# Supporting Marine Ecosystems Through Nature-Inclusive Design

## Final Agenda (Times are in U.S. East Coast Time)

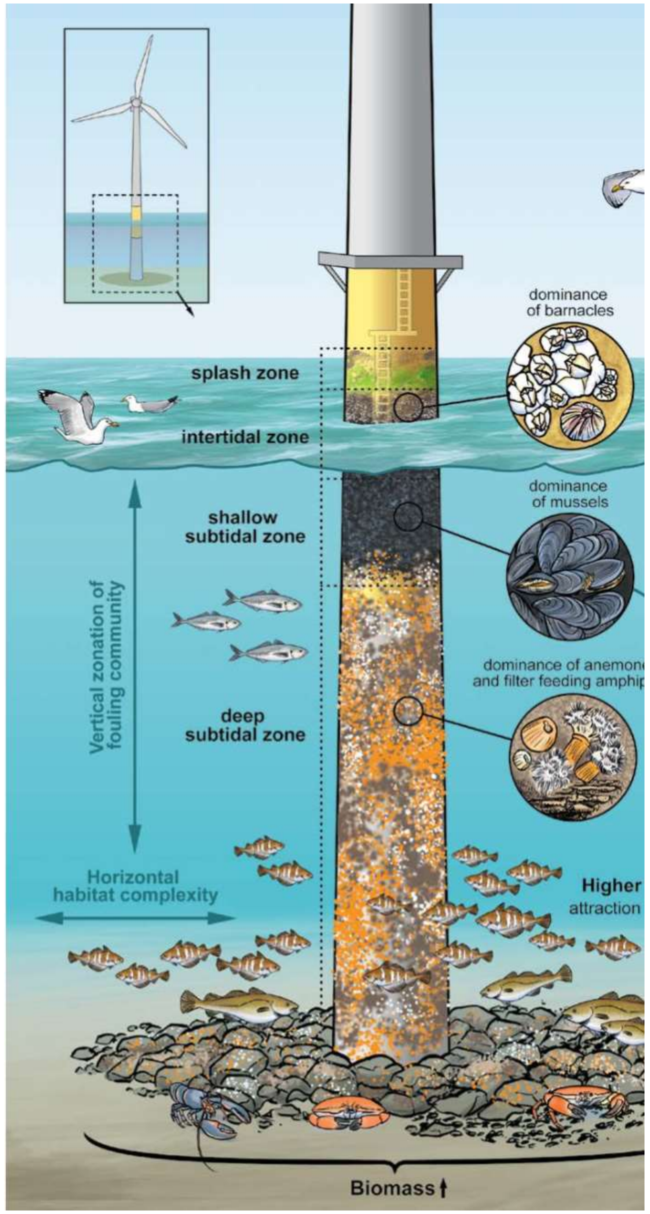
10:00 – 10:10: Welcome and Project Introduction, Workshop Objectives, & Logistics
10:10 – 10:50: Part 1: Presentations on Motivation and Examples for Nature-Inclusive Design
10:50 – 11:50: Part 2: Discussions on Four Topics Central to the Ongoing Project for BOEM
11:50 – 12:00: Next Steps (Results of Survey)

## Part 1: Presentations on Motivations and Examples for Nature-Inclusive Design (40 minutes)

1.1 Synthesis of Environmental Effects Research Project (NREL and PNNL)
1.2 Environmental Observations on Offshore Wind Structures including RODEO Project (Inspire Environmental)
1.3 Developer/Academic Initiatives in Nature-Inclusive Design (Orsted / Wageningen Univ.)
1.4 Artificial Reefs, Offshore Wind Farms as Sanctuaries, and Defining Success (Boskalis)

## Part 2: Discussions on Four Topics Central to Ongoing Project for BOEM (60 Minutes)

2.1. Impact of Perforations and Cathodic Protection on Marine Growth (Monica Maher, DOE)
2.2. Biofouling Profiles (Andrew Want, Heriot-Watt University)
2.3. Internal Chemistry in Monopiles (Bruinsma and Jansen, Deltares)
2.4. Interactions between Marine Growth and Internal Water Chemistry (Swain, Florida Tech.)



BOEM
Bureau of Ocean Energy Management

BSEE
Bureau of Safety and Environmental Enforcement

## Funding Opportunity Announcement

*Topic 2: Analyze the use of Corrosion Protection inside enclosed spaces of large diameter monopile structures*

**Objective:** To determine if BOEM should recommend corrosion protection measures inside monopile offshore wind foundations.
Excerpts from announcement……The use of Cathodic Protection inside enclosed spaces potentially leads to other harmful (gasification) or deleterious effects (acidification of the entrapped water). Designers have proposed methods of venting gases and perforation of the monopile to allow for water exchange….
A rigorous look at the problem and recommendations as to the calculations required to ensure adequate water exchange and safe venting of the gasses would benefit the industry and help BOEM to ensure our mission.

**Elements of our Research Project**

1. Impact of Corrosion Protection System (CPS) and Performations on Chemistries and Corrosion
2. Impact of Perforations on Loadings and Structural Design
3. Impact of CPS and Perforations on Marine Growth and Habitats
4. Develop Plans for Needed Field and Laboratory Studies
   Plus Field Study Planned to Get Underway in Summer of 2022

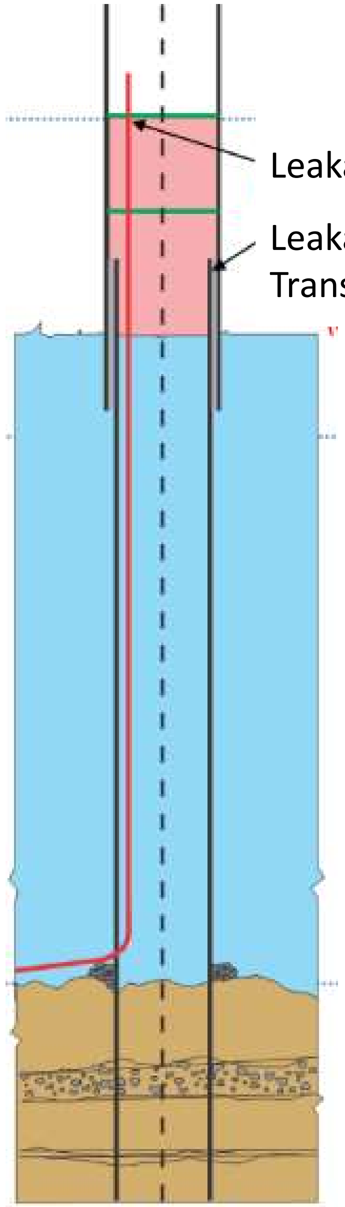
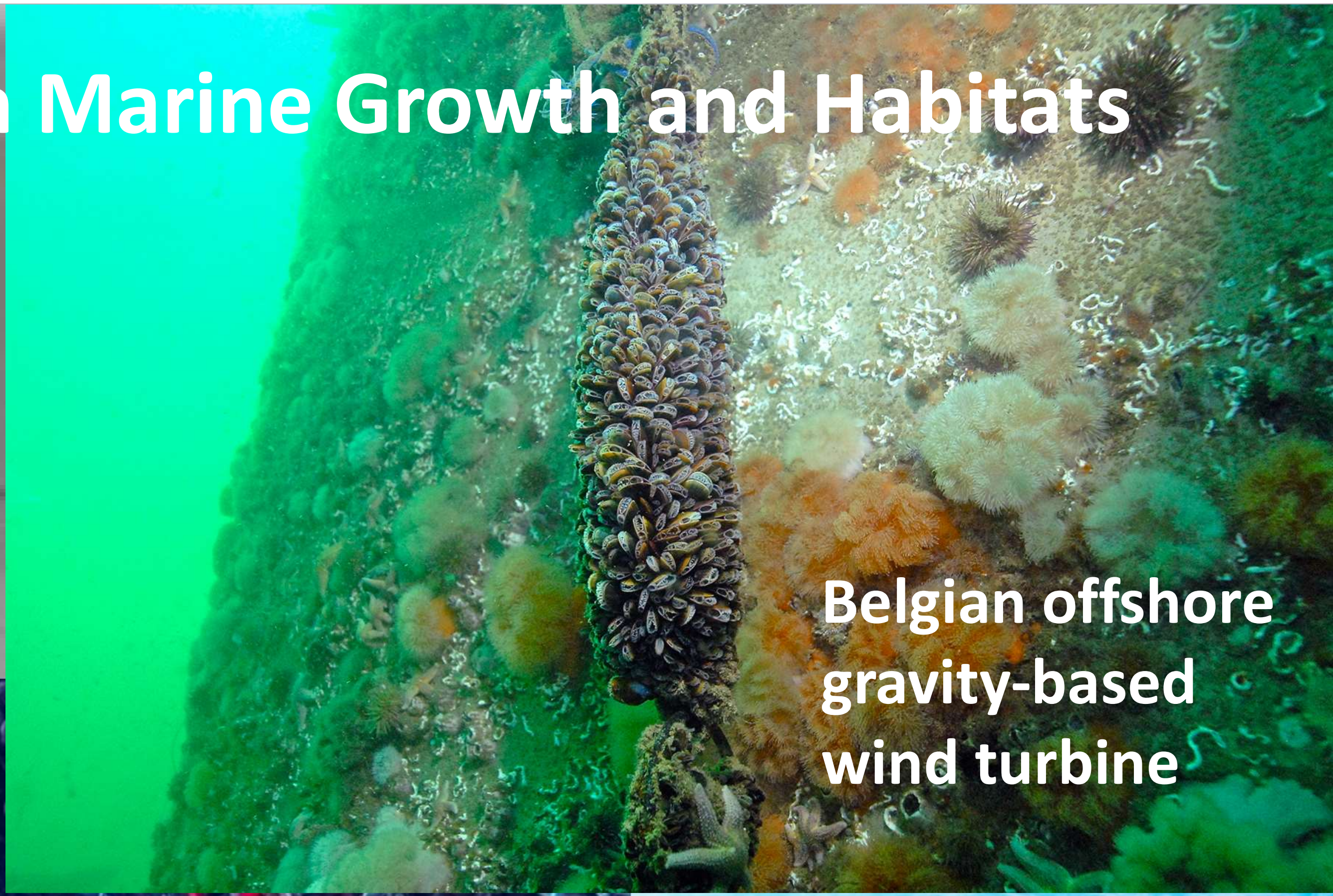


Photo Credit: Lars Lichtenstein

# 3. Effect of Perforations and CPS on Marine Growth and Habitats

Fish and Crustaceans Living in Perforated Pipe +CP



Belgian offshore gravity-based wind turbine

Block Island Wind Farm

Virginia Wind Farm

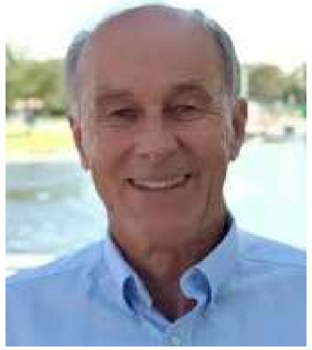
A Belgian-Dutch consortium “Wier & Wind” Seaweed Mariculture

