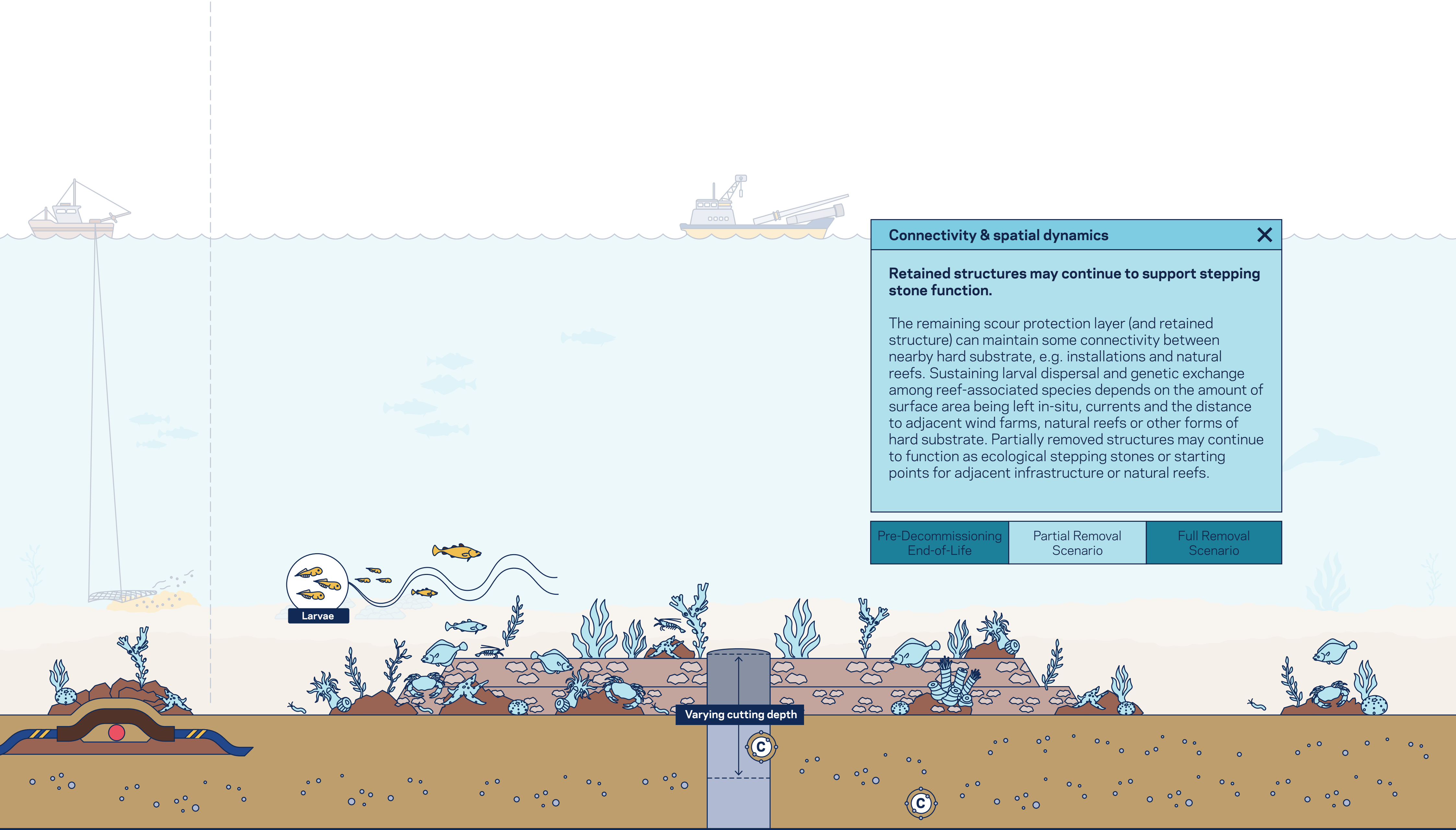


Connectivity & spatial dynamics

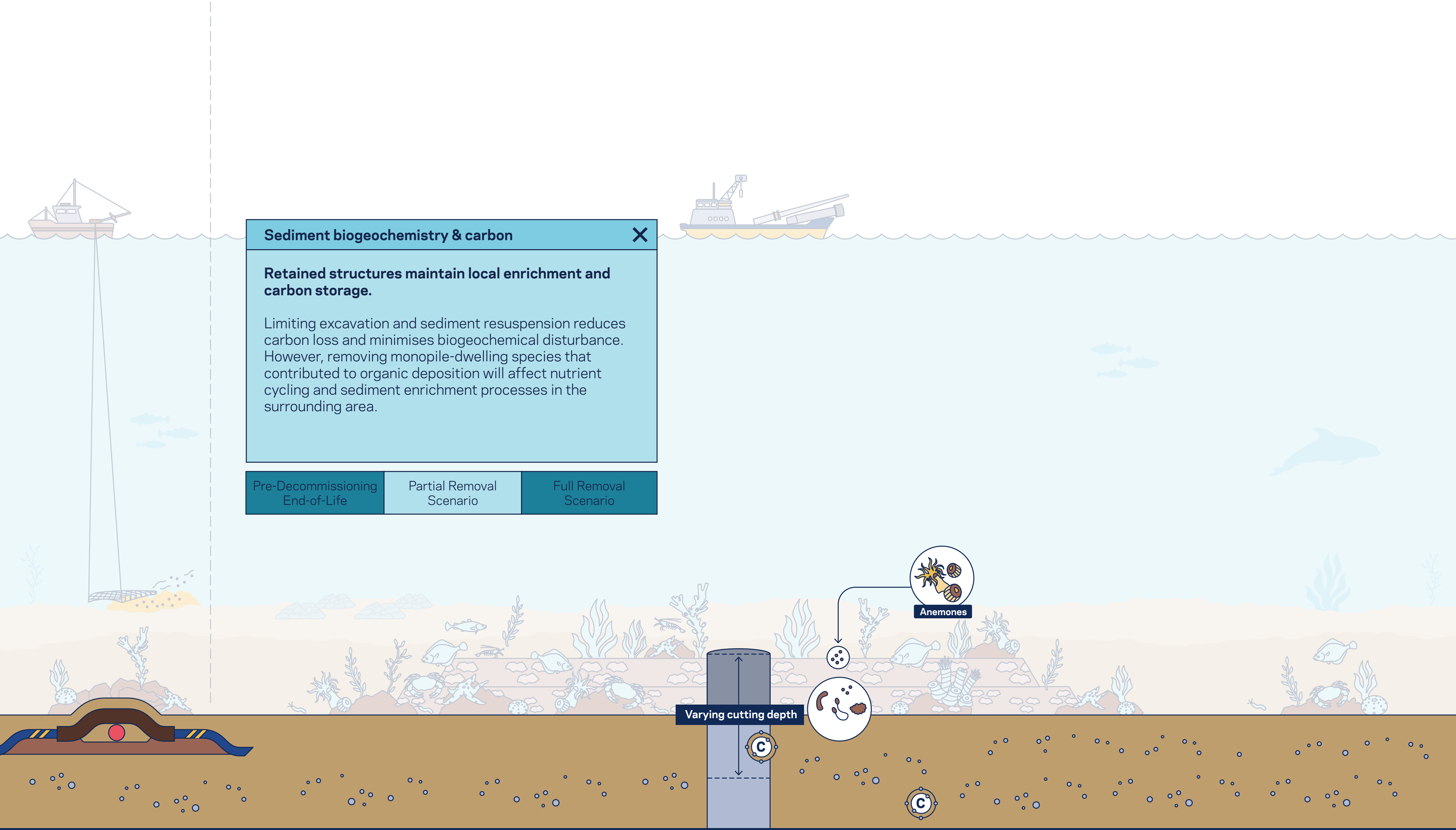
Retained structures may continue to support stepping stone function.

The remaining scour protection layer (and retained structure) can maintain some connectivity between nearby hard substrate, e.g. installations and natural reefs. Sustaining larval dispersal and genetic exchange among reef-associated species depends on the amount of surface area being left in-situ, currents and the distance to adjacent wind farms, natural reefs or other forms of hard substrate. Partially removed structures may continue to function as ecological stepping stones or starting points for adjacent infrastructure or natural reefs.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Partial Removal Scenario

The wind farm is no longer operational. Blades, turbine, tower and most of the monopile foundation are removed and transported to shore. Scour protection and (part of) sub-seabed foundations remain in place to (partially) preserve biodiversity and minimise disturbance. **Monopile cutting depth (below, at, or above seabed) affects habitat disturbance levels.** This approach retains some structural complexity and connectivity for reef-associated species, though removing monopile communities disrupts nutrient cycling. Selective cable recovery balances material circularity with ecological impact.



Sediment biogeochemistry & carbon

Retained structures maintain local enrichment and carbon storage.

Limiting excavation and sediment resuspension reduces carbon loss and minimises biogeochemical disturbance. However, removing monopile-dwelling species that contributed to organic deposition will affect nutrient cycling and sediment enrichment processes in the surrounding area.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Partial Removal Scenario

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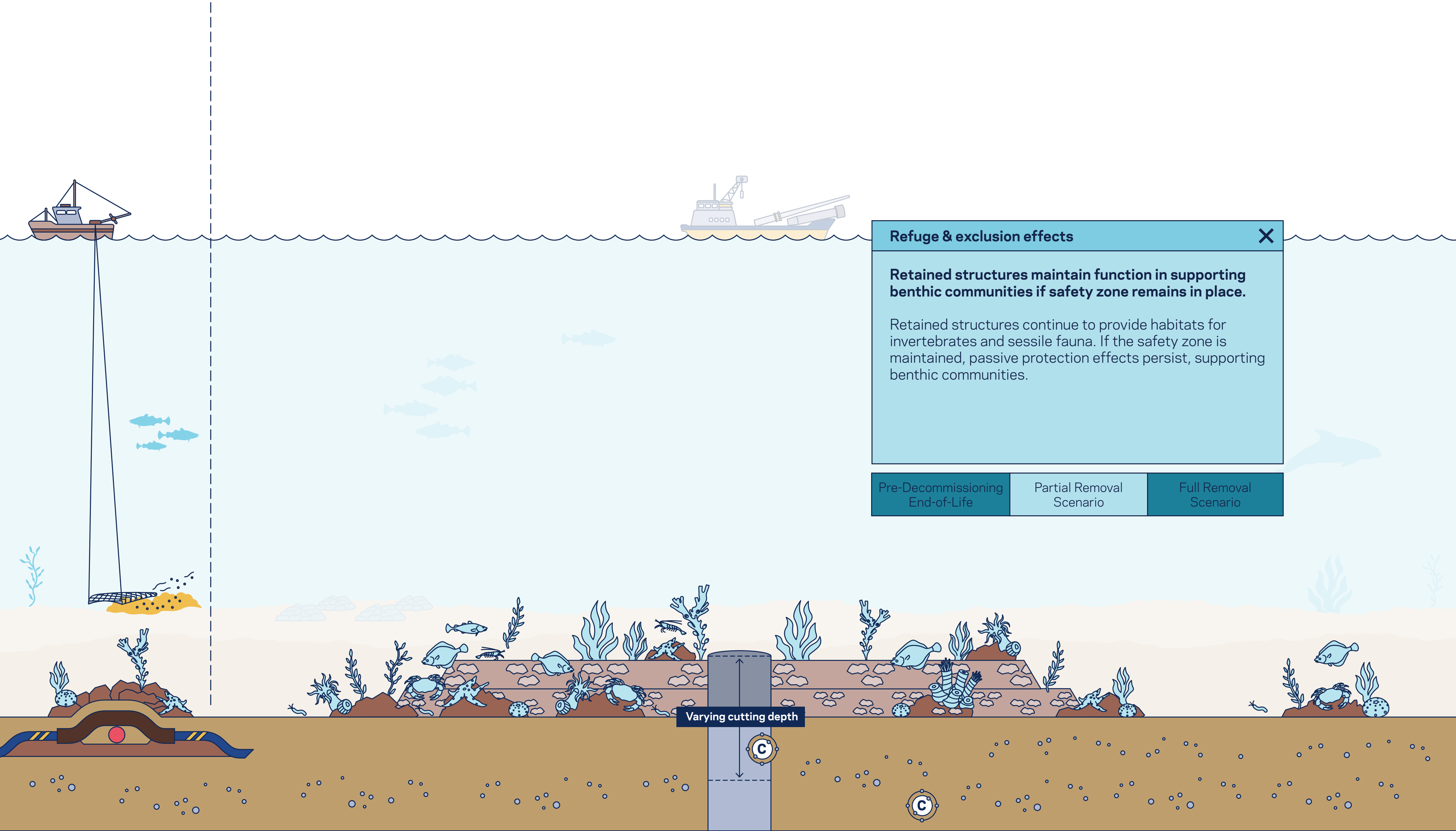

Refuge & exclusion effects

Retained structures maintain function in supporting benthic communities if safety zone remains in place.