# Contracted Research Team

Florida Institute of Technology

Woods Hole Oceanographic Institution
1930

Tufts University | School of Engineering

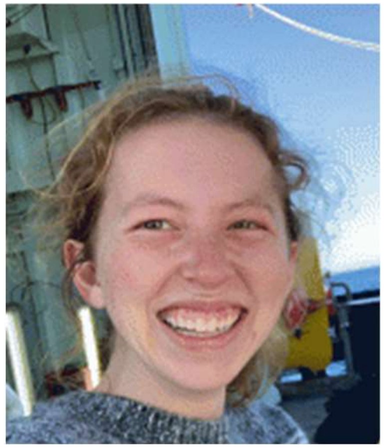


Geoff Swain

Colleen Hansel

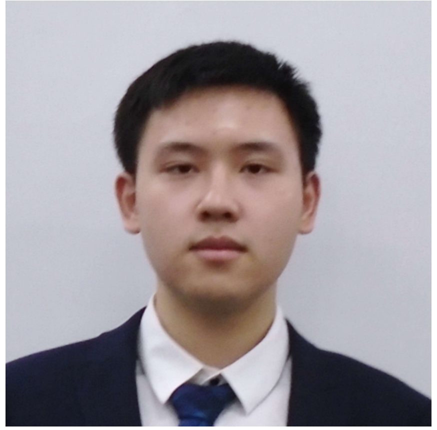
Dan Kuchma

Caglar Erdogan



Lina Taenzer

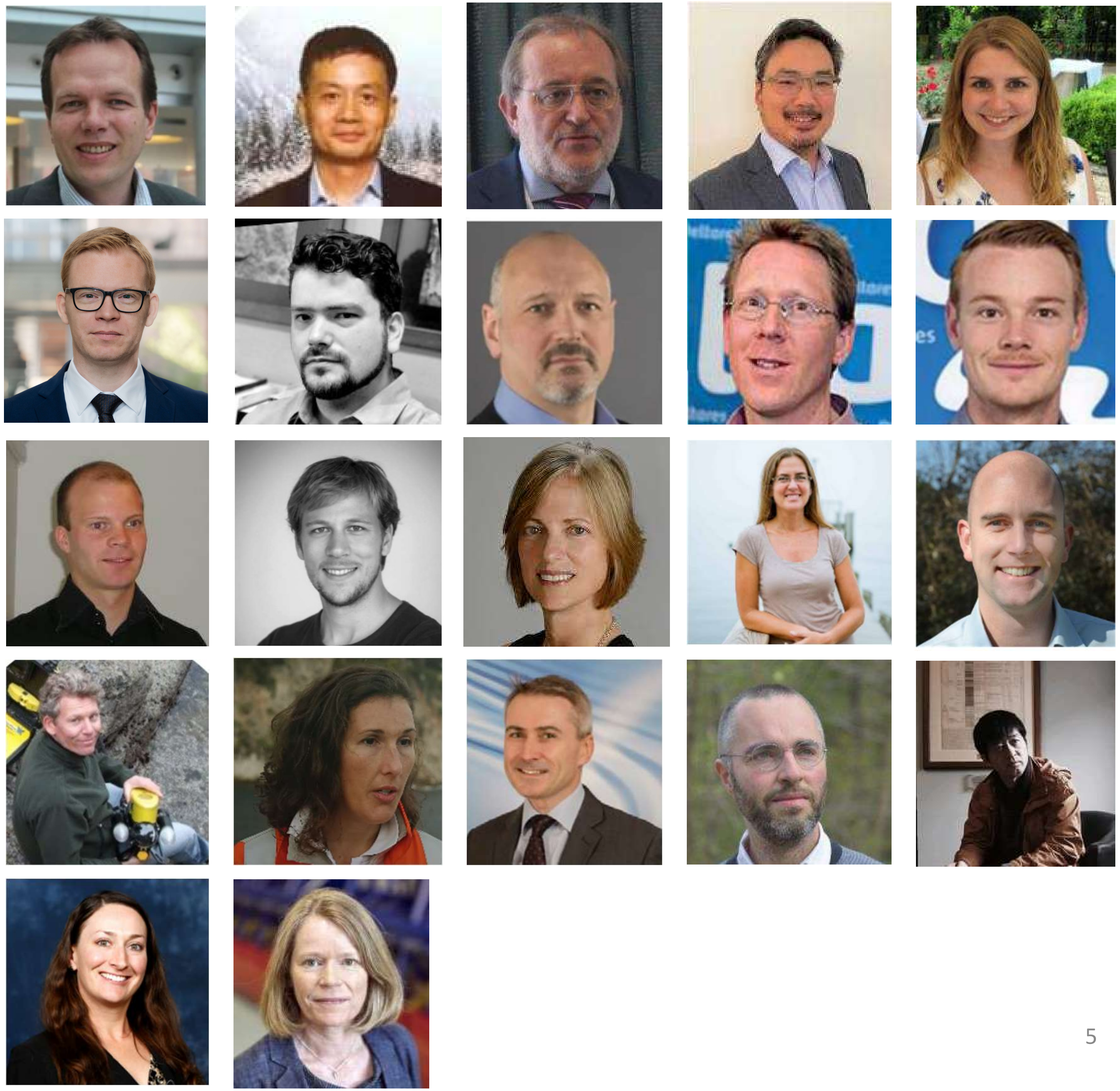
John DeFrancisci



Guodong Feng

# Advisory Panel

1. Lars Lichtenstein (DNV GL)
2. George Wang (Formerly ABS)
3. Brian Wyatt (Corrosion Control Ltd.)
4. Anthony Setiadi (Woods Thilsted)
5. Ingrid Kummin Husby (Equinor)
6. Jacob Jansson (COWI)
7. Matthew Taylor (Deepwater)
8. Claus Erik Weinell (Denmark Tech. Univ.)
9. Stefan Jansen & Niek Bruinsma (Deltares)
10. Thomas and Jacob Andersen (Univ. Aalborg)
11. Fara Courtney (Outer Harbor)
12. Loretta Robertson (Marine Biology Lab)
13. Thomas Vance (Plymouth Marine Lab)
14. Andrew Want (Herriot Watt University)
15. Jamie Lescinski (Boskalis)
16. Feargal Brennan (University of Strathclyde)
17. Richard Pijpers (TNO)
18. Wangwen Zhao (formerly ODE)
19. Monica Maher (Dept. of Energy, WETO)
20. Deborah Greaves (Univ. of Plymouth)



Webinar:
Informative
Presentations

This Workshop May 16

Last Workshop Feb 11

Technical
Committee
Meeting

**Meeting Logistics**

Please stay muted unless speaking

Meeting will be recorded

**Use of Chat**

- Self Introductions – Organization and Role in Offshore Wind Industry and Marine Environment – with links
- References to Projects and the Literature – with links
- Suggestions for Ongoing or Future work
- Questions for Speakers, Moderators, or Anyone Else
- Chat will be recorded and included with the summary of the workshop
- Questions that could not be addressed in workshop will try to be answered in the distributed summary
- Names will not be included in chat record

**Discussion**

- Raise hand if you have a question and you would like to ask, and you will be called in sequence; turning your video from being off to being on is a helpful way to identify that you have a question or comment

## Part 1: Presentations on Motivations and Examples for Nature-Inclusive Design (40 minutes)

1.1 Synthesis of Environmental Effects Research Project (NREL and PNNL)

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1.3 Developer/Academic Initiatives in Nature-Inclusive Design (Orsted / Wageningen Univ.)

1.4 Artificial Reefs, Offshore Wind Farms as Sanctuaries, and Defining Success (Boskalis)

Rebecca
Green

National Renewable Energy Laboratory

Mark
Severy

Pacific Northwest National Laboratory

Drew
Carey

INSPIRE ENVIRONMENTAL

Anthony
Dvarskas

Ørsted

Marcel
Rozemeijer

WAGENINGEN UNIVERSITY & RESEARCH

Jamie
Lescinski

Boskalis

SEER

U.S. OFFSHORE WIND
SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# SEER Project Overview

Workshop - Marine Ecosystems for Offshore Wind Support Structures
*May 16, 2022*

**Rebecca Green, Ph.D.**
National Renewable Energy Laboratory

**Mark Severy, P.E.**
Pacific Northwest National Laboratory

NREL
Transforming ENERGY

Pacific Northwest
NATIONAL LABORATORY

U.S. OFFSHORE WIND
SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# Introduction to SEER

**At the direction of the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy Wind Energy Technologies Office, Pacific Northwest National Laboratory and National Renewable Energy Laboratory are jointly leading a multi-year collaborative effort to facilitate knowledge transfer for offshore wind (OSW) research.**

## Project Objectives

- Summarize the international understanding of environmental effects, monitoring tools, and mitigation strategies for OSW and how it applies to the U.S. Atlantic and Pacific Coasts.
- Examine which of the state-of-the-art methods and technologies are relevant to environmental issues specific to U.S. offshore wind development.
- Identify knowledge and research gaps based on the diversity of species, habitat uses, and stressors; U.S. environmental legal/regulatory structure; and technological innovations.
- Collaboratively develop outcomes together with existing science entities and regional working groups to fully leverage community expertise.

SEER
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SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# Introduction to SEER

**Research Briefs**
Review state of the knowledge on stressor/receptor interactions, monitoring methods and technologies, mitigation measures, and cumulative impacts.

**Webinar Series**
Disseminate findings presented in Research Briefs to the offshore wind industry and others who are interested.

**Research Recommendations**
Summarize information gaps, barriers, and current challenges for U.S. Atlantic and Pacific Coasts to inform or guide future development efforts.

***For more information, visit: https://tethys.pnnl.gov/seer***

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EFFECTS RESEARCH

# Educational Research Brief Topics

Underwater Noise Effects on Marine Life

Bat and Bird Interactions with Offshore Wind Energy

Risk to Marine Life from Marine Debris & Floating Cable Systems

Benthic Disturbance from Foundations, Anchors, & Cables

Introduction of New Structures: Effects on Fish Ecology

Vessel Collision: Effects on Marine Life

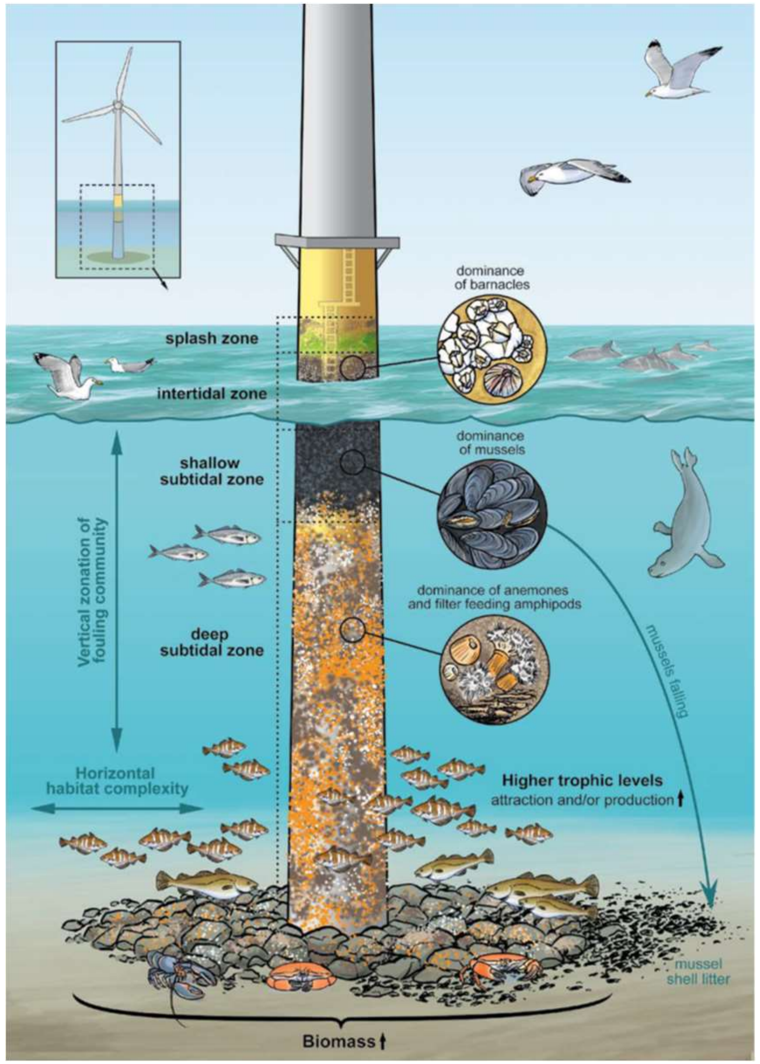
Electromagnetic Field (EMF) Effects on Marine Life

U.S. OFFSHORE WIND
SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# Introduction of New Offshore Wind Farm Structures: Effects on Fish Ecology

## Main Takeaways

- Placement of new structures during construction can temporarily or permanently alter the habitat in vicinity of fixed-bottom turbine foundations, depending on foundation type, materials used, and sediment type.
- Artificial reef effects documented at OSW farms: e.g., attraction of fish and invertebrate species to turbine structures which provide a combo of hard vertical and horizontal substrates.
- Floating OSW farms are still relatively nascent technology but may have less of a direct effect because of limited vertical profile and smaller footprint of mooring and anchoring.
- Monitoring for changes in the biological community at OSW farms should be driven by specific objectives and hypotheses.
- Effective monitoring includes BACI or BAG approaches and data collection (e.g., trawls, traps, habitat surveys, fish tagging).
- Best management practices include siting away from sensitive habitats and minimizing seafloor disturbance during construction. Structures have potential benefits if specifically designed for life requirements of target population or habitat need.



Credit: Degraer et al (2021)

Science summary available at: https://tethys.pnnl.gov/summaries/introduction-new-offshore-wind-farm-structures-effects-fish-ecology

# Benthic Disturbance from Offshore Wind Foundations, Anchors, and Cables

## Main Takeaways

- Foundations, anchors, and cables associated with offshore wind (OSW) energy development may alter the benthic environment during and after construction.
- Most physical effects on benthic habitat are localized to the areas closest to OSW farm infrastructure and not spread throughout the entire wind farm area.
- Benthic disturbance from displacement and suspension of seafloor sediment during construction tends to be temporary and recovery of the physical and biological conditions on the seafloor typically occurs within a few years.
- OSW foundations, anchors, exposed cables, and scour protection can alter the diversity and abundance of benthic organisms throughout the operational life of a wind farm. The components provide new hard substrate on the seafloor and in the water column that will favor some organisms over others, possibly leading to habitat conversion.

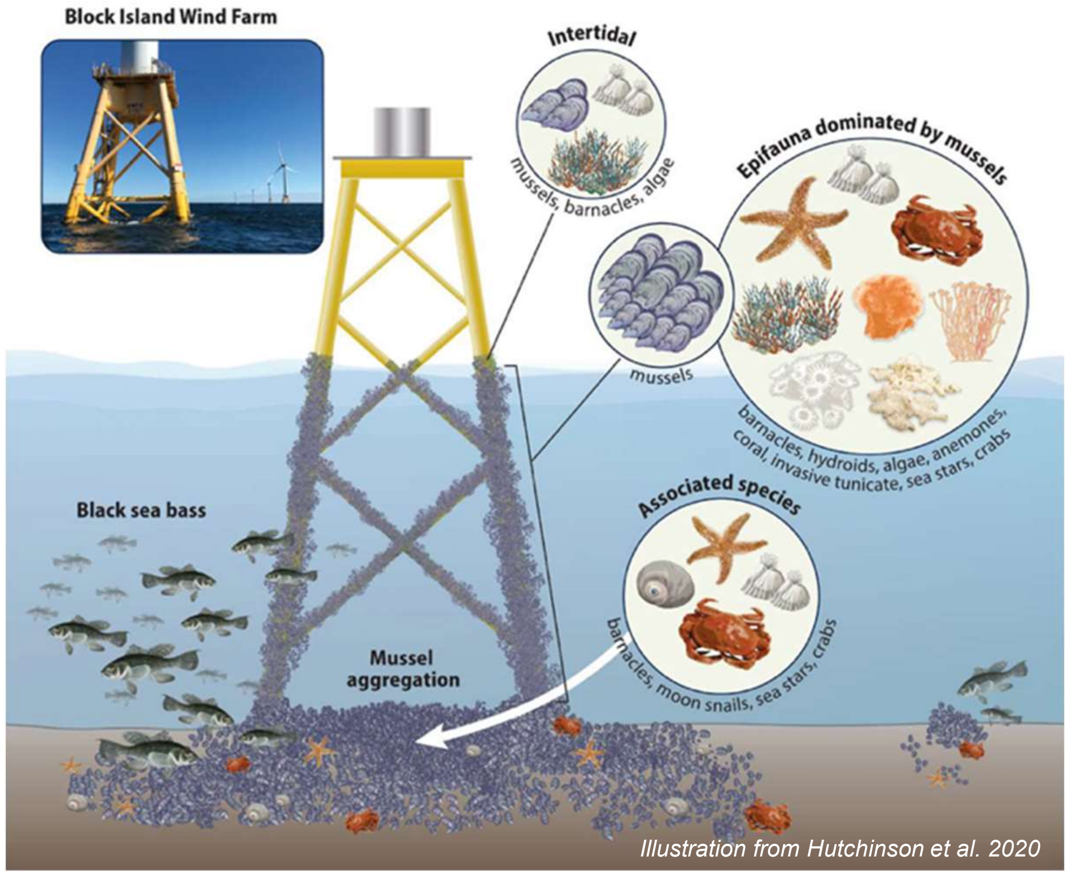


*Illustration from Hutchinson et al. 2020*

Science summary available at: https://tethys.pnnl.gov/summaries/benthic-disturbance-offshore-wind-foundations-anchors-cables

# Next Steps

- Developing research recommendations for U.S. Atlantic and Pacific coasts
- Maintain a database of source documents that contain research priorities
- Continue working with the community and regional organizations to highlight research needs for supporting environmentally responsible development of offshore wind
- Update findings based on evolving fixed bottom and floating technologies
- Support the evolving needs of regional organizations

U.S. OFFSHORE WIND
SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# Contact Information

:

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**SEER Research Briefs and Webinar Recordings are available at:**
**https://tethys.pnnl.gov/seer**

# Environmental Observations on Offshore Wind Structures including RODEO Project

Block Island Wind Farm and Results of European Studies

Drew Carey, Jennifer Dannheim, Zoe Hutchison and Steven Degraer

INSPIRE ENVIRONMENTAL

AWI

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

museum

Royal Belgium Institute
of Natural Sciences

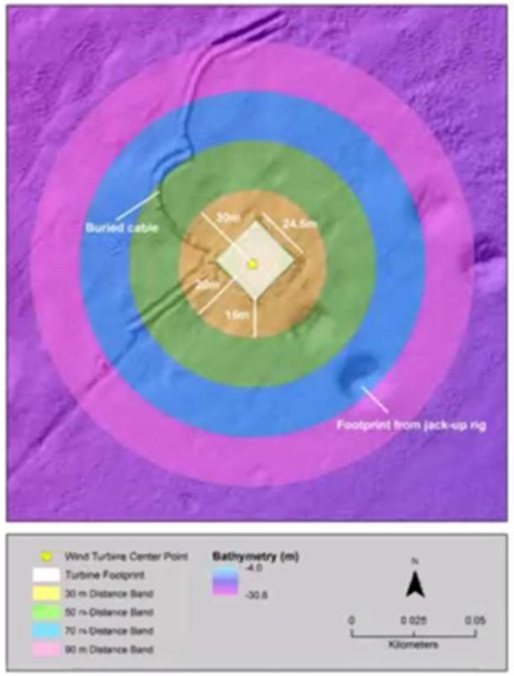
INSITE

University of
St Andrews

ICES CIEM

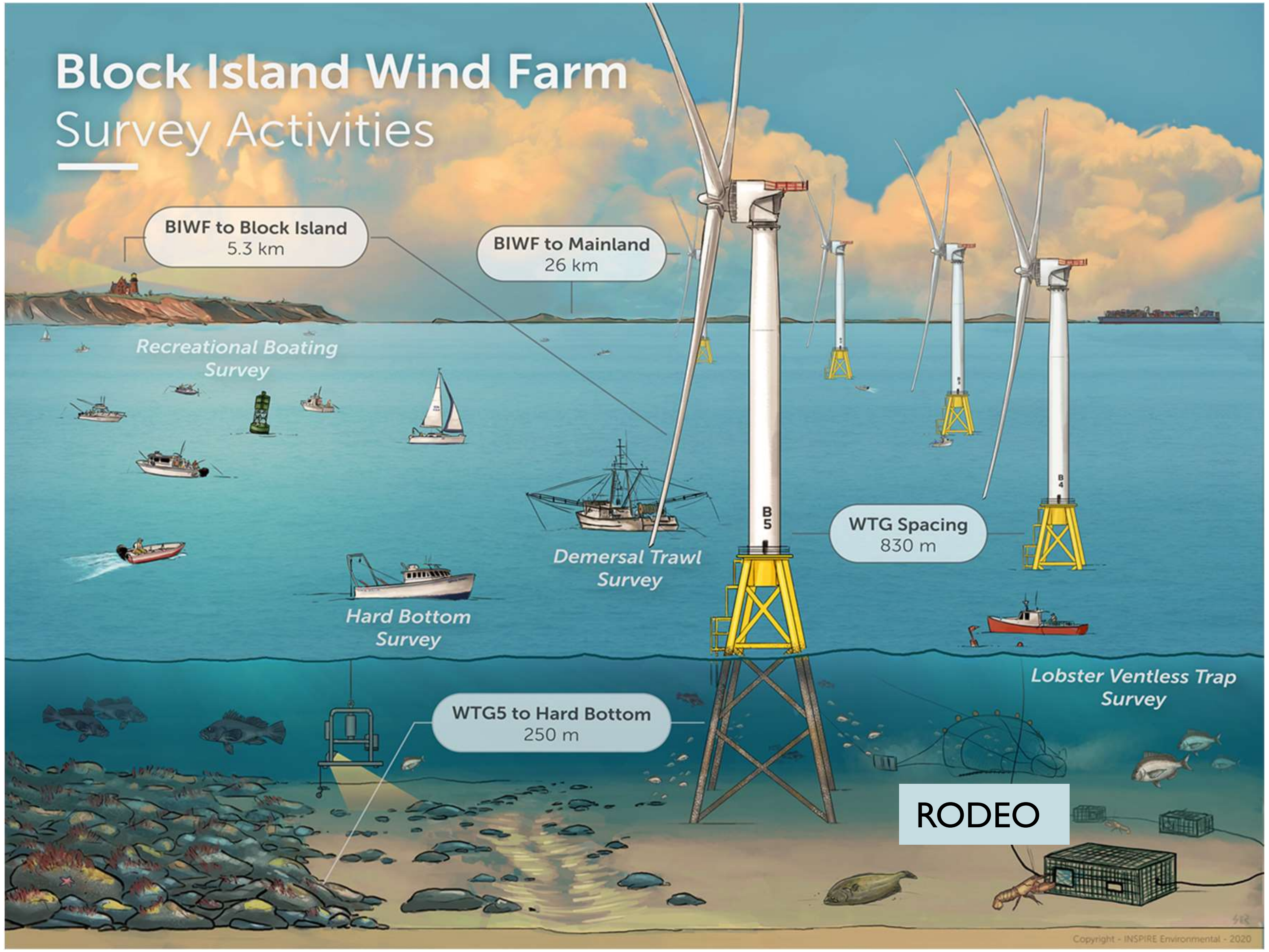
ICES
WGMBRED

Turbines 1, 3 & 5



What was measured:

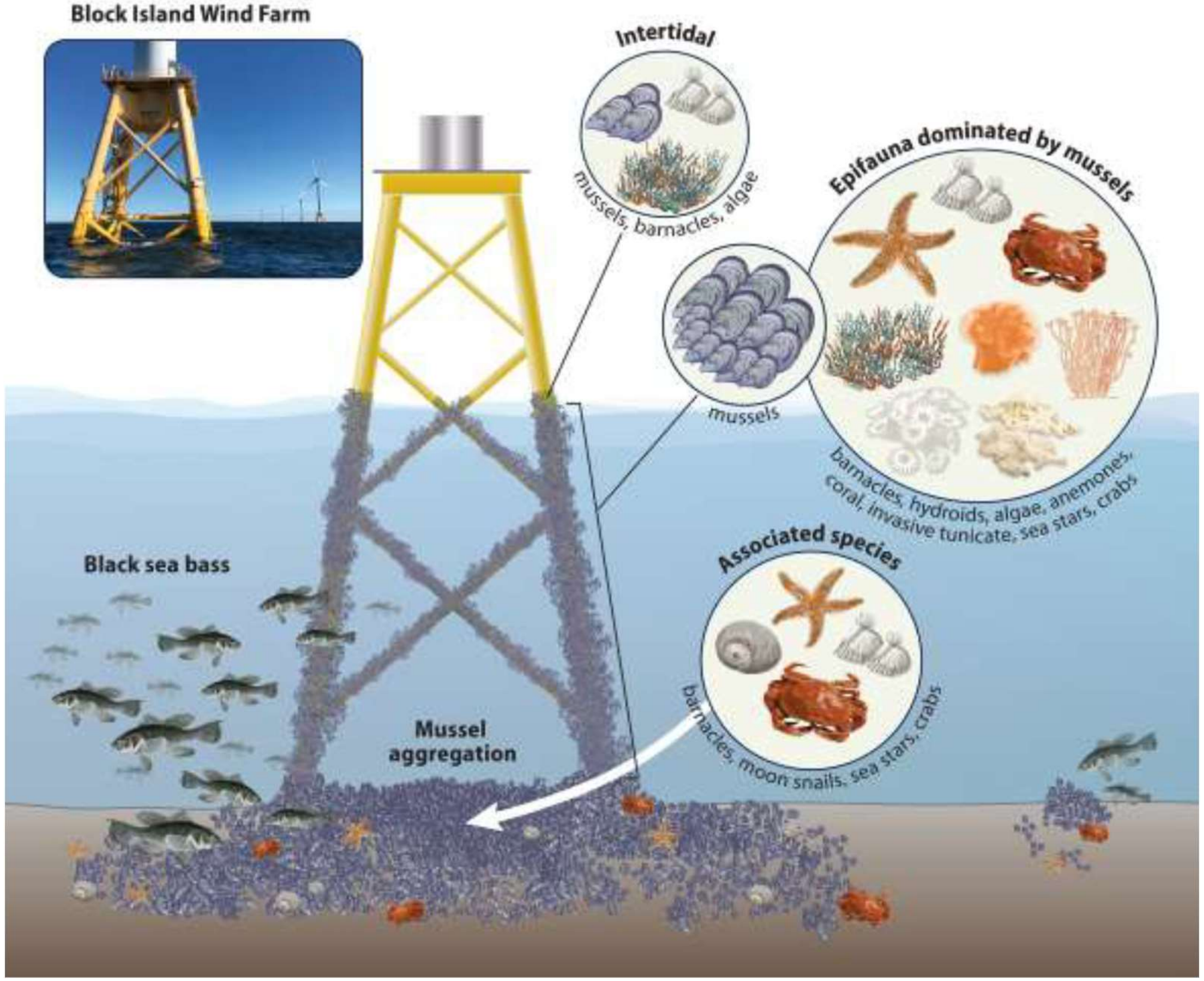
- Sediment grain size
- Organic enrichment
- Benthic macrofauna community characteristics
- Epifaunal community characteristics



Guarinello and Carey 2020. Multi-modal Approach for Benthic Impact Assessments in Moraine Habitats: a Case Study at the Block Island Wind Farm
Carey et al. 2020 Effects of the Block Island Wind Farm on Coastal Resources: Lessons Learned
Wilber et al. 2022a Offshore wind farm effects on flounder and gadid dietary habits and condition on the northeastern US coast
Wilber et al. 2022b Demersal fish and invertebrate catches relative to construction and operation of North America's first offshore wind farm

# Benthic Habitat Modification

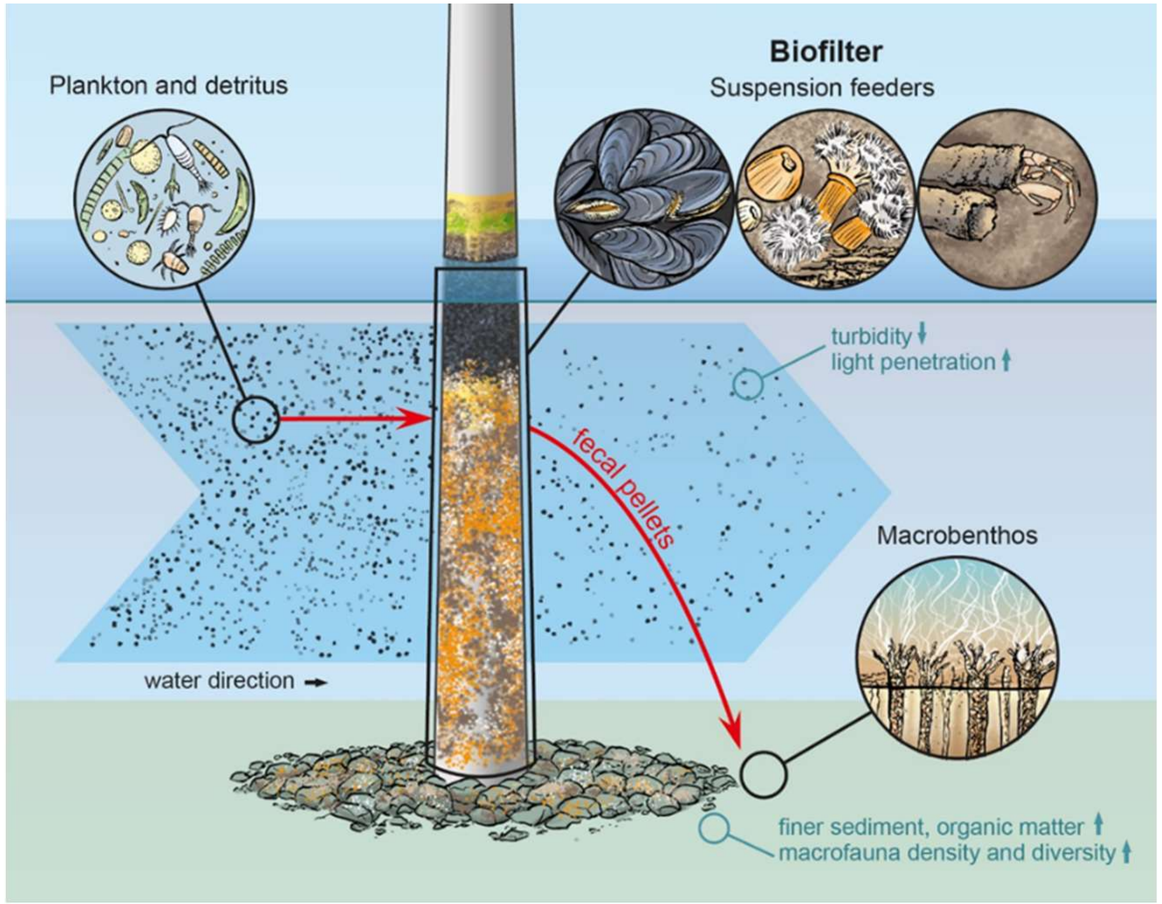
- Introduction of intertidal-subtidal surface
- Bottom sediment modification
- Changes to benthic-pelagic coupling
- Key cumulative effects: export of energy and changes in local food webs