Retained structures continue to provide habitats for invertebrates and sessile fauna. If the safety zone is maintained, passive protection effects persist, supporting benthic communities.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure

Partial Removal Scenario

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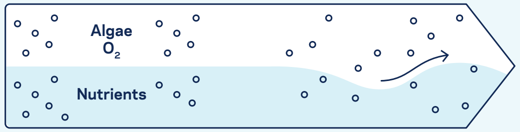
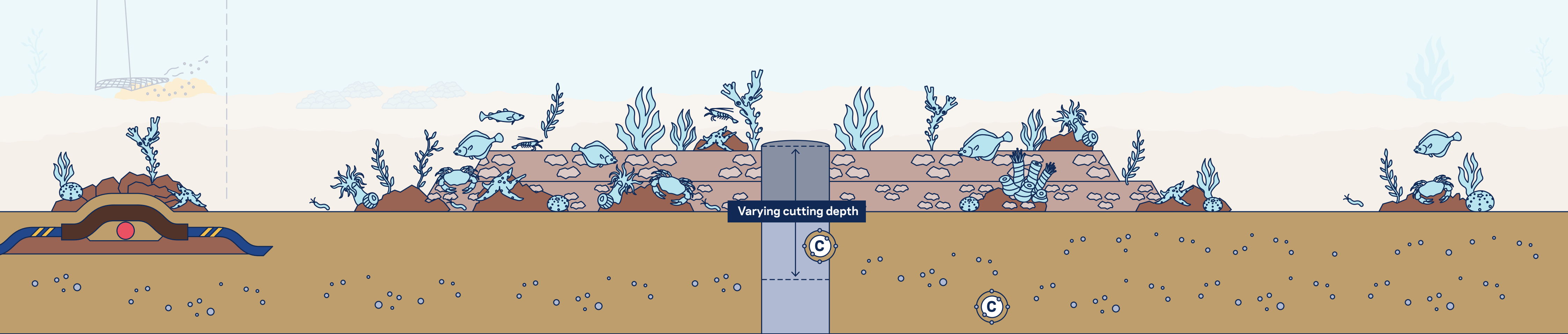
Hydrodynamics & stratification

Local hydrodynamics may be marginally impacted, depending on cutting depth.

Hydrodynamic effects largely disappear once above-seabed structures are removed, although some limited turbulence and sediment mixing may persist around remaining structures, depending upon their height. The ecological consequences depend on local hydrography and seasonal conditions but remain uncertain.





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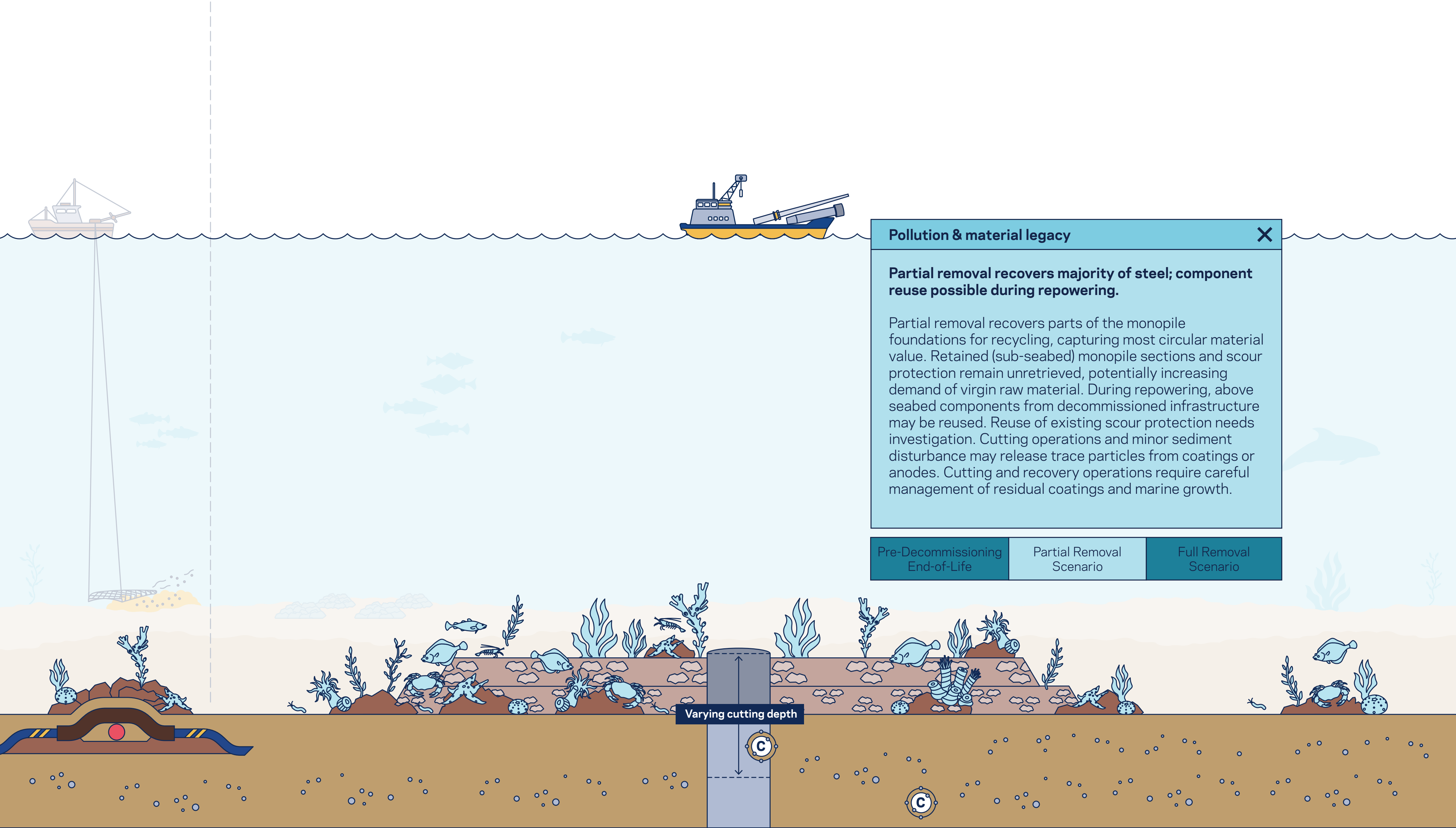

Pollution & material legacy

Partial removal recovers majority of steel; component reuse possible during repowering.

Partial removal recovers parts of the monopile foundations for recycling, capturing most circular material value. Retained (sub-seabed) monopile sections and scour protection remain unretrieved, potentially increasing demand of virgin raw material. During repowering, above seabed components from decommissioned infrastructure may be reused. Reuse of existing scour protection needs investigation. Cutting operations and minor sediment disturbance may release trace particles from coatings or anodes. Cutting and recovery operations require careful management of residual coatings and marine growth.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Partial Removal Scenario

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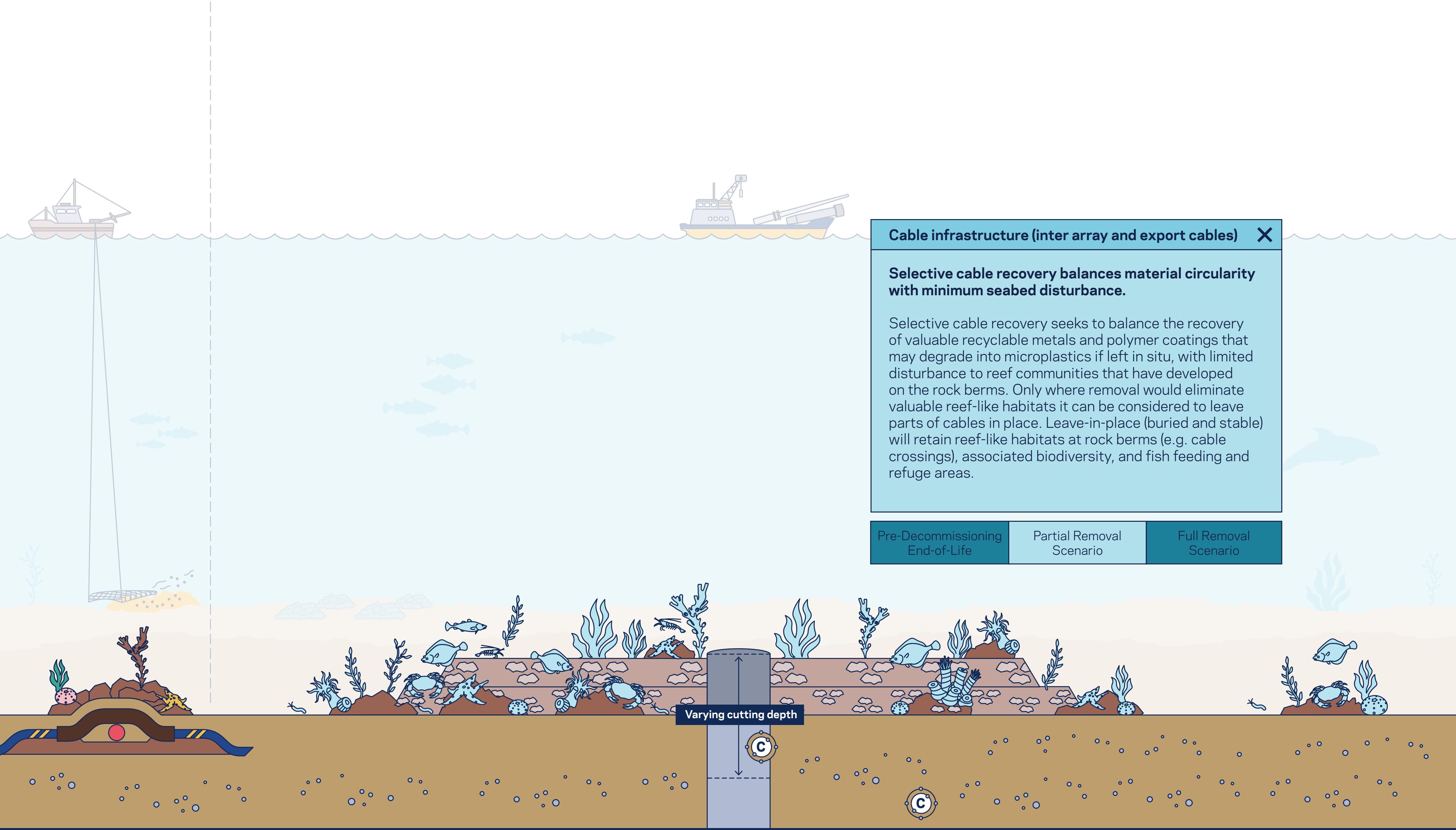

Cable infrastructure (inter array and export cables)

Selective cable recovery balances material circularity with minimum seabed disturbance.