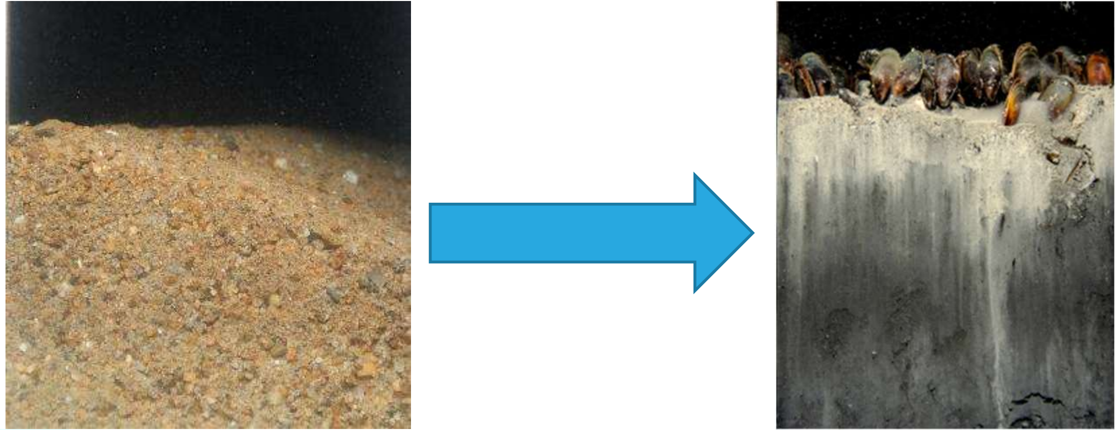
HDR. 2020. Benthic and Epifaunal Monitoring During Wind Turbine Installation and Operation–OCS Study BOEM 2020-044.

# Bottom Sediment Modification

- Organic enrichment
- Energy flow
- What we know
  - Changes in particle size
  - Changes in organic content
  - Changes to flora and fauna
- What we need to know
  - What is the fate of the energy?
  - What is the appropriate spatial scale?

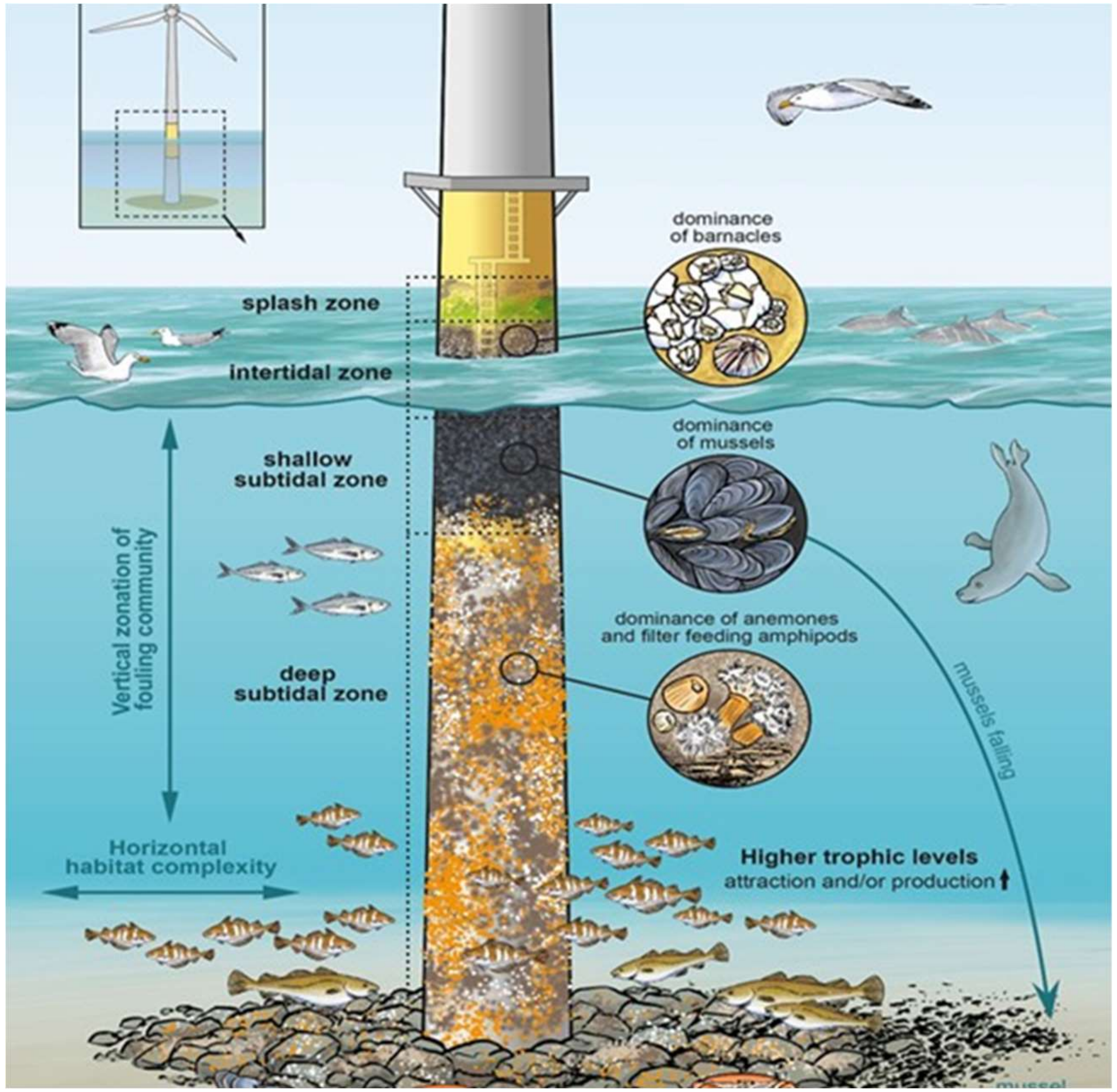


Degraer et al., 2020, Oceanography Special Issue Vol. 33, 4



# Enrichment

- Predation and increase in prey species
- Brings demersal species into water column
  - Starfish
  - Demersal-pelagic finfish (structure loving)
  - Crabs
- Top trophic species attracted to predators
  - Marine mammals
  - Highly migratory species
- Benthic food web responds to energy and complexity



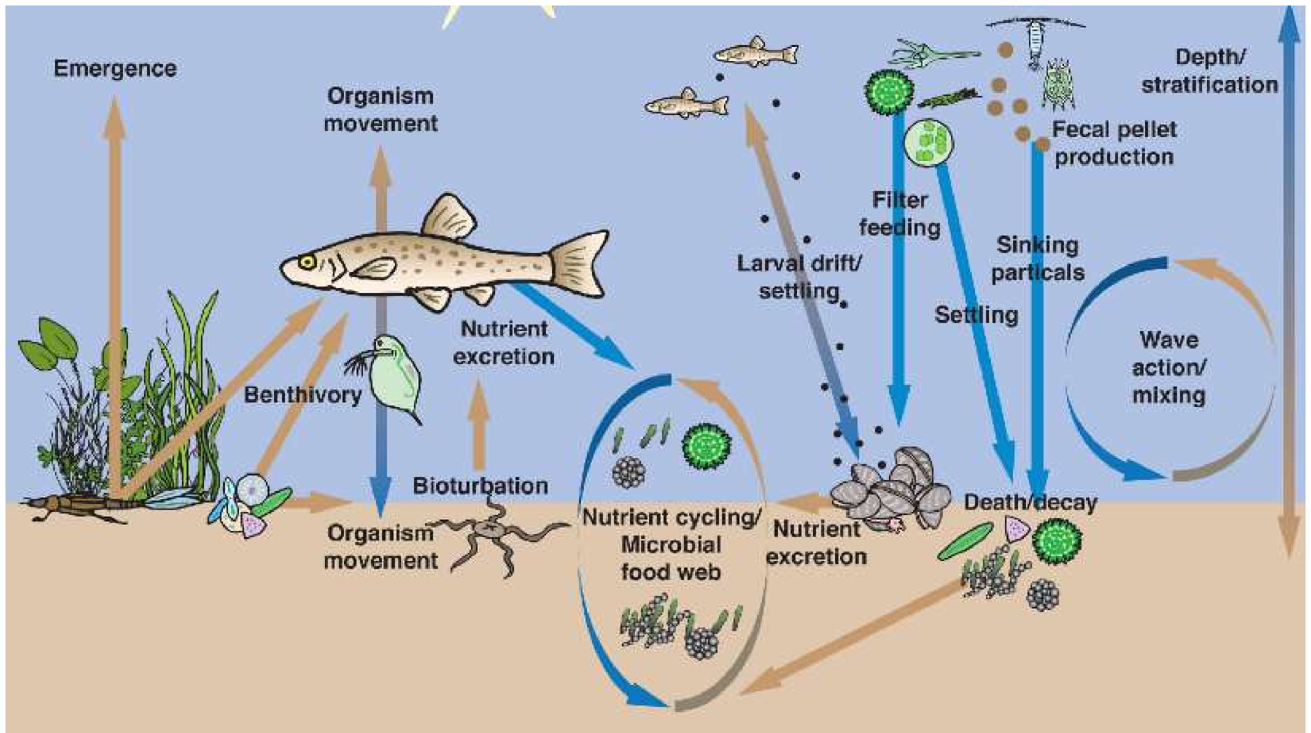
Wilber et al., 2022

# Biomass exported

- Mobile predators move away from site – energy export
- Mobile predators stay at site – energy to benthos
- Suspension feeders feed on waste – energy to benthos
- Detritus and shell litter – energy to benthos (some refractory)
- Remineralization of detritus in benthos
- Release of energy back to water column

Role of Nature Based Design

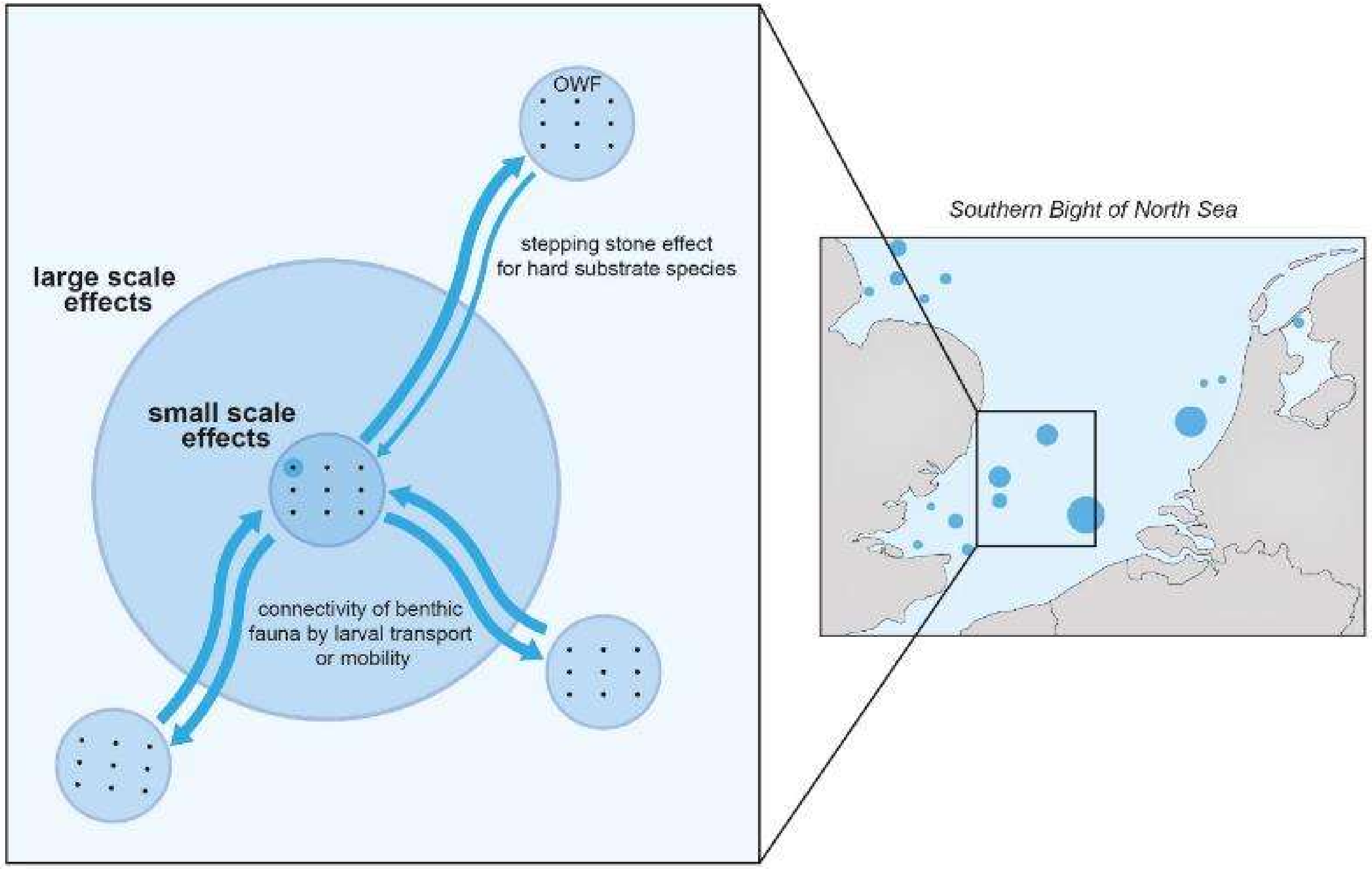
Enhance export
Enhance refuge
Protect juvenile fish
Support spawning



Baustian et al. 2015

# Connectivity

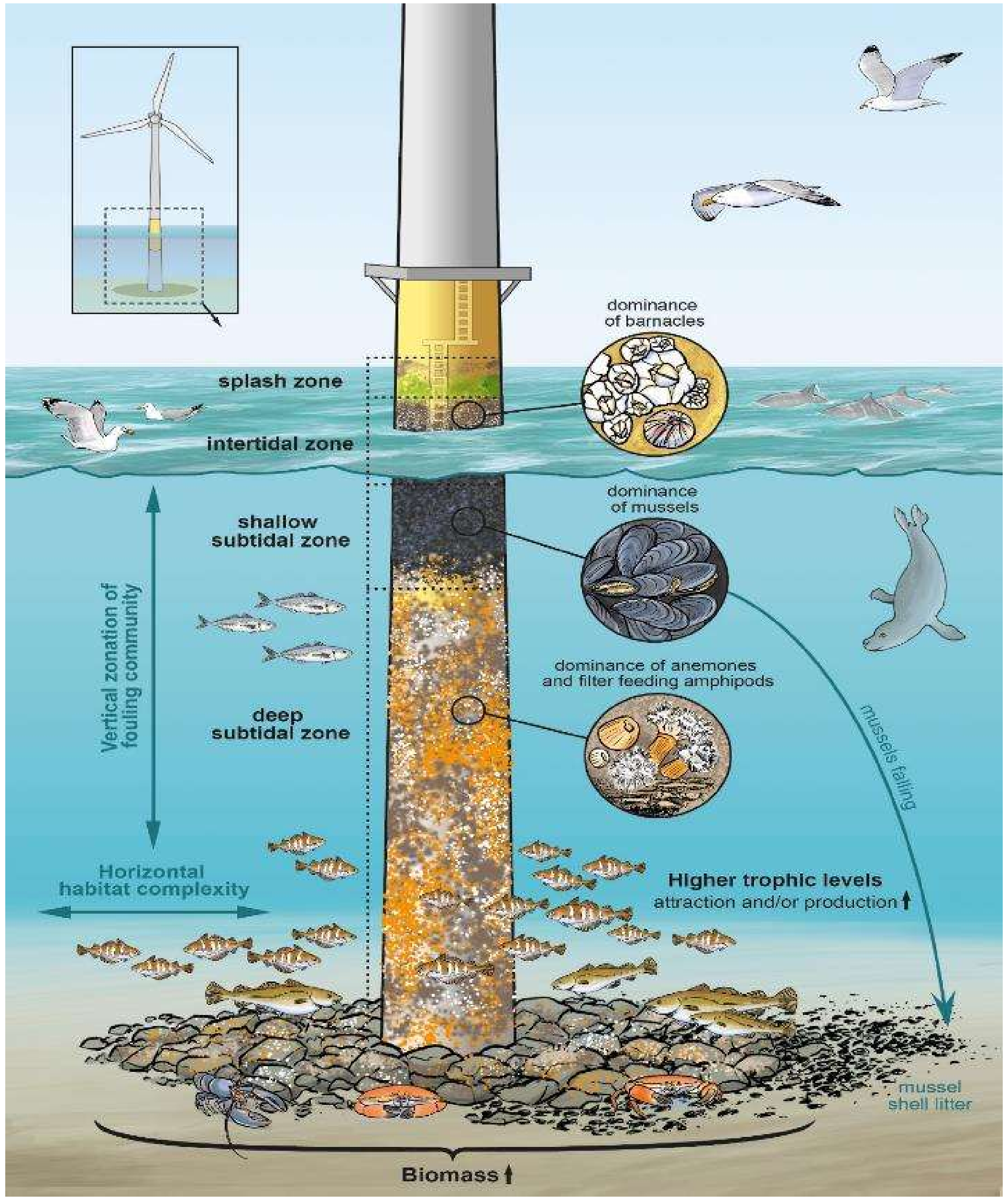
- Introduction of inter-tidal habitat in deeper water
- Potential habitat expansion for both desirable and undesirable species.
- May be affected by the nature of benthic habitats near projects (Wilhelmsson and Malm, 2008)
- What we know
  - Inter-tidal species colonize offshore structures
- What we need to know
  - At what scale does this connectivity move from small-scale effect to large scale effect?



Degraer et al., 2020, Oceanography Special Issue Vol. 33, 4

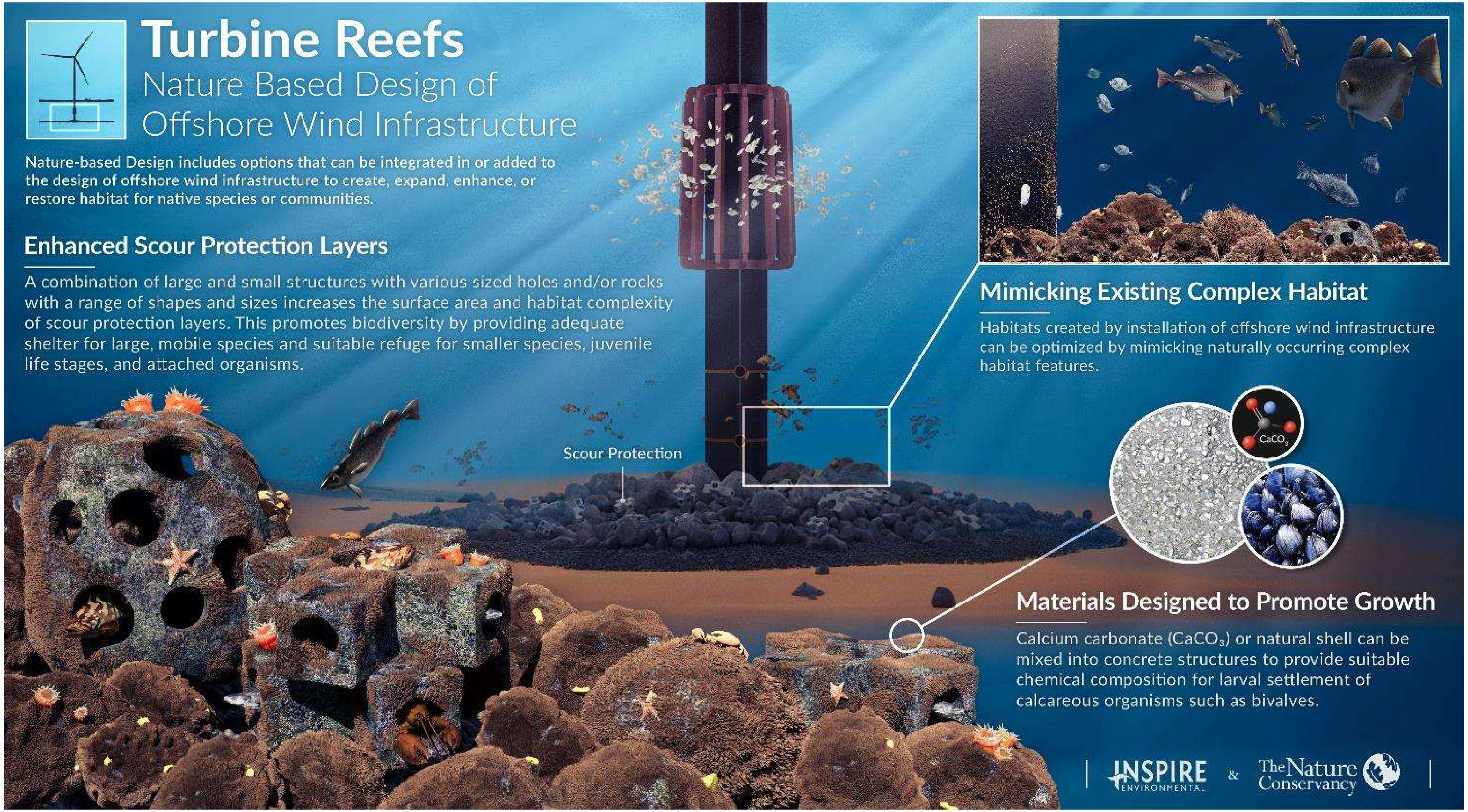
# Habitat Suitability

- Food web dynamics
  - Primary productivity
  - Predator-prey relationships
- What we know
  - Documentation of species presence/absence
  - Spatial/temporal resolution
- What we need to know
  - How does this affect habitat function?
  - How is it functioning at an ecosystem scale?
  - Is effect positive or negative? Functionally equivalent?



Degraer et al., 2020, Oceanography Special Issue Vol. 33, 4

# Nature Based Design to be tested at Coastal Virginia Offshore Wind



## Turbine Reefs

### Nature Based Design of Offshore Wind Infrastructure

Nature-based Design includes options that can be integrated in or added to the design of offshore wind infrastructure to create, expand, enhance, or restore habitat for native species or communities.

### Enhanced Scour Protection Layers

A combination of large and small structures with various sized holes and/or rocks with a range of shapes and sizes increases the surface area and habitat complexity of scour protection layers. This promotes biodiversity by providing adequate shelter for large, mobile species and suitable refuge for smaller species, juvenile life stages, and attached organisms.

### Mimicking Existing Complex Habitat

Habitats created by installation of offshore wind infrastructure can be optimized by mimicking naturally occurring complex habitat features.

### Materials Designed to Promote Growth

Calcium carbonate ($CaCO_3$) or natural shell can be mixed into concrete structures to provide suitable chemical composition for larval settlement of calcareous organisms such as bivalves.

# Our biodiversity ambition

As part of Ørsted's new 2030 strategy, the company has set **the ambition to deliver net-positive biodiversity impact in all renewable energy projects it commissions from 2030**, strengthening the green energy build-out in balance with nature

# ReCoral by Ørsted™

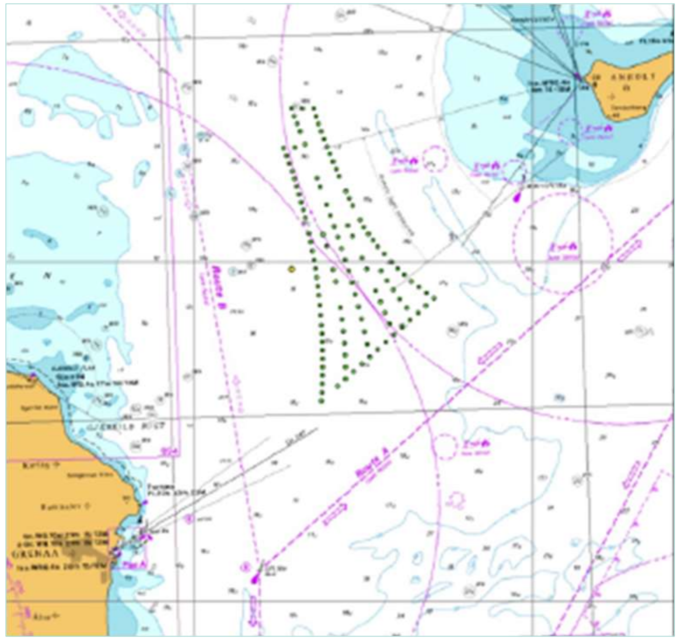
## *Coral restoration experiment*

- Surplus indigenous coral spawn collected from shoreline of Penghu Islands, west of Taiwan mainland
- Spawn incubated in laboratory to coral larvae
- Transferred to Greater Changhua turbine foundations for settlement
- Proof-of-concept trial—could be scaled up if successful

# Anholt wind farm boulder reefs

## *Artificial reef creation*

- Naturally occurring boulder reefs, and their accompanying flora and fauna, are now a rare features in Danish waters
- Ørsted relocated 5,000 large boulders, as part of the construction of the Anholt offshore wind farm (DK) in 2012, and used them to create 23 artificial reefs



# Biohuts in Grenå

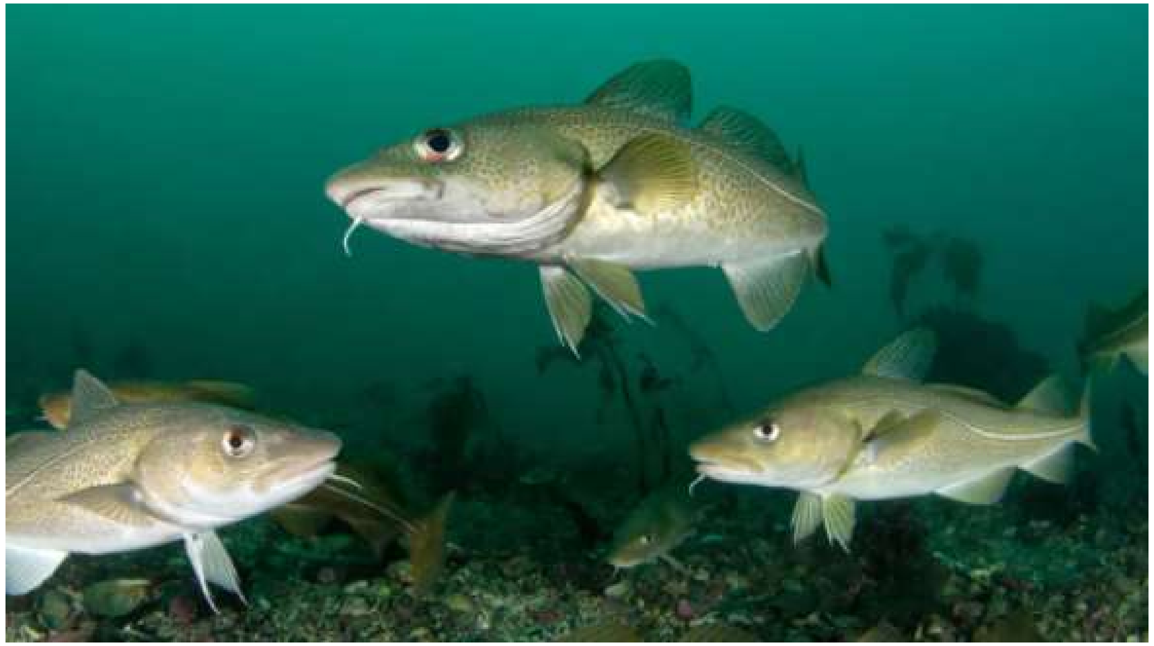
## *Artificial reef creation*

- In 2021 Ørsted collaborated with WWF to install 10 BioHuts in Grenå harbour in the Danish Kattegat
- Will provide shelter for juvenile fish with the intention of restoring both cod populations and wider ecosystem balance