Selective cable recovery seeks to balance the recovery of valuable recyclable metals and polymer coatings that may degrade into microplastics if left in situ, with limited disturbance to reef communities that have developed on the rock berms. Only where removal would eliminate valuable reef-like habitats it can be considered to leave parts of cables in place. Leave-in-place (buried and stable) will retain reef-like habitats at rock berms (e.g. cable crossings), associated biodiversity, and fish feeding and refuge areas.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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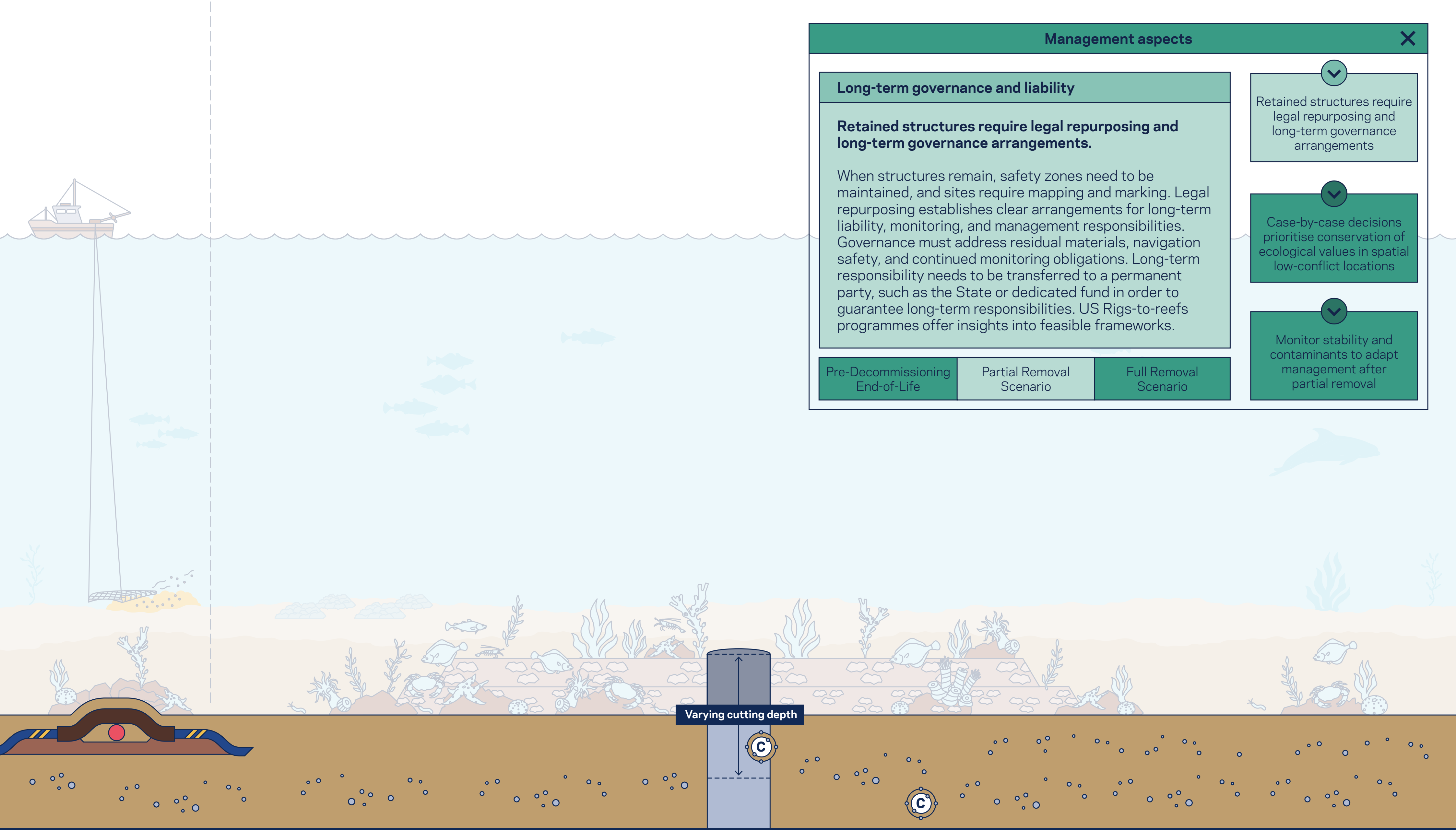

Management aspects

Long-term governance and liability

Retained structures require legal repurposing and long-term governance arrangements.

When structures remain, safety zones need to be maintained, and sites require mapping and marking. Legal repurposing establishes clear arrangements for long-term liability, monitoring, and management responsibilities. Governance must address residual materials, navigation safety, and continued monitoring obligations. Long-term responsibility needs to be transferred to a permanent party, such as the State or dedicated fund in order to guarantee long-term responsibilities. US Rigs-to-reefs programmes offer insights into feasible frameworks.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

- Retained structures require legal repurposing and long-term governance arrangements
- Case-by-case decisions prioritise conservation of ecological values in spatial low-conflict locations
- Monitor stability and contaminants to adapt management after partial removal

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Partial Removal Scenario

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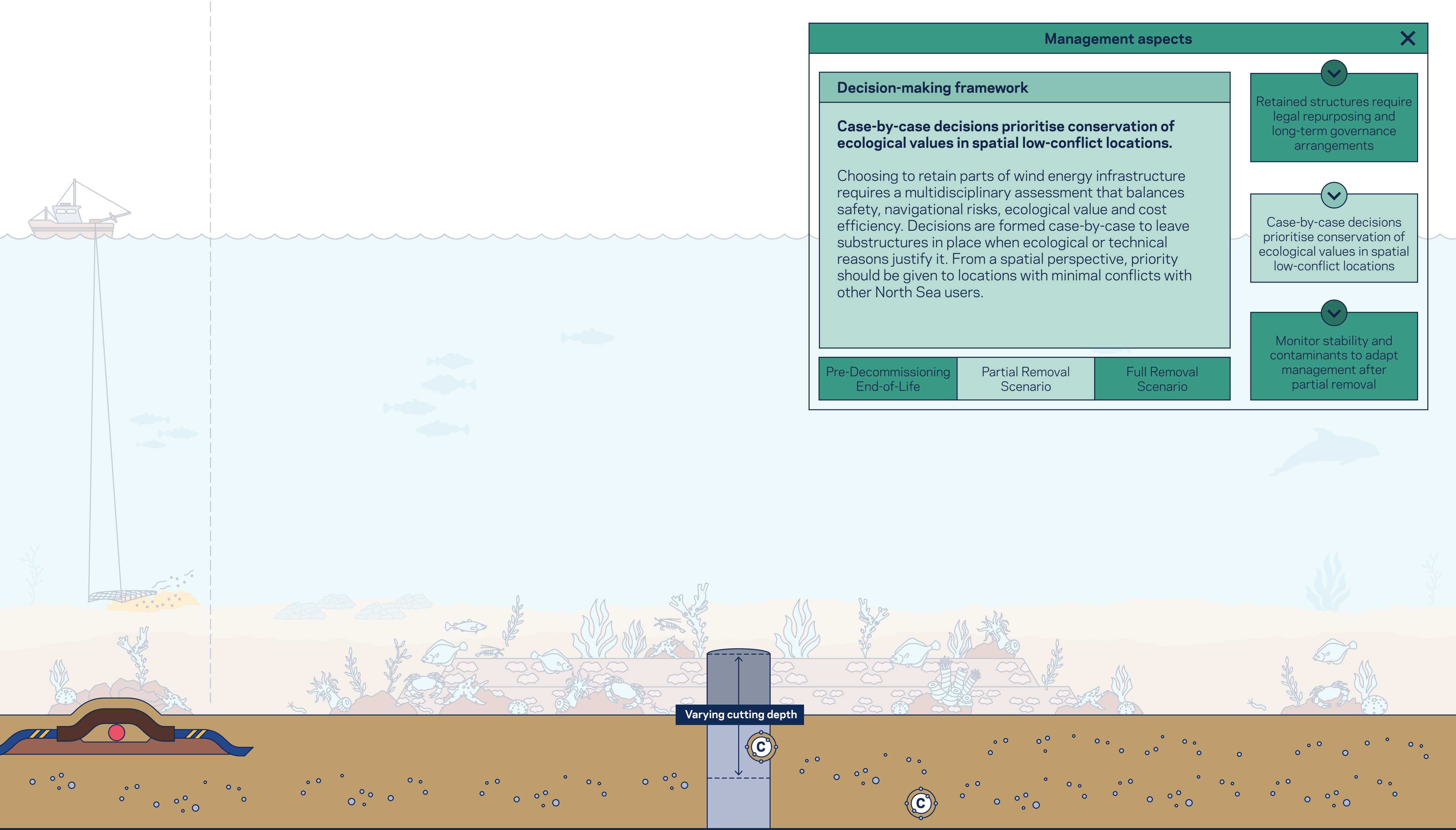

Management aspects

Decision-making framework

Case-by-case decisions prioritise conservation of ecological values in spatial low-conflict locations.

Choosing to retain parts of wind energy infrastructure requires a multidisciplinary assessment that balances safety, navigational risks, ecological value and cost efficiency. Decisions are formed case-by-case to leave substructures in place when ecological or technical reasons justify it. From a spatial perspective, priority should be given to locations with minimal conflicts with other North Sea users.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

- Retained structures require legal repurposing and long-term governance arrangements
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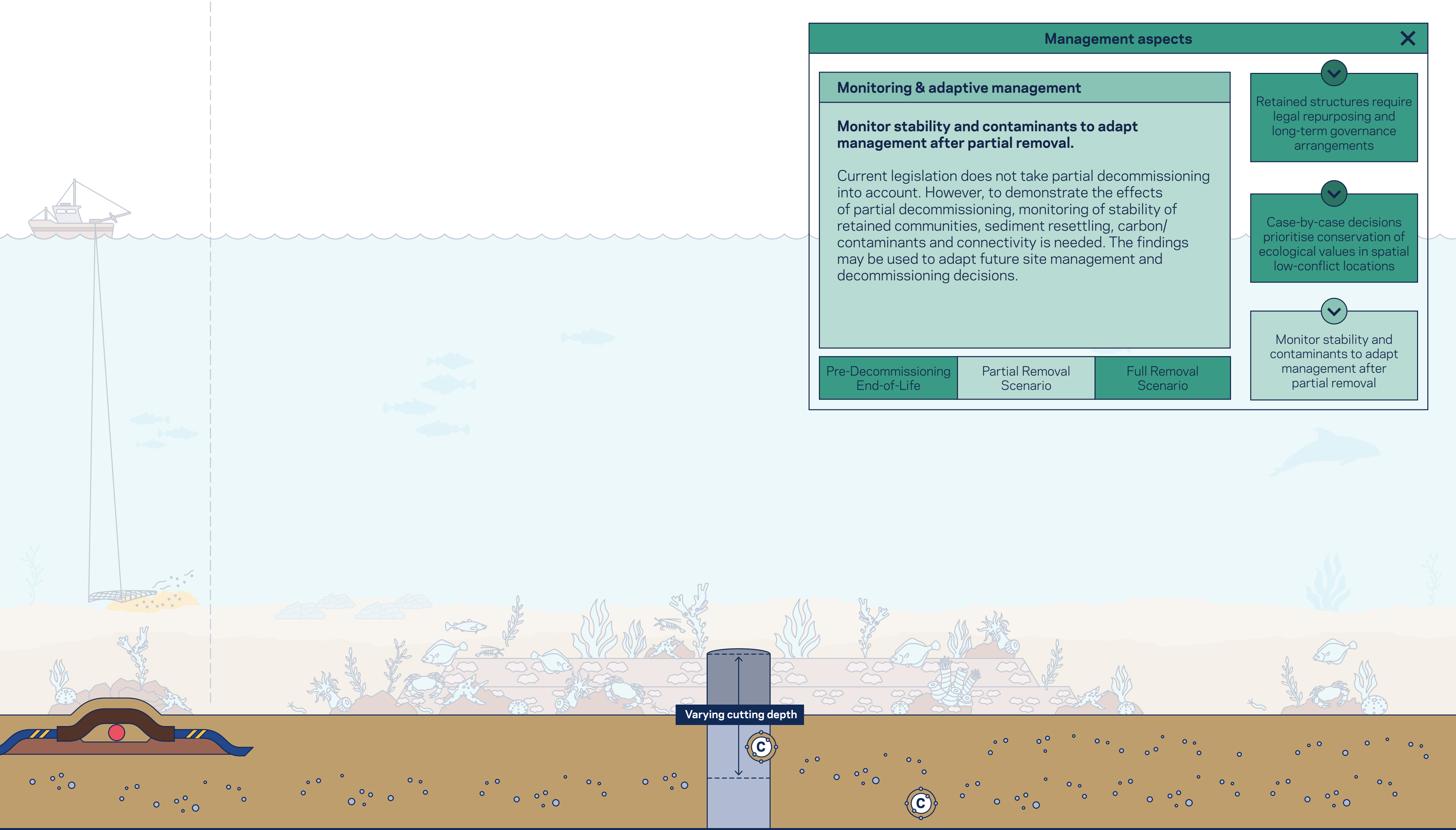

Management aspects

Monitoring & adaptive management

Monitor stability and contaminants to adapt management after partial removal.

Current legislation does not take partial decommissioning into account. However, to demonstrate the effects of partial decommissioning, monitoring of stability of retained communities, sediment resettling, carbon/contaminants and connectivity is needed. The findings may be used to adapt future site management and decommissioning decisions.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

- Retained structures require legal repurposing and long-term governance arrangements
- Case-by-case decisions prioritise conservation of ecological values in spatial low-conflict locations
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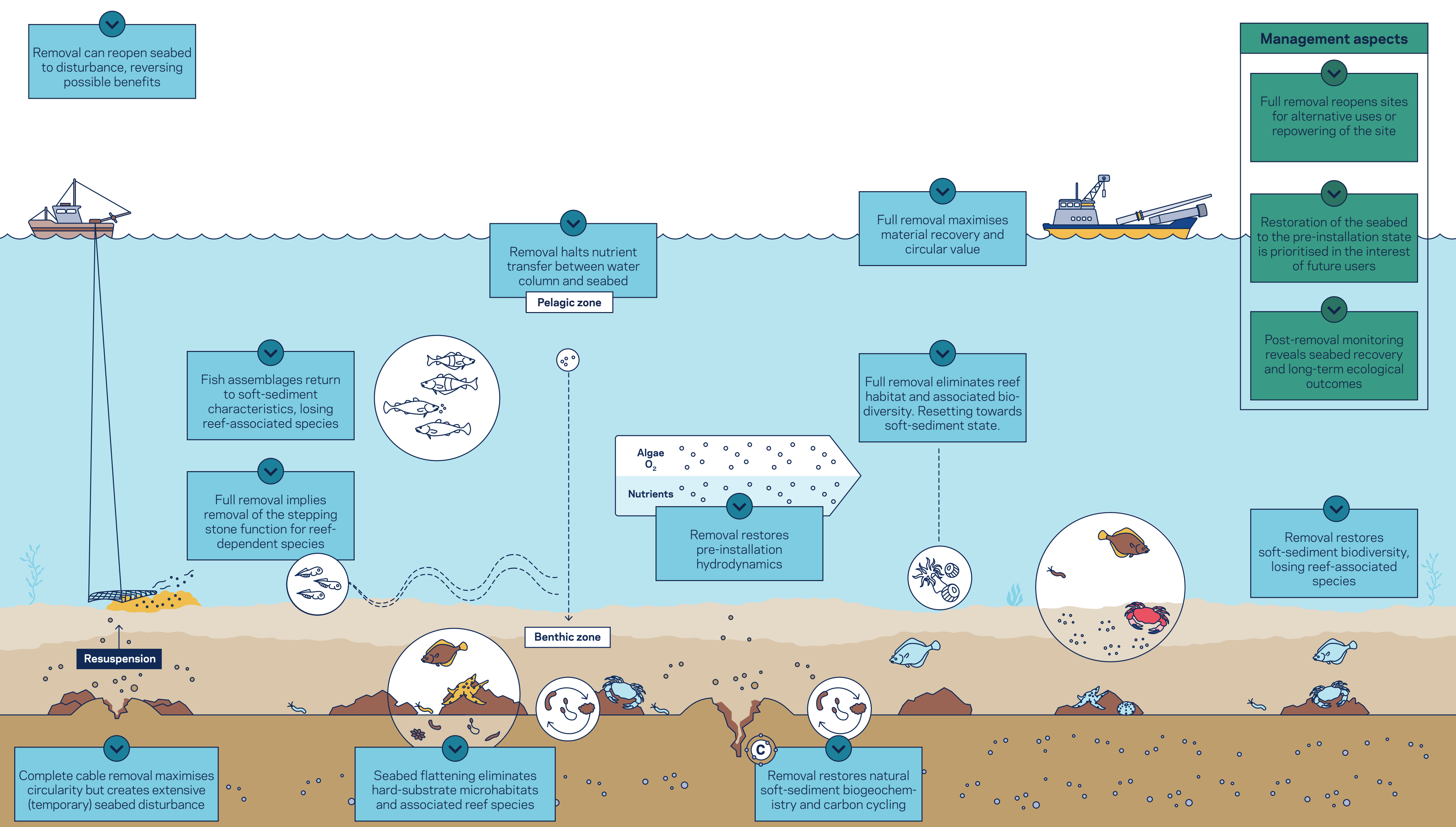
Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

The wind farm is no longer operational. All infrastructure – blades, turbine, tower, monopile, scour protection, cables, and crossings – is removed for recycling, maximising material circularity. This eliminates hard-substrate reef communities, returning the seabed towards its pre-construction soft-sediment state and restoring natural hydrodynamics. Reef-associated species lose habitat, whilst soft-sediment biodiversity may gradually recolonise. Sites can potentially reopen to fishing and seabed-disturbing activities, which will remove any natural reefs or marine growth formed between the turbines.



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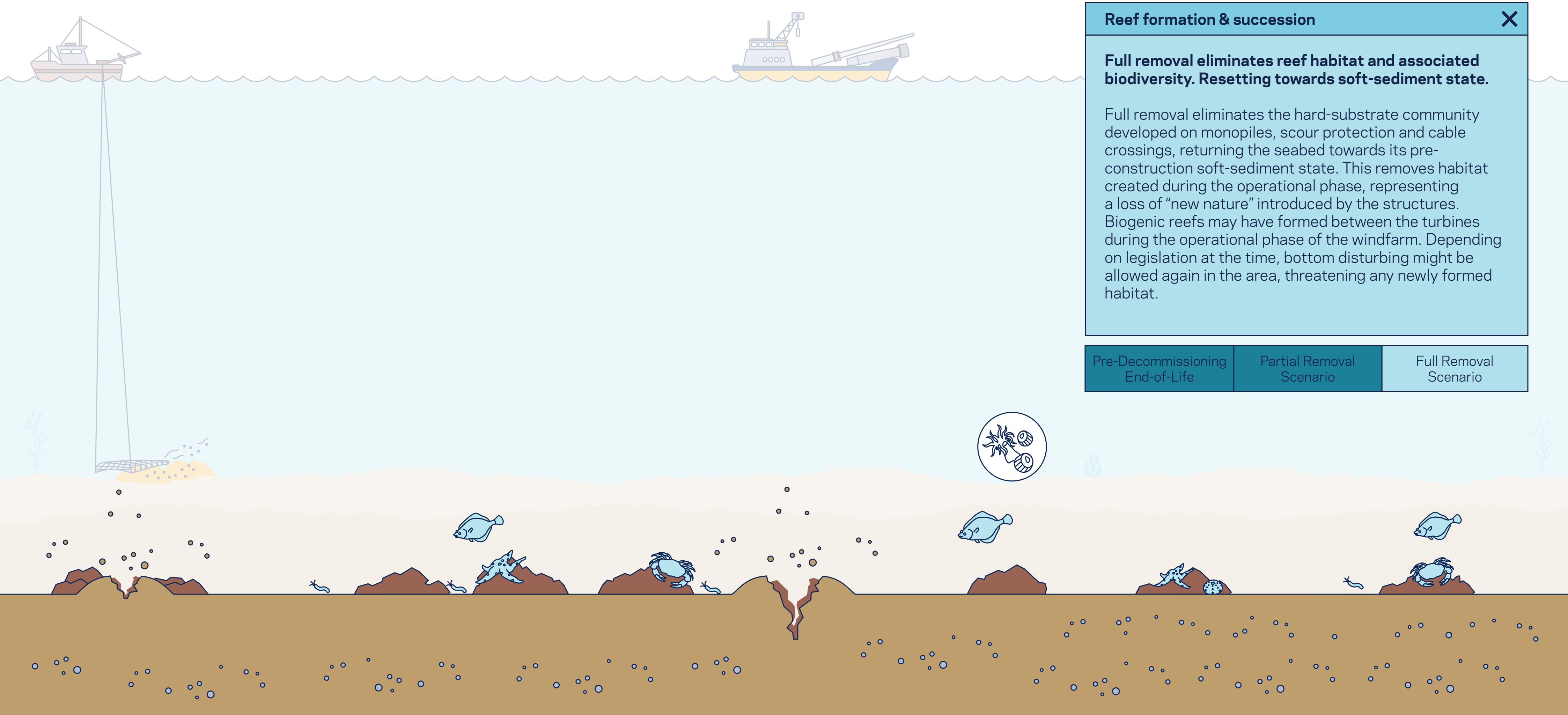

Reef formation & succession

Full removal eliminates reef habitat and associated biodiversity. Resetting towards soft-sediment state.

Full removal eliminates the hard-substrate community developed on monopiles, scour protection and cable crossings, returning the seabed towards its pre-construction soft-sediment state. This removes habitat created during the operational phase, representing a loss of "new nature" introduced by the structures. Biogenic reefs may have formed between the turbines during the operational phase of the windfarm. Depending on legislation at the time, bottom disturbing might be allowed again in the area, threatening any newly formed habitat.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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Full Removal Scenario