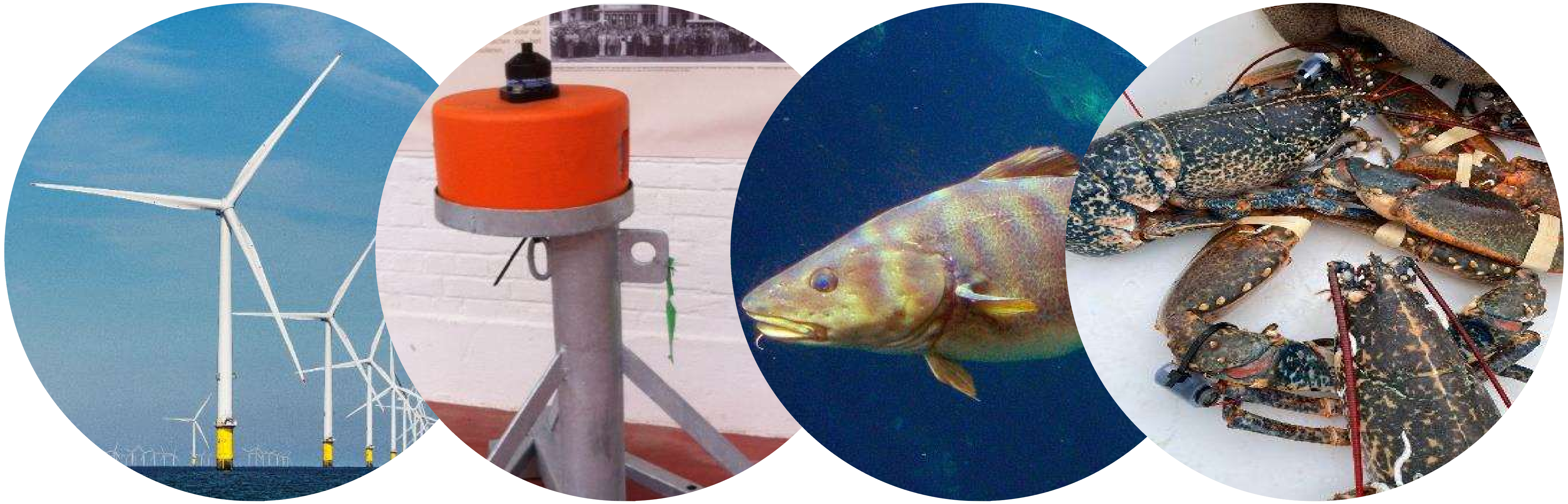
# Cod pipe reefs in Borssele wind farm (NL)

## *Artificial reef creation*

- As part of the 2020 construction of the Borssele 1 & 2 offshore wind farm in Dutch waters, Ørsted designed and installed 4 purpose-built cod-pipe reefs
- Each cod-pipe-reef is about 10 m in diameter and vary from ca. 0,5 -3 m in height.
- Provide much-needed habitat for Atlantic cod - identified by the Dutch authorities as a 'policy-relevant target-species'
- Ongoing monitoring of cod and lobster behaviour (acoustic monitoring) and biodiversity (eDNA) in and around the reefs



# Borssele 2021 science activities



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WAGENINGEN UR

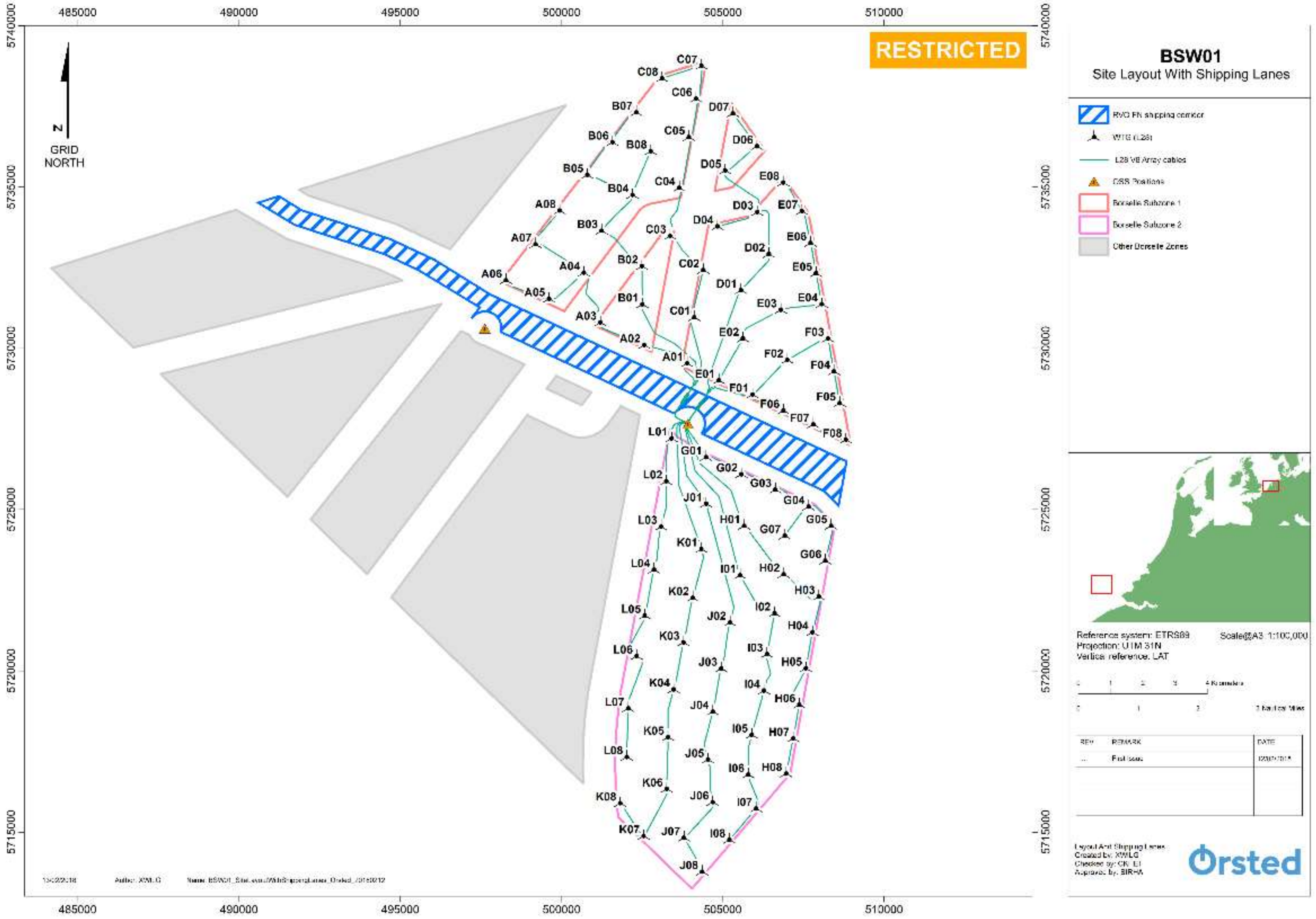
Ørsted

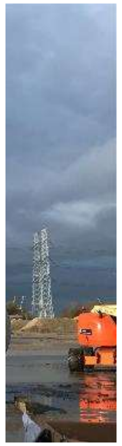
De Rijke Noordzee

WIN WIND

mede mogelijk gemaakt door
TKI WIND OP ZEE
Topsector Energie

# Geographical setup





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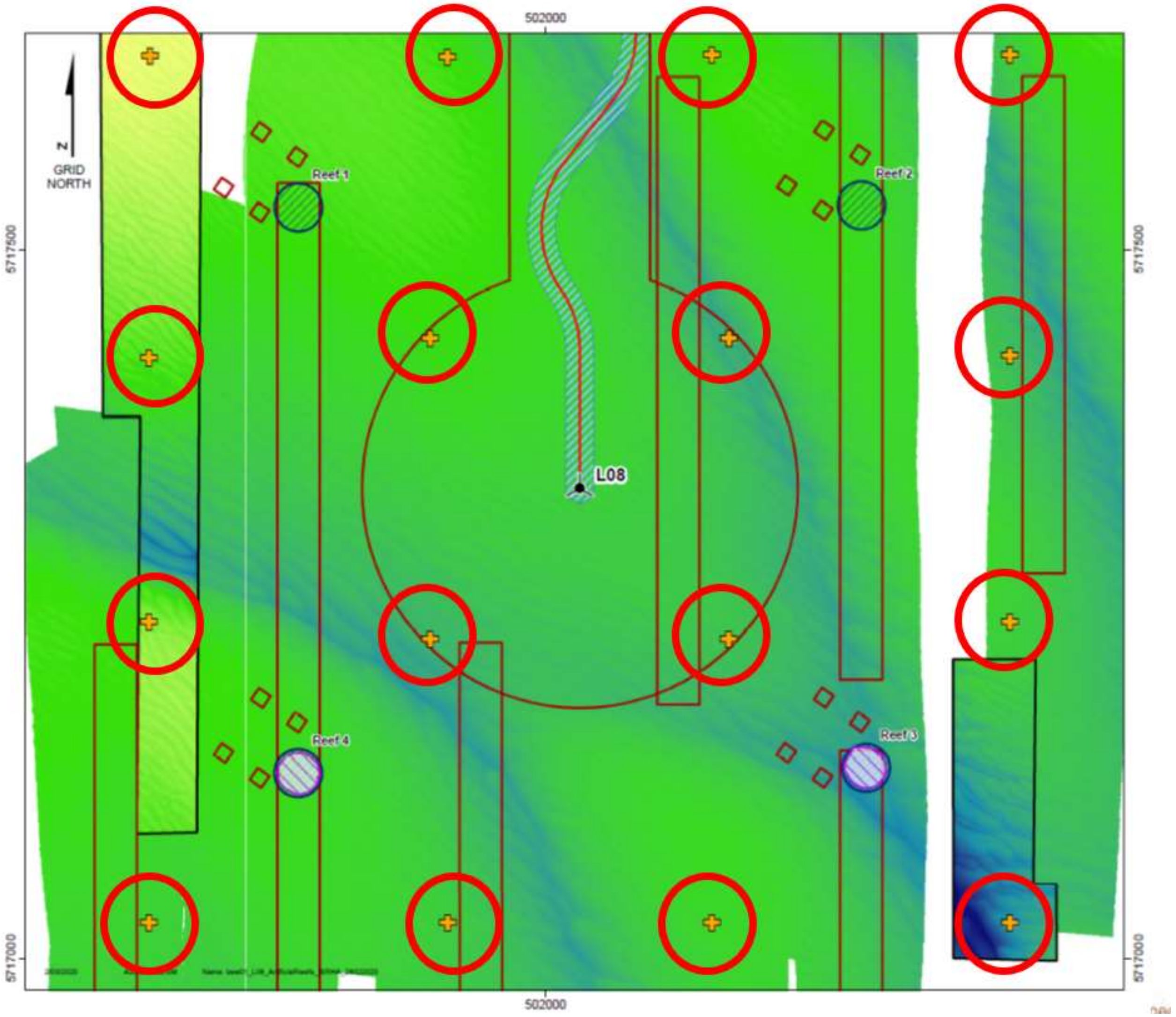
Topsector Energie

# Reefs and acoustic receivers

- 4 artificial reefs placed in 2020
- Southern reefs include scour protection
- 16 frames in total to provide fine spatial resolution