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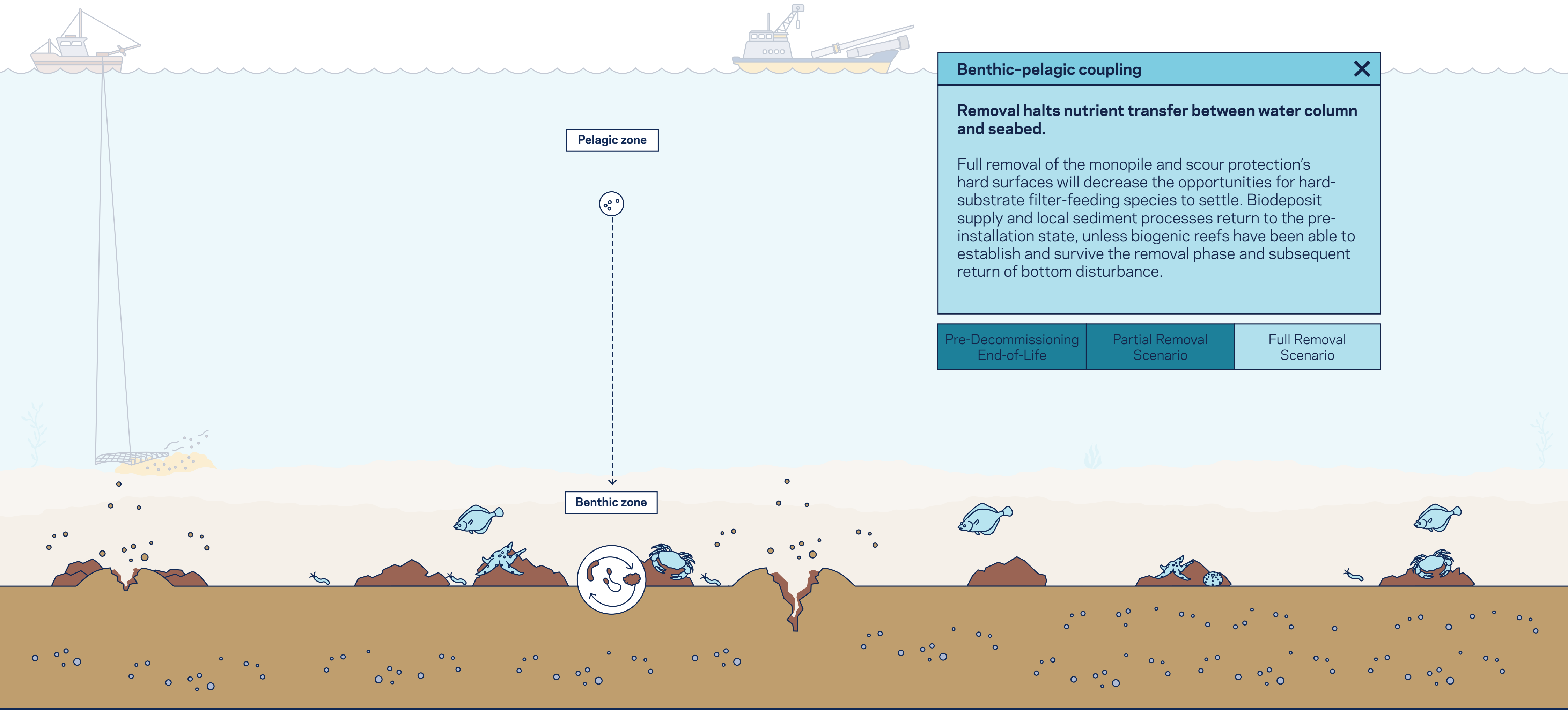

Benthic-pelagic coupling

Removal halts nutrient transfer between water column and seabed.

Full removal of the monopile and scour protection's hard surfaces will decrease the opportunities for hard-substrate filter-feeding species to settle. Biodeposit supply and local sediment processes return to the pre-installation state, unless biogenic reefs have been able to establish and survive the removal phase and subsequent return of bottom disturbance.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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Full Removal Scenario

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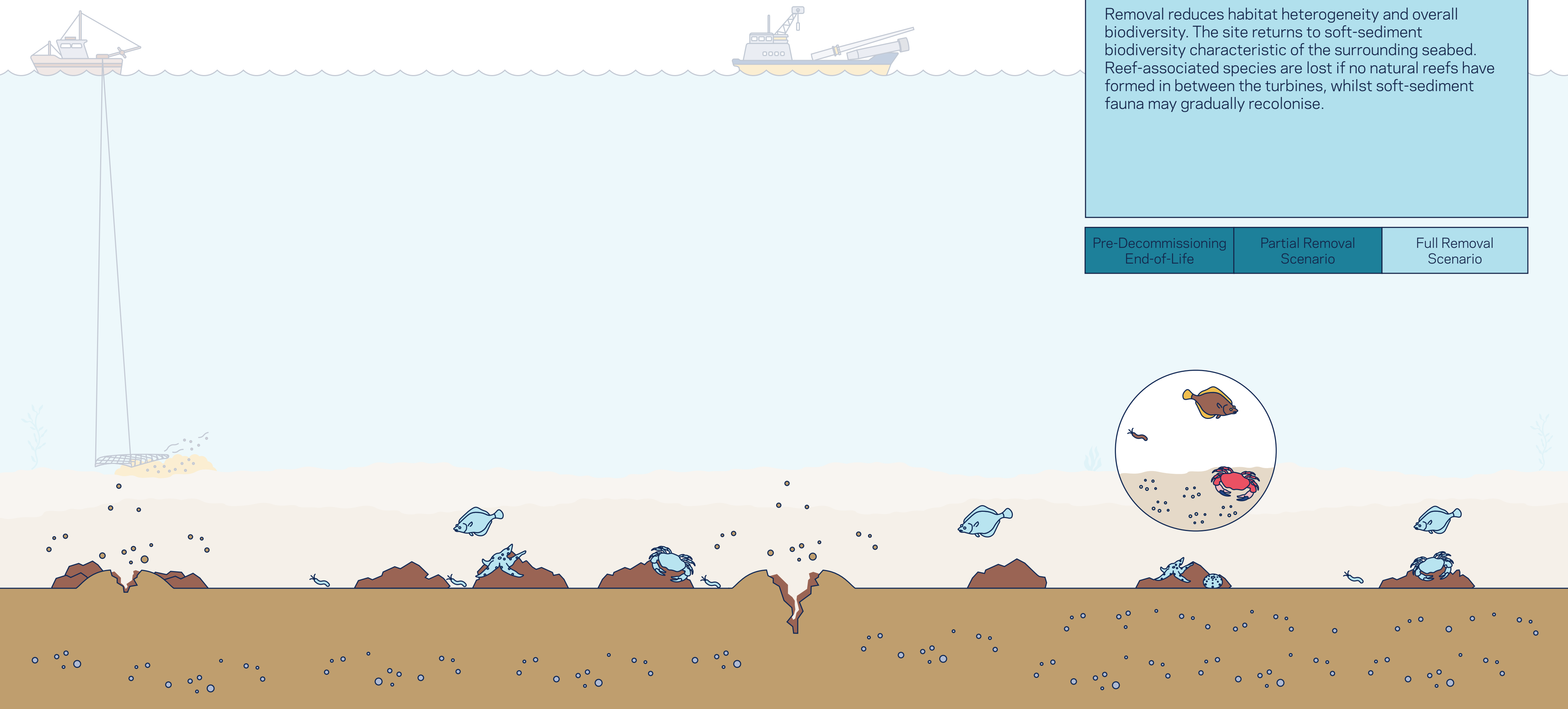

Biodiversity & species richness

Removal restores soft-sediment biodiversity, losing reef-associated species.

Removal reduces habitat heterogeneity and overall biodiversity. The site returns to soft-sediment biodiversity characteristic of the surrounding seabed. Reef-associated species are lost if no natural reefs have formed in between the turbines, whilst soft-sediment fauna may gradually recolonise.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
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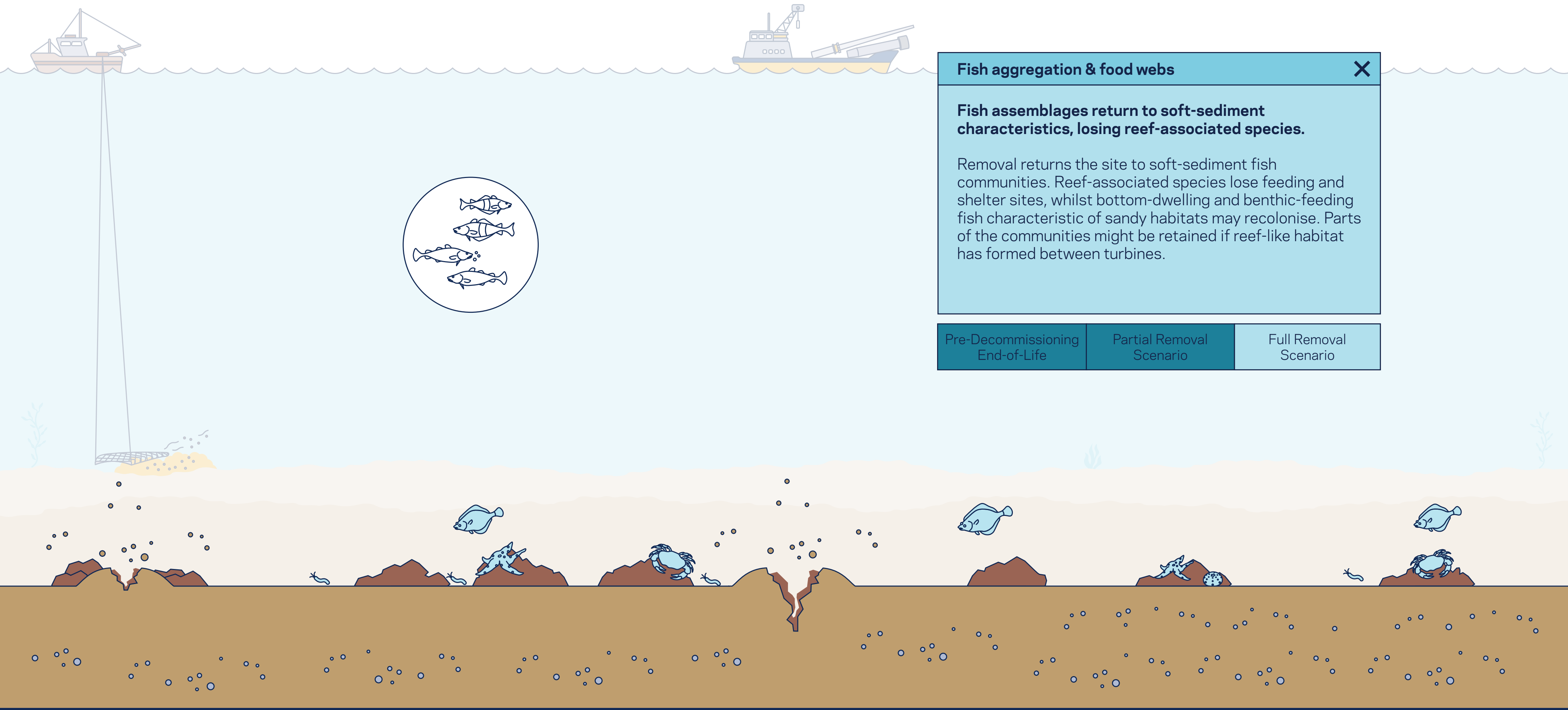

Fish aggregation & food webs

Fish assemblages return to soft-sediment characteristics, losing reef-associated species.

Removal returns the site to soft-sediment fish communities. Reef-associated species lose feeding and shelter sites, whilst bottom-dwelling and benthic-feeding fish characteristic of sandy habitats may recolonise. Parts of the communities might be retained if reef-like habitat has formed between turbines.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

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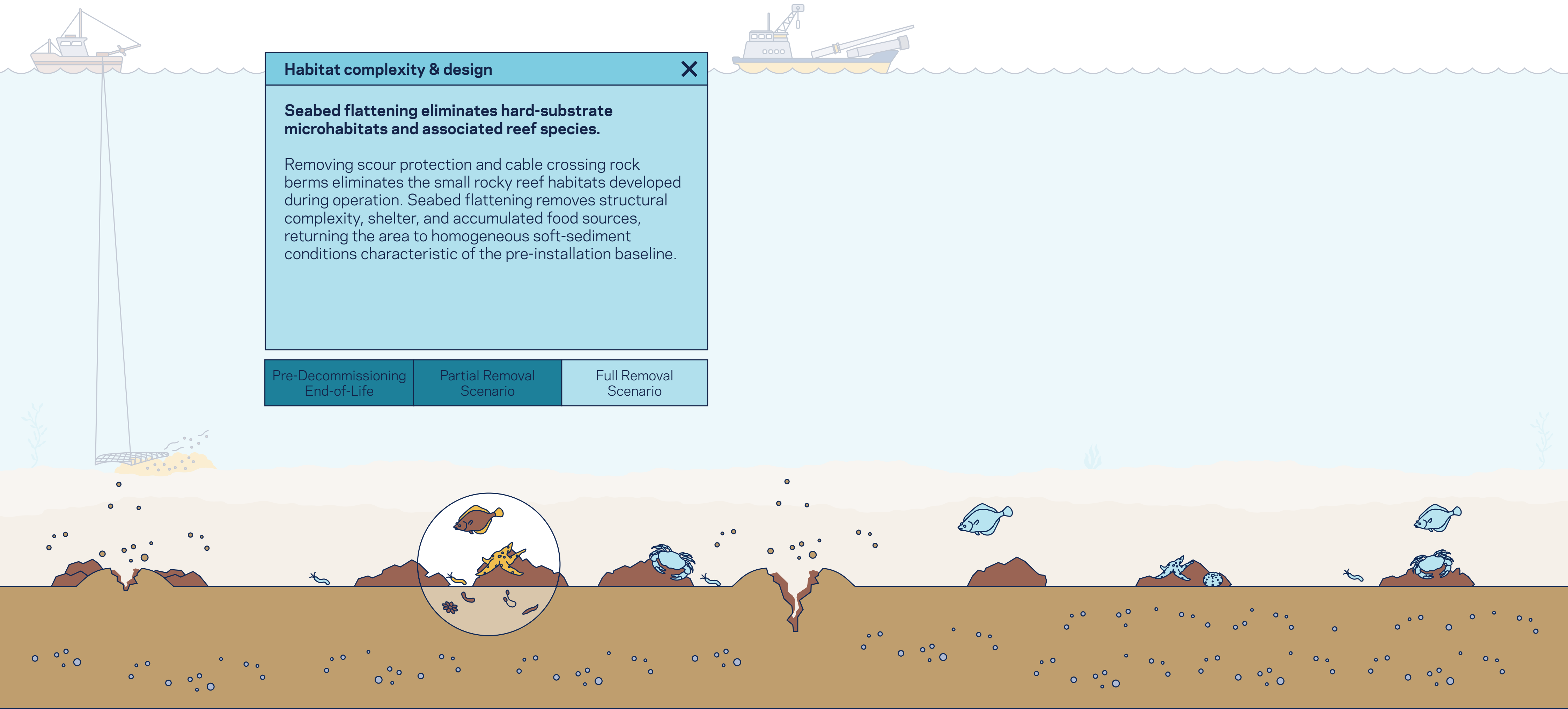

Habitat complexity & design

Seabed flattening eliminates hard-substrate microhabitats and associated reef species.

Removing scour protection and cable crossing rock berms eliminates the small rocky reef habitats developed during operation. Seabed flattening removes structural complexity, shelter, and accumulated food sources, returning the area to homogeneous soft-sediment conditions characteristic of the pre-installation baseline.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
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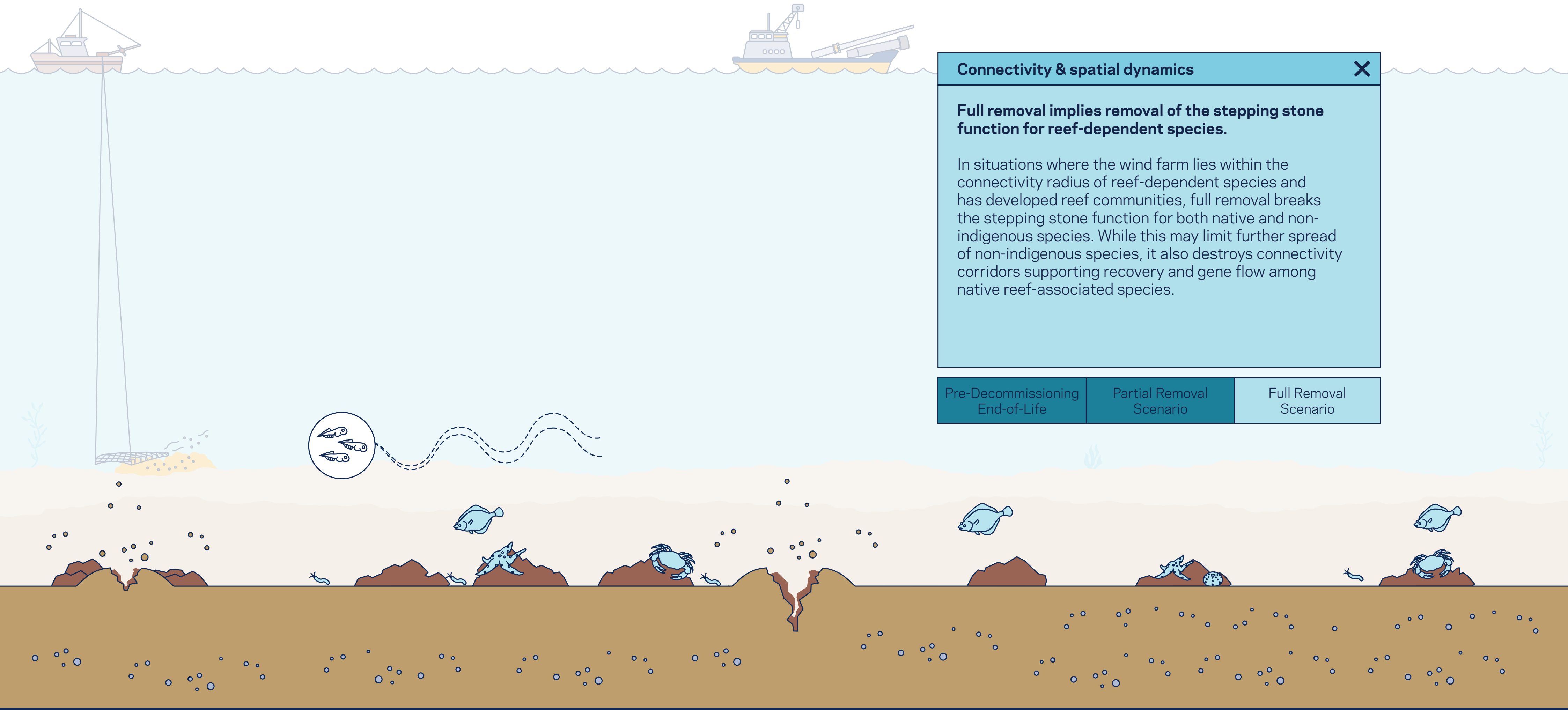

Connectivity & spatial dynamics

Full removal implies removal of the stepping stone function for reef-dependent species.

In situations where the wind farm lies within the connectivity radius of reef-dependent species and has developed reef communities, full removal breaks the stepping stone function for both native and non-indigenous species. While this may limit further spread of non-indigenous species, it also destroys connectivity corridors supporting recovery and gene flow among native reef-associated species.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

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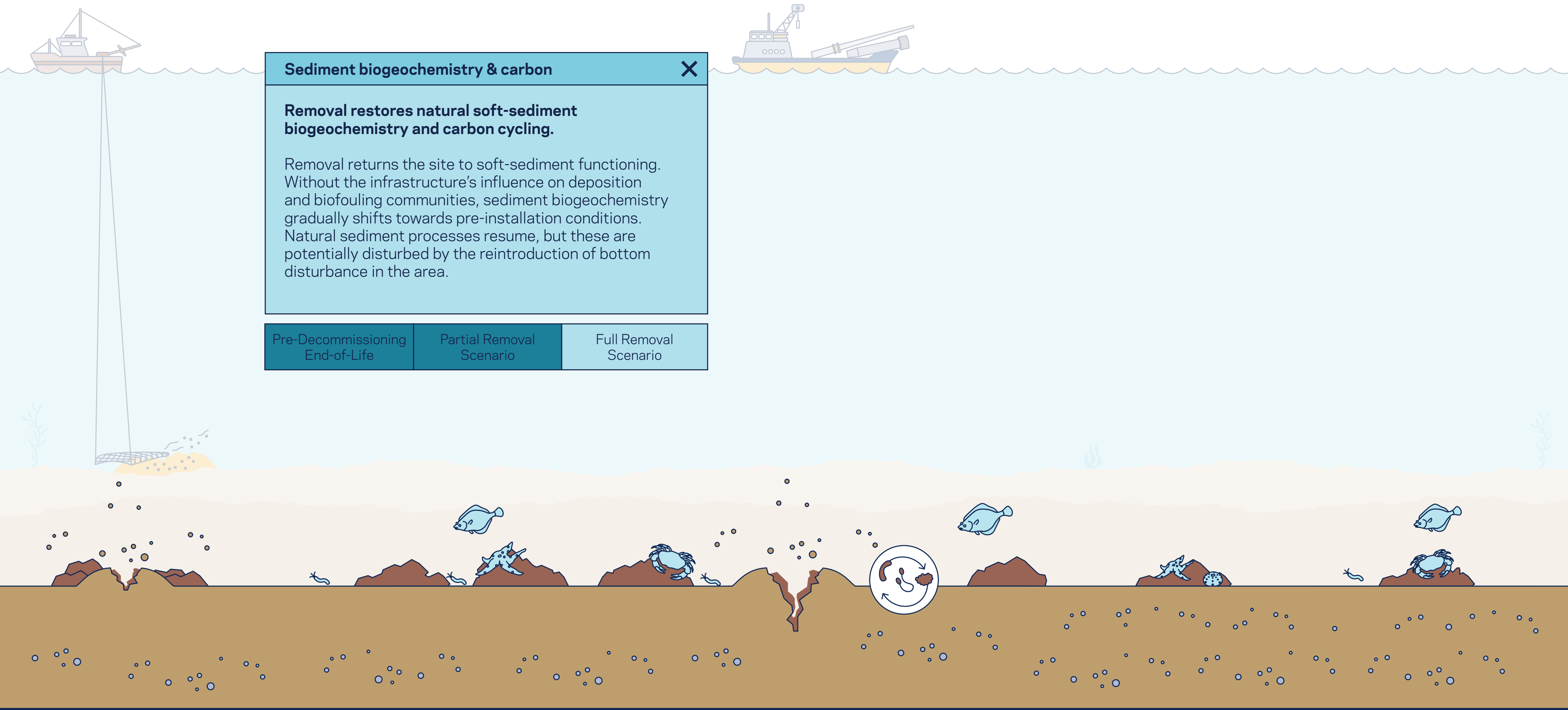

Sediment biogeochemistry & carbon

Removal restores natural soft-sediment biogeochemistry and carbon cycling.