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# Cod tagging

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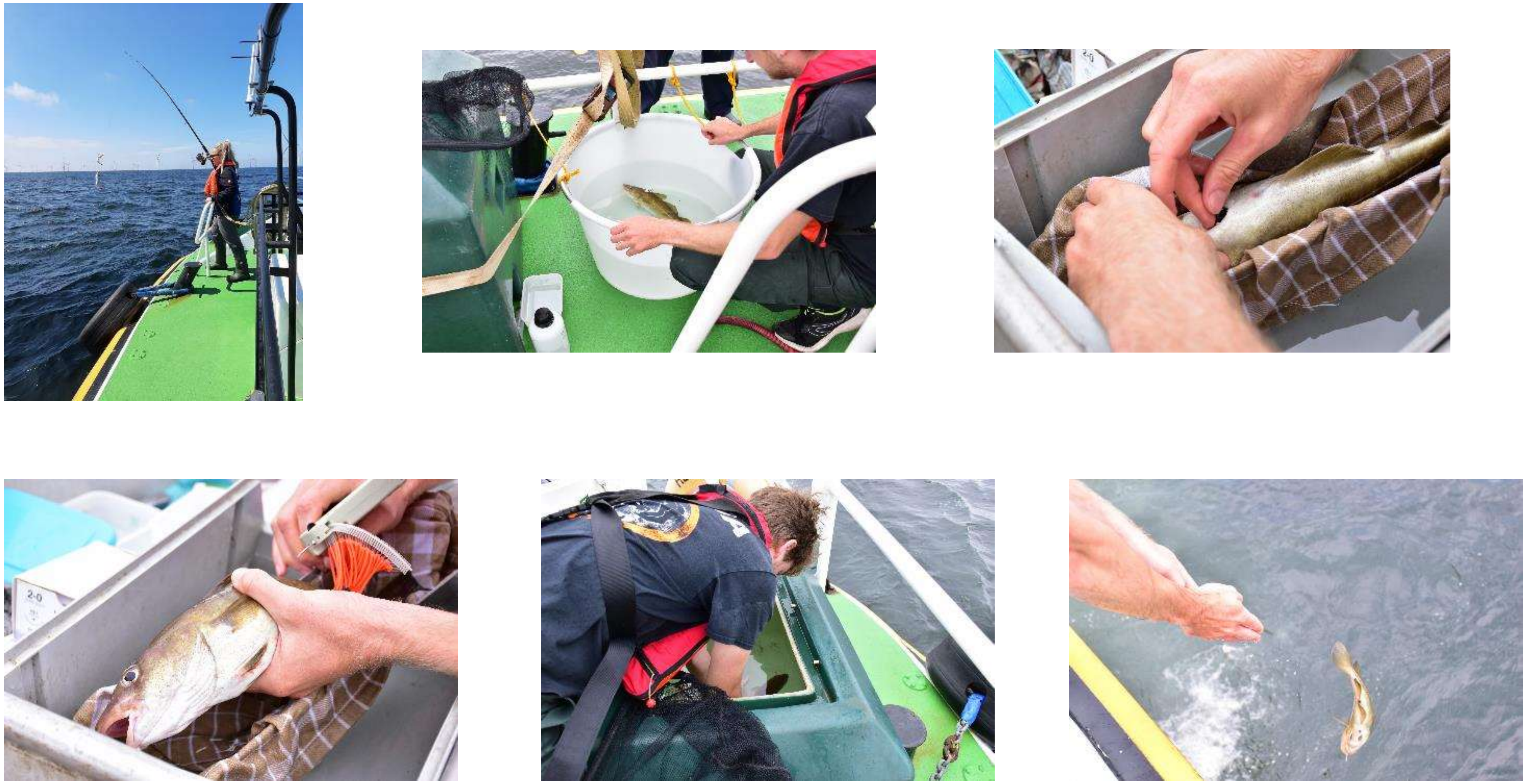
# Research questions cod

- 45 tags in total around all reefs
- What is the distribution in time and space?
- Are there differences between the reefs between themselves and with monopile

# Tagging procedure



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# Lobster tagging

# Research questions European lobster

- Habitat use in relation to reefs
  - Is soft substrate used?
  - Speed in relation type substrate
- Rhythms:
  - Daily
  - Seasonal
- Distances covered:
  - Is it likely that fishery cages at ≥250 m can serve to catch?

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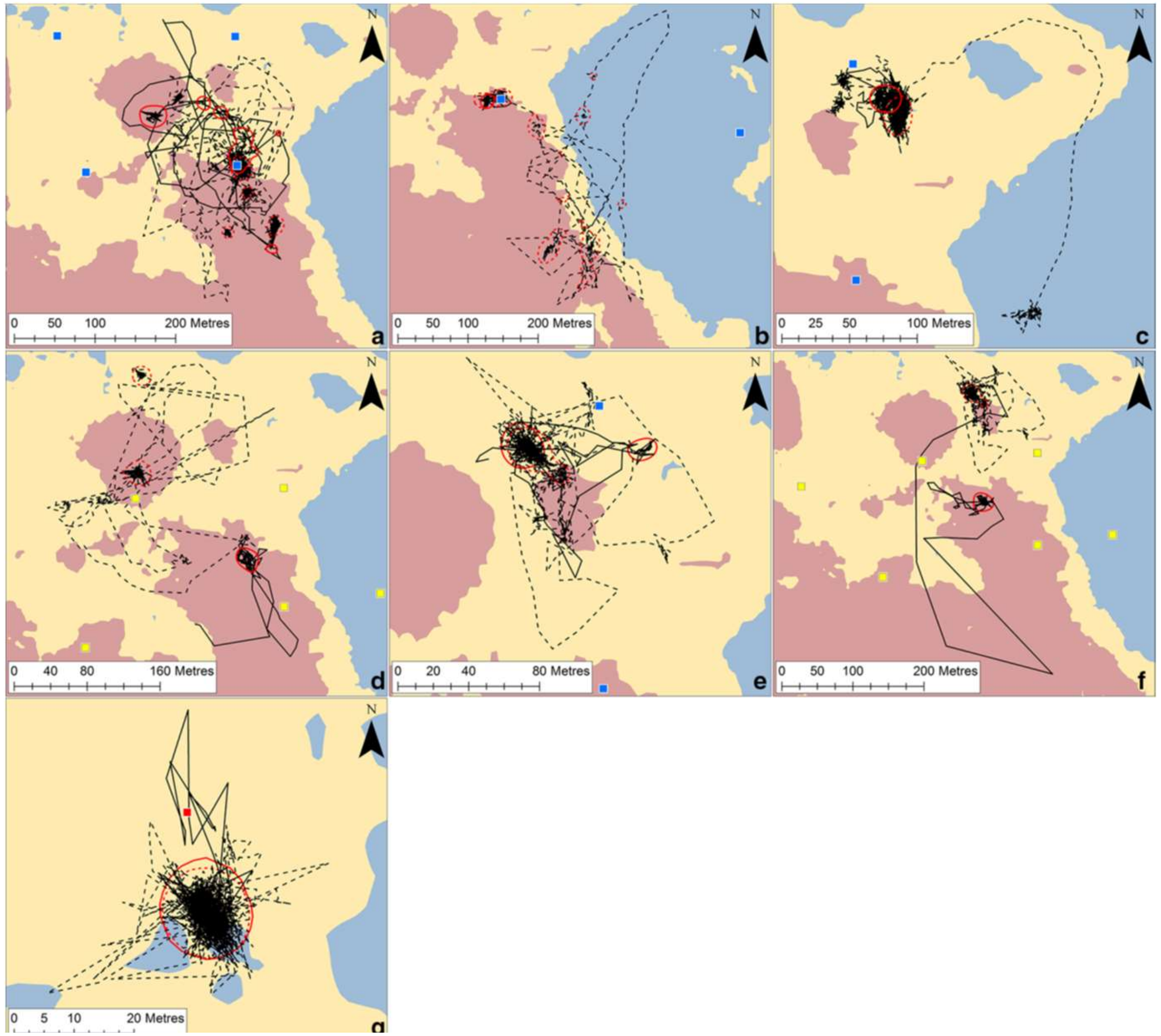
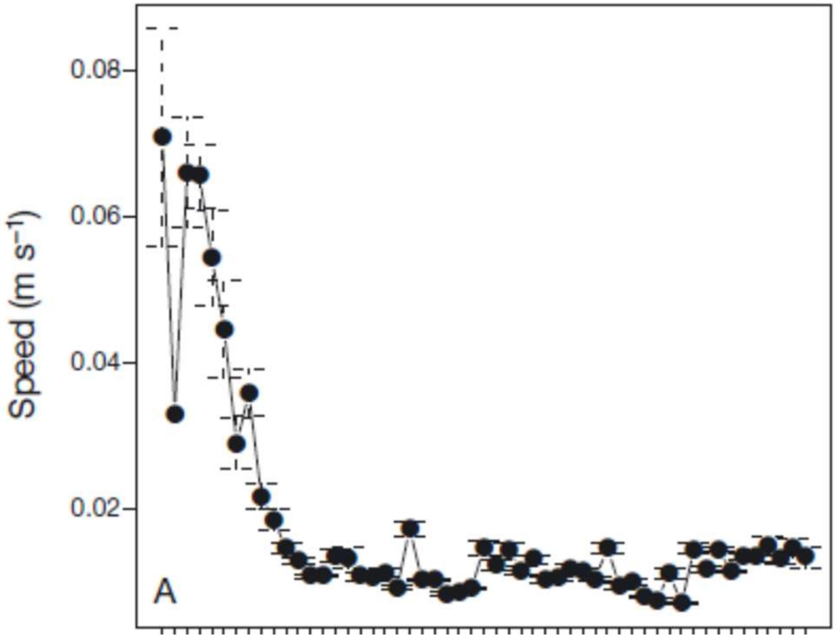
# Tagging procedure and outcomes

- European lobsters obtained
- At each reef 3 released (12 in total)
- Vemco tag: 1
- T-Bar tags:
  - 1 with Vemco;
  - 1 in back

# Anticipated tagging outcomes





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Topsector Energie

# eDNA sampling

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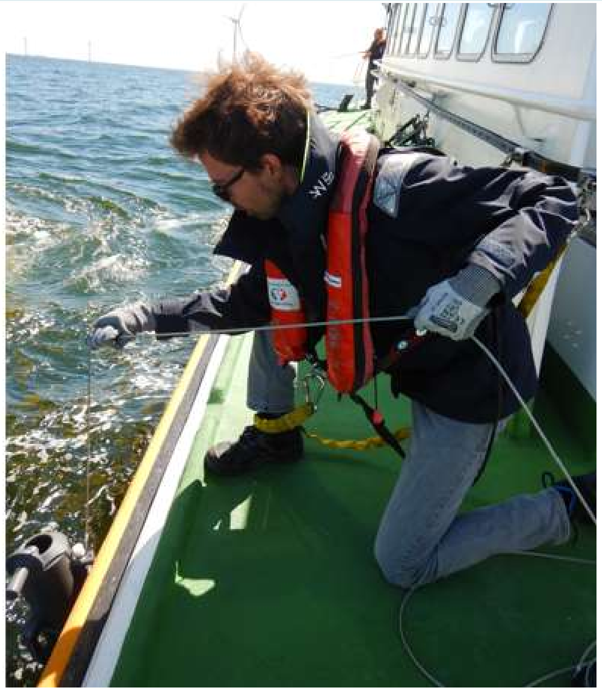
# Sampling procedure



1. Taking of sample water from location near reef

2. Filtrate water sample and store filtered eDNA

3. Send to lab for analysis

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# First results

# Status by 2022 and first results

Recovery and redeployment in early spring 2022 (~1-2 days)

- 13 recovered
- 1 data recovered; frame lost
- 2 stuck

Tagging in May 2022 (~5 days): in preparation

# Questions?

**Contact details:**

- Marcel Rozemeijer
- marcel.rozemeijer@wur.nl
- +31-6-20854613

wind & water works

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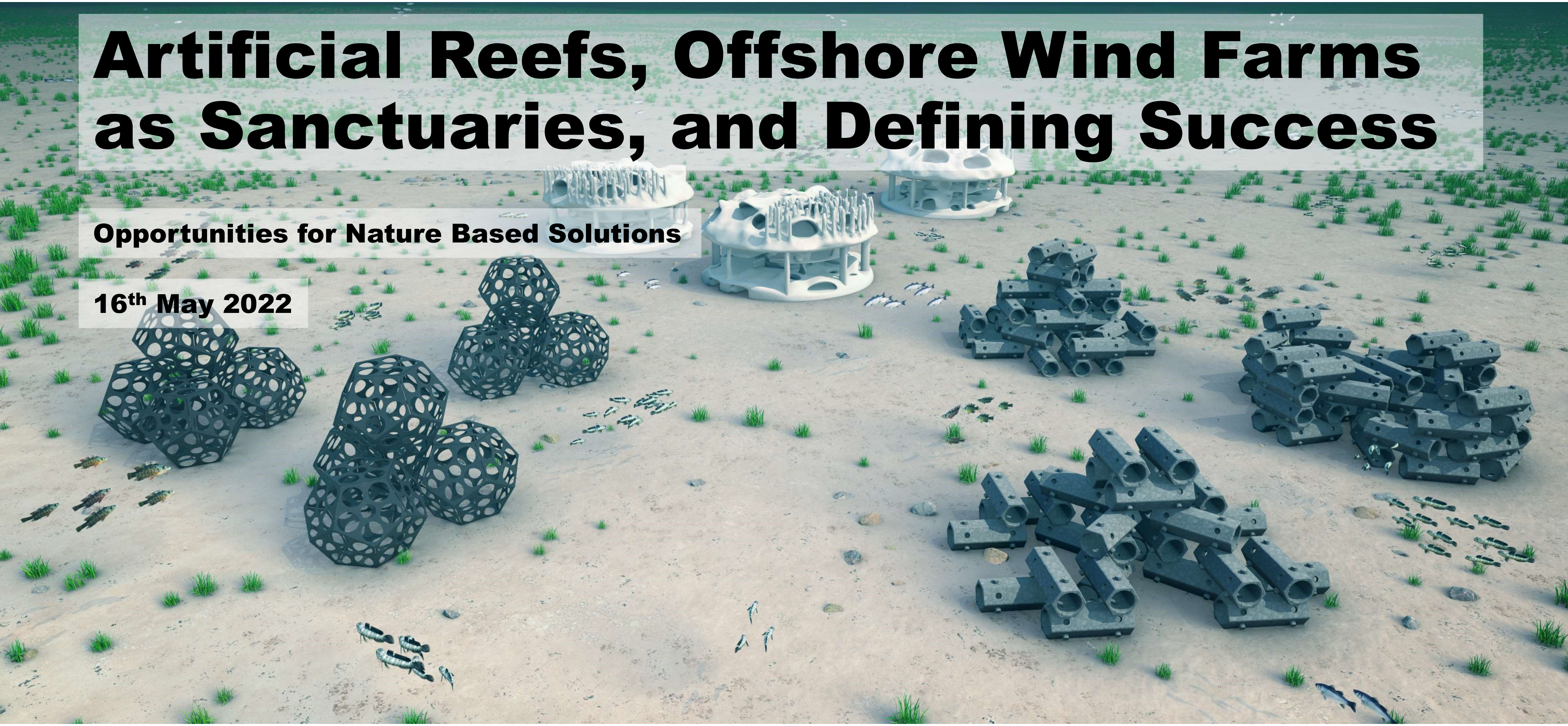
Boskalis

# Artificial Reefs, Offshore Wind Farms as Sanctuaries, and Defining Success

## Opportunities for Nature Based Solutions

16th May 2022



# The value of artificial reefs

## KEY QUALITIES

- Instant habitat creation
- Scalable applications for measurable positive impacts
- Designed for site-specific ecological and metocean conditions

## KEY BENEFITS

- Support fisheries, coastal protection and biodiversity
- Increase ecological interconnectivity within offshore windfarms
- Restoration of degraded marine environments facing permanent change
- Create opportunities for research and community involvement

# Offshore windfarms present unique opportunities which are all linked

- Key stakeholders:
  - Clients
  - Fisheries
  - Governments
  - Marine Contractors
  - Knowledge institutions
  - Non-governmental organizations

Governance

Engineering

Ecology

Boskalis is looking for pilot opportunities in the US for the application of artificial reefs

# Boskalis' reef approach

## REEF DEVELOPMENT IN MARINE PROJECTS

- As integral part of living breakwaters: sustainable design combining hydraulic and ecological functions.
- As compensation / rehabilitation: ecosystem value, permit enablers
- Creation of new stand-alone reef systems – marine sanctuaries

## OUR APPROACH

- Developing ecological / hydraulic knowledge via pilots (key for success)
- Creating and expanding a strong network – use local network!
- Proposing solutions in alternative bids – encourage idea exchange
- Front-running the large-scale approach: creating positive impact
- Our approach has culminated in our Boskalis Artificial Reefs Program

# Artificial Reefs Program
## Tested Concepts

**3D printed systems**

*DShape Monaco units*

**Modular systems**

*ReefSystems MOSES*

*Boskalis Endless Reef*

*Reefy Blocks*

# ARTIFICIAL REEFS PROGRAM

## OVERVIEW

- **Goal**: The development and application of large-scale artificial reefs as enablers for marine infrastructure or coastal protection works.
- **Strategy**: Artificial reefs directly address our strategy focus areas biodiversity & climate change mitigation
- **Results**: Provide state-of-the-art, fit-for-purpose solutions with a clear business case.