Removal returns the site to soft-sediment functioning. Without the infrastructure's influence on deposition and biofouling communities, sediment biogeochemistry gradually shifts towards pre-installation conditions. Natural sediment processes resume, but these are potentially disturbed by the reintroduction of bottom disturbance in the area.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
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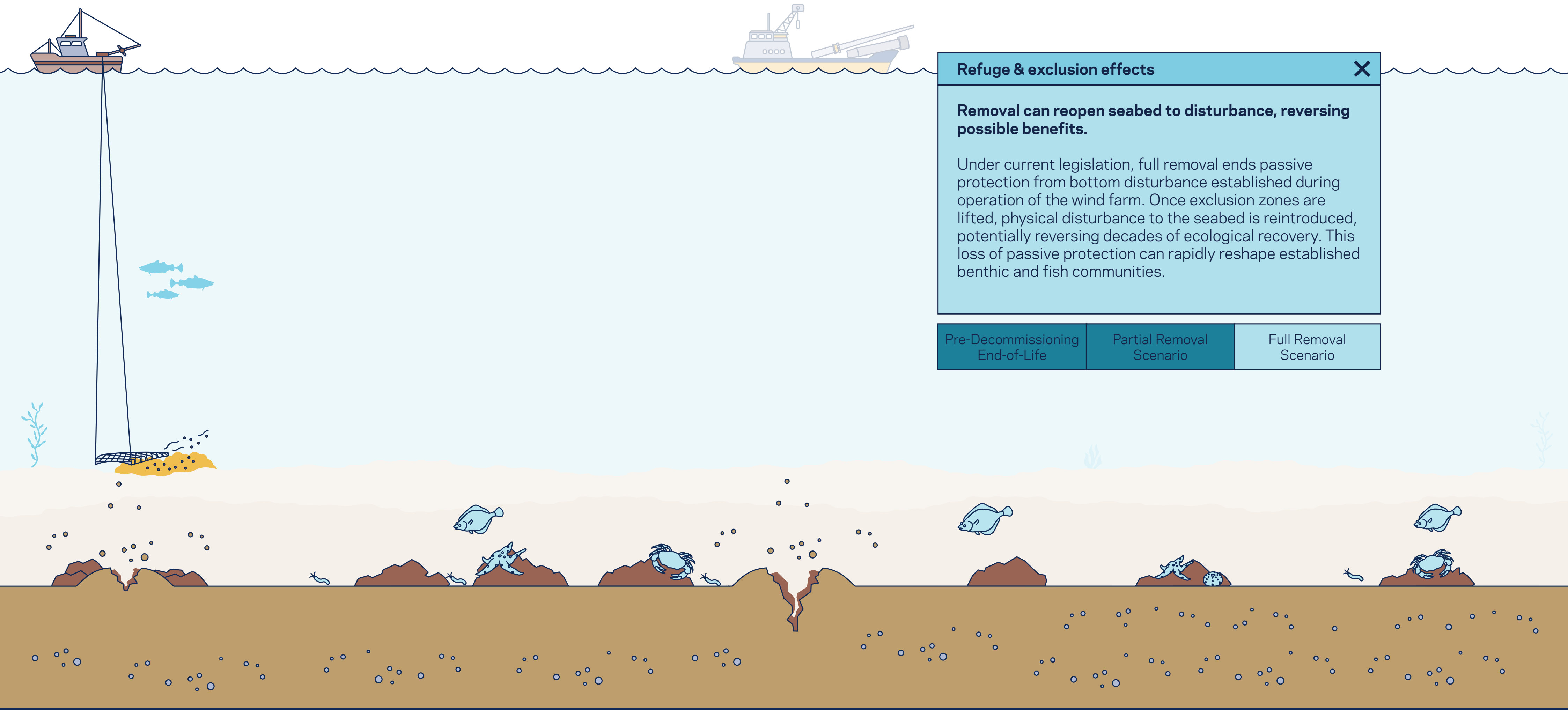

Refuge & exclusion effects

Removal can reopen seabed to disturbance, reversing possible benefits.

Under current legislation, full removal ends passive protection from bottom disturbance established during operation of the wind farm. Once exclusion zones are lifted, physical disturbance to the seabed is reintroduced, potentially reversing decades of ecological recovery. This loss of passive protection can rapidly reshape established benthic and fish communities.

Pre-Decommissioning End-of-Life
Partial Removal Scenario
Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

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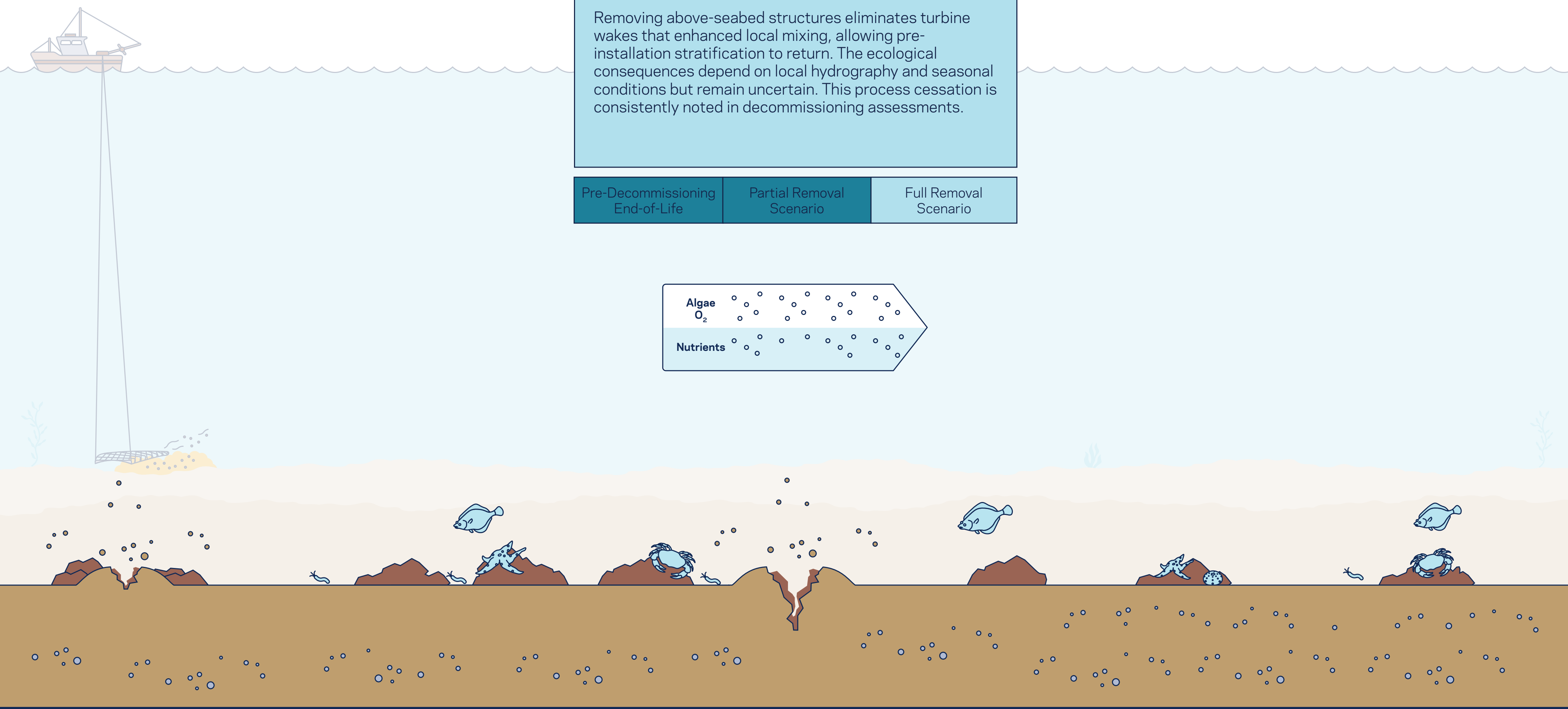
Hydrodynamics & stratification

Removal restores pre-installation hydrodynamics.

Removing above-seabed structures eliminates turbine wakes that enhanced local mixing, allowing pre-installation stratification to return. The ecological consequences depend on local hydrography and seasonal conditions but remain uncertain. This process cessation is consistently noted in decommissioning assessments.

Pre-Decommissioning End-of-Life
Partial Removal Scenario
Full Removal Scenario



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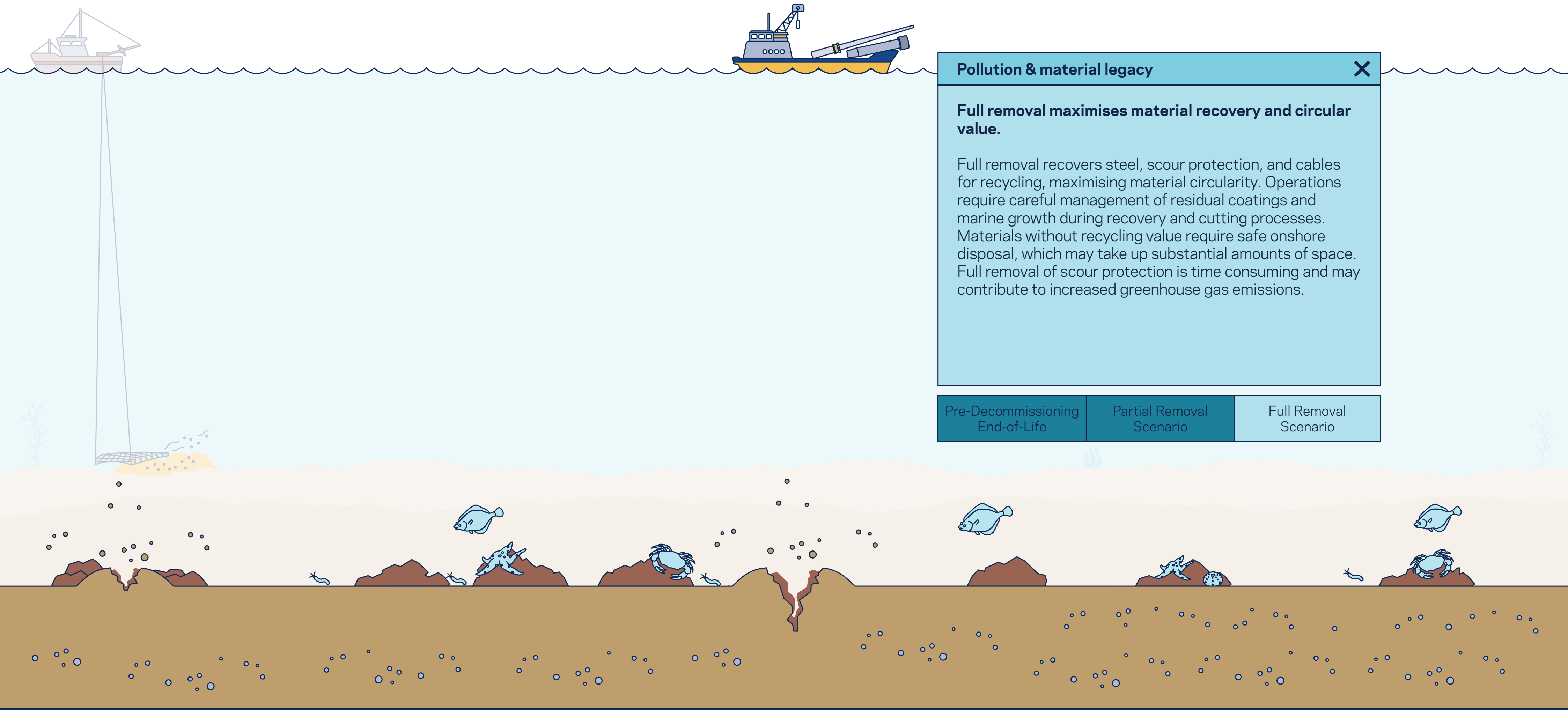

Pollution & material legacy

Full removal maximises material recovery and circular value.

Full removal recovers steel, scour protection, and cables for recycling, maximising material circularity. Operations require careful management of residual coatings and marine growth during recovery and cutting processes. Materials without recycling value require safe onshore disposal, which may take up substantial amounts of space. Full removal of scour protection is time consuming and may contribute to increased greenhouse gas emissions.

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Full Removal Scenario

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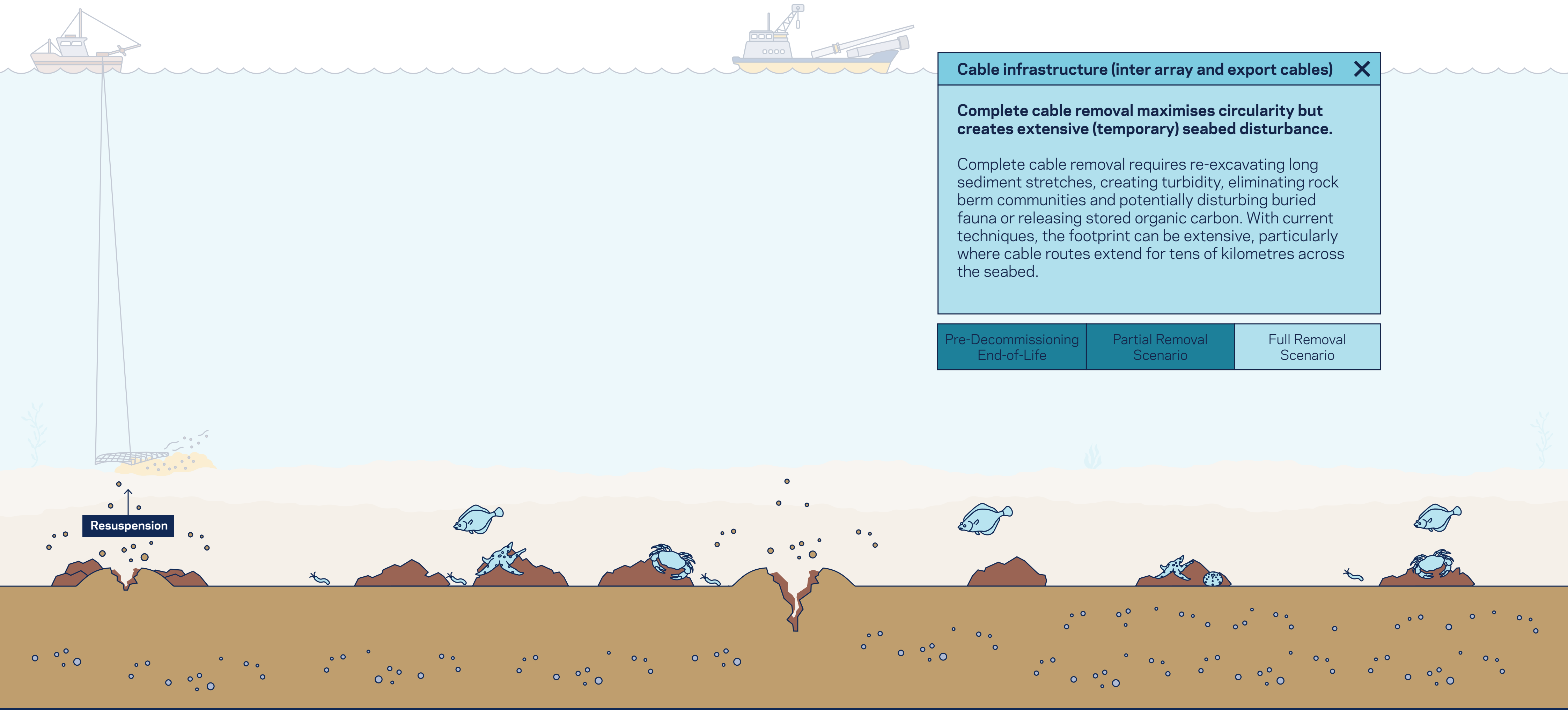

Cable infrastructure (inter array and export cables)

Complete cable removal maximises circularity but creates extensive (temporary) seabed disturbance.

Complete cable removal requires re-excavating long sediment stretches, creating turbidity, eliminating rock berm communities and potentially disturbing buried fauna or releasing stored organic carbon. With current techniques, the footprint can be extensive, particularly where cable routes extend for tens of kilometres across the seabed.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

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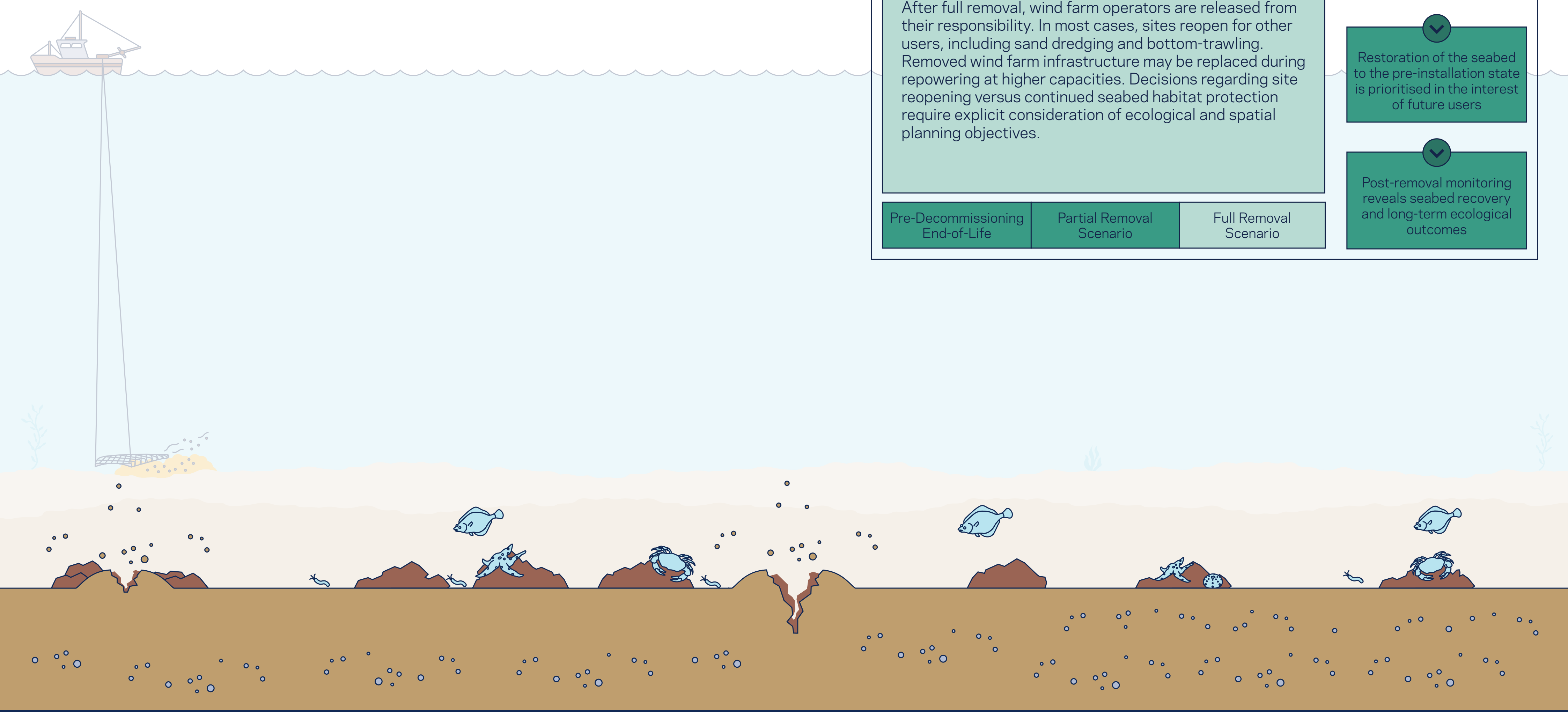

Management aspects

Long-term governance and liability

Full removal reopens sites for alternative uses or repowering of the site.

After full removal, wind farm operators are released from their responsibility. In most cases, sites reopen for other users, including sand dredging and bottom-trawling. Removed wind farm infrastructure may be replaced during repowering at higher capacities. Decisions regarding site reopening versus continued seabed habitat protection require explicit consideration of ecological and spatial planning objectives.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

- Full removal reopens sites for alternative uses or repowering of the site
- Restoration of the seabed to the pre-installation state is prioritised in the interest of future users
- Post-removal monitoring reveals seabed recovery and long-term ecological outcomes

Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

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Management aspects

Decision-making framework

Restoration of the seabed to the pre-installation state is prioritised in the interest of future users.

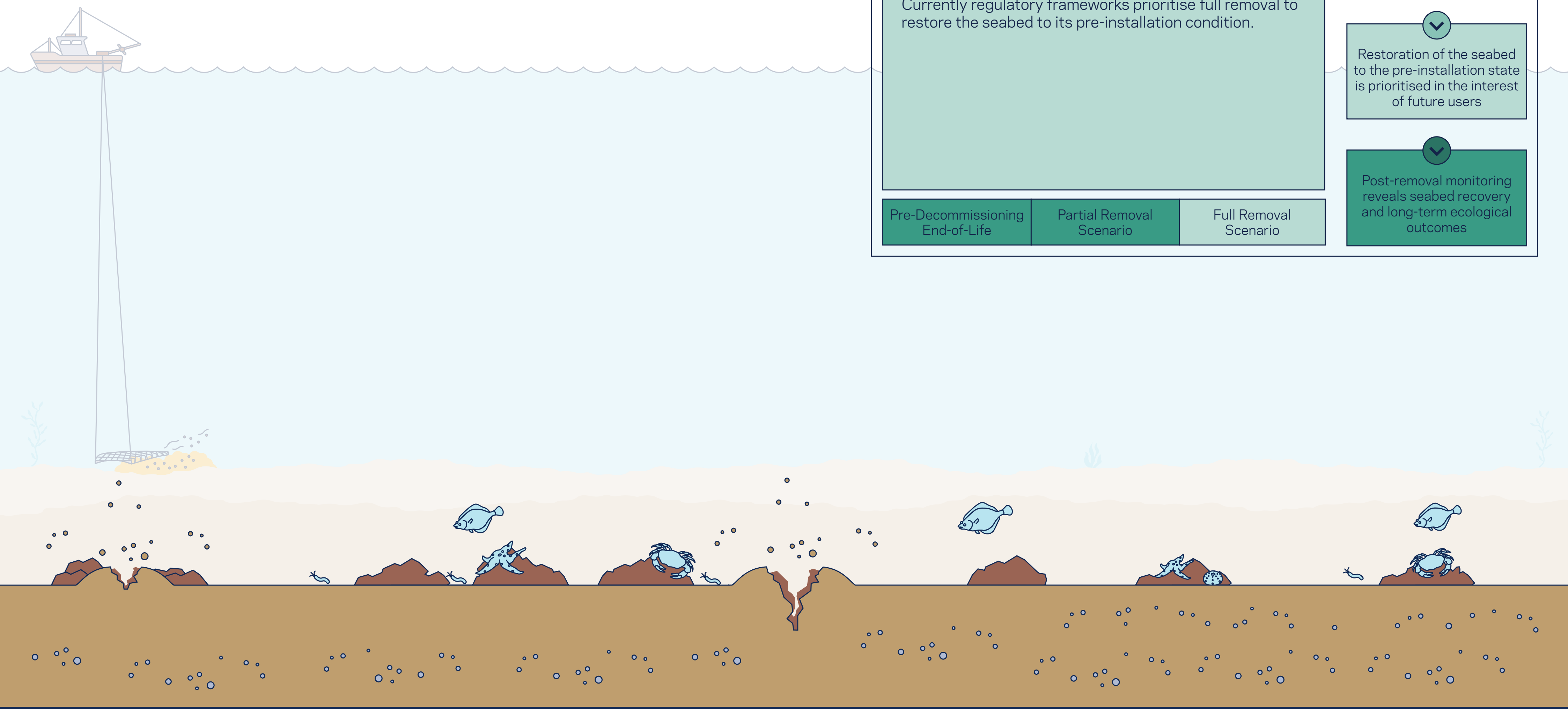
Currently regulatory frameworks prioritise full removal to restore the seabed to its pre-installation condition.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Full removal reopens sites for alternative uses or repowering of the site

Restoration of the seabed to the pre-installation state is prioritised in the interest of future users

Post-removal monitoring reveals seabed recovery and long-term ecological outcomes



Effects of Decommissioning Offshore Wind and Grid Infrastructure
Full Removal Scenario

The wind farm is no longer operational. All infrastructure – blades, turbine, tower, monopile, scour protection, cables, and crossings – is removed for recycling, maximising material circularity. This eliminates hard-substrate reef communities, returning the seabed towards its pre-construction soft-sediment state and restoring natural hydrodynamics. Reef-associated species lose habitat, whilst soft-sediment biodiversity may gradually recolonise. Sites can potentially reopen to fishing and seabed-disturbing activities, which will remove any natural reefs or marine growth formed between the turbines.

Management aspects

Monitoring & adaptive management

Post-removal monitoring reveals seabed recovery and long-term ecological outcomes.

Post-removal monitoring, where implemented, provides insight into how the seabed and associated communities develop after disturbance, improving understanding of long-term ecological outcomes.

Pre-Decommissioning End-of-Life | Partial Removal Scenario | Full Removal Scenario

Full removal reopens sites for alternative uses or repowering of the site

Restoration of the seabed to the pre-installation state is prioritised in the interest of future users

Post-removal monitoring reveals seabed recovery and long-term ecological outcomes