## OUR APPROACH

- Strong strategic partnerships at the forefront of (modular) engineering.
- Build upon symbiotic dynamics: provide opportunities for (pilot) projects. Share key insights and technical requirements for artificial reef designs in challenging environments.
- In return, our strategic partners provide us with a diverse range of artificial reef options to serve our clients and markets.

www.boskalis.com/artificialreefs

Utrecht University

SCUBAPANAMA PROFESSIONAL

coralive.org

van hall larenstein
university of applied sciences

TU Delft

d-shape

WAGENINGEN
UNIVERSITY & RESEARCH

UNIVERSIDAD MARITIMA INTERNACIONAL
UMIP
PANAMA

ReefSystems

REEFSCAPERS

NIOZ
Royal Netherlands Institute
for Sea Research

Reef2reef
FOUNDATION PANAMA

ECONCRETE

PRINCE ALBERT II
OF MONACO
FOUNDATION

Port of
Rotterdam

Université
Nice
Sophia Antipolis

hyperion
robotics

reefy
Innovation for nature

REEF BALL
FOUNDATION

**Part 2: Discussions on Four Topics Central to Ongoing Project for BOEM (60 Minutes)**

2.1. Impact of Perforations and Cathodic Protection on Marine Growth (Monica Maher, DOE)

2.2. Biofouling Profiles (Andrew Want, Heriot-Watt University)

2.3. Internal Chemistry in Monopiles (Deltares)

2.4. Interactions between Marine Growth and Internal Water Chemistry (Swain, Florida Tech.)

Monica
Maher

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

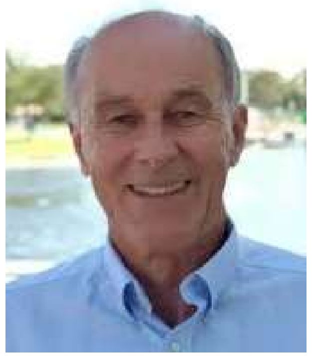
Andrew
Want

HERIOT WATT UNIVERSITY

Niek
Bruinsma

Stefan
Jansen

Deltares



Geoff
Swain

FLORIDA INSTITUTE OF TECHNOLOGY · AD ASTRA PER SCIENTIAM · 1958

# 2.1. Impact of Perforations and Cathodic Protection on Marine Growth

Monica Maher, DOE)

Center for Corrosion
and
Biofouling Control

# 2018 Field Study

**Monica M. Maher**

**2019 Corrosion Innovation of the Year**

CATHODIC & ANODIC **PROTECTION**

## Corrosion Control and Ecosystems Enhancement for Offshore Monopiles

**AUGUST 2019 VOL. 59, NO. 8**

**Monica M. Maher and Geoff Swain,**
*Center for Corrosion and Biofouling Control, Florida Institute of Technology, Melbourne, Florida, USA*

*Corrosion has been reported inside hollow steel monopile foundations used to support offshore wind-powered turbines. This research investigated incorporating perforations in the monopile walls that allow the free flow of ambient seawater into the interior, the installation of cathodic protection, and enable the interior structure to provide a habitat for marine life. Partially submerged steel pipes with different treatments were deployed. The results demonstrated that a cathodically protected perforated monopile structure creates an environment with more favorable corrosion mitigation and water chemistry compared to a sealed structure. Furthermore, the perforated cathodically protected pipe recruited a diverse population of settled and mobile organisms.*

**The offshore wind industry has experi**enced corrosion problems on the interior surfaces of submerged steel monopile foundations. This research investigated the feasibility of incorporating perforations in the monopile walls that would allow the free flow of ambient seawater into the interior. This would allow conventional cathodic protection (CP) design for corrosion control and promote the creation of a habitat for marine life. Stewardship of coastal waters is required to ensure that fisheries, endangered species, and water quality are maintained and enhanced. Offshore structures should, therefore, integrate designs that have a positive impact on marine biology and the ecosystem. This article is based on the 2018 Master's thesis, "The Corrosion and Biofouling Characteristics of Sealed vs. Perforated Offshore Monopile Interiors."[1]

### Steel Monopiles for the Offshore Wind Industry

Steel monopiles provide the most common foundation for offshore wind turbine support towers. They may be deployed in water depths up to 30 m, are typically 5 to 7.5 m in diameter, and 60+ m in length. The foundation design under consideration is driven into the seabed, extends up through the water column, and has an air gap at the top above water level. A transition piece sits on top of the monopile extending the tower upwards toward the wind turbine height. Even with the large cost of power-generation turbines, the installation and maintenance of foundations consumes a significant portion of windfarm lifetime costs.[2] Corrosion mitigation must be optimized to keep monopiles adequately strong and reliable throughout their design life.

Corrosion of the submerged internal surfaces of early windfarm monopiles was assumed to be controlled by sealing the structures and preventing ingress of oxygen. Oxygen is the main driver for corrosion reactions, so an enclosed

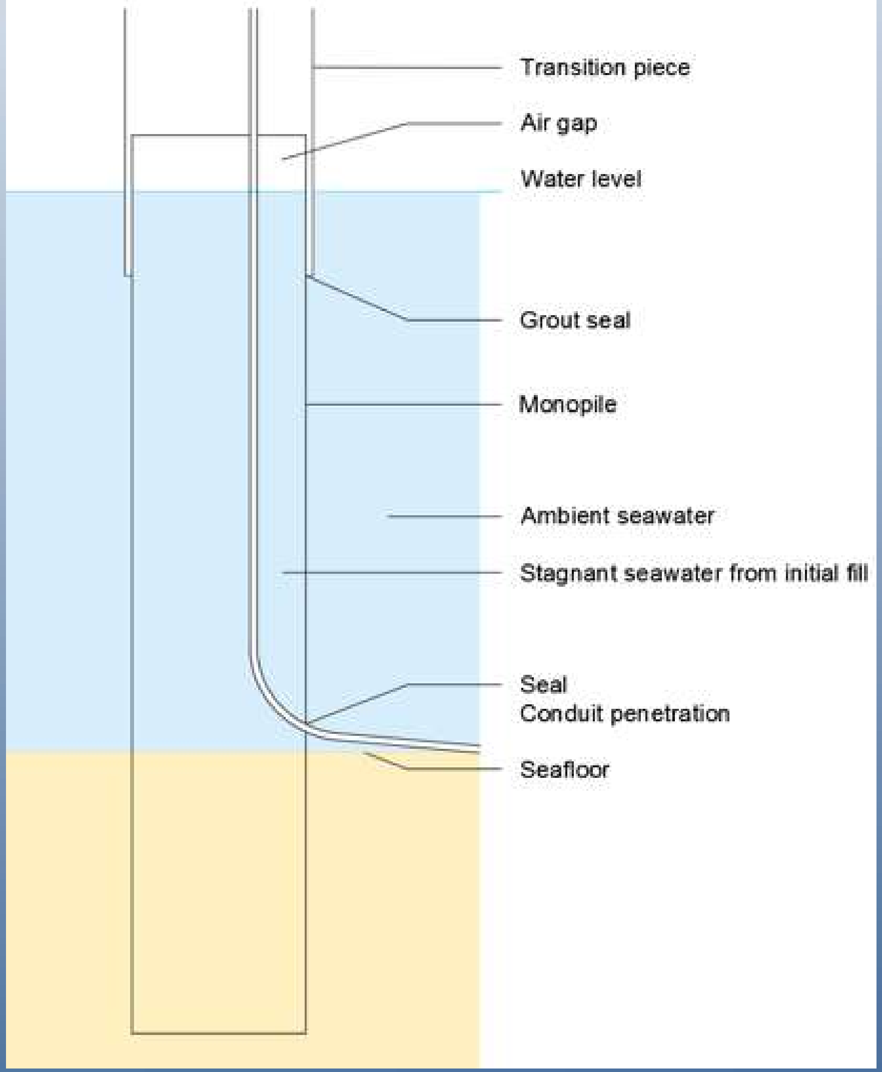
MATERIALS PERFORMANCE

# Monopile Internal Corrosion

Cathodic protection inside the confined space can affect air quality and water chemistry.

Aluminum anodes installed in monopile interiors cause:

- $H_2S$ formation (hydrogen sulfide)
- Water acidification
  - attributed to aluminum sacrificial anodes
  - pH < 5
- Unique localized corrosion

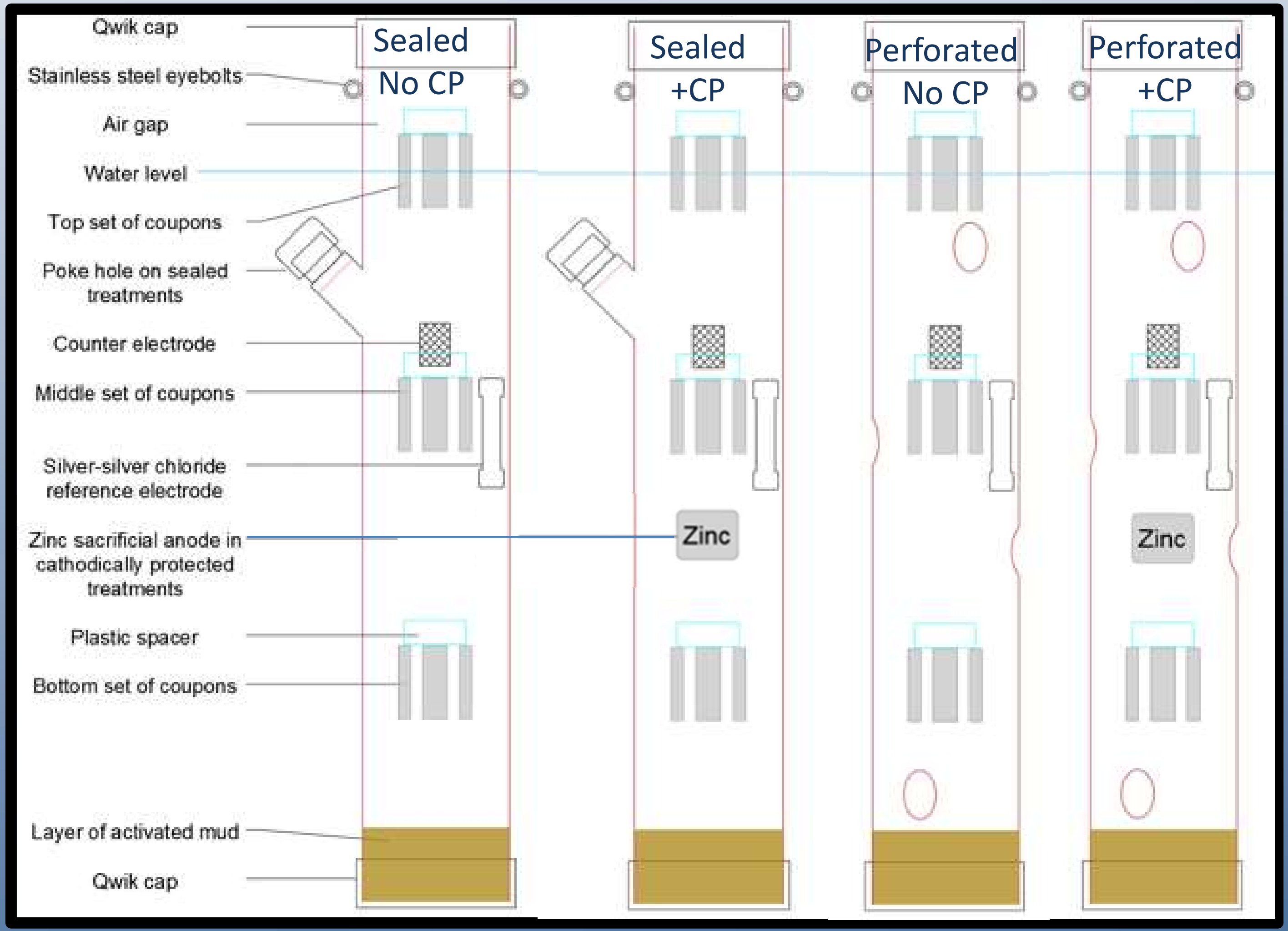


# Hypotheses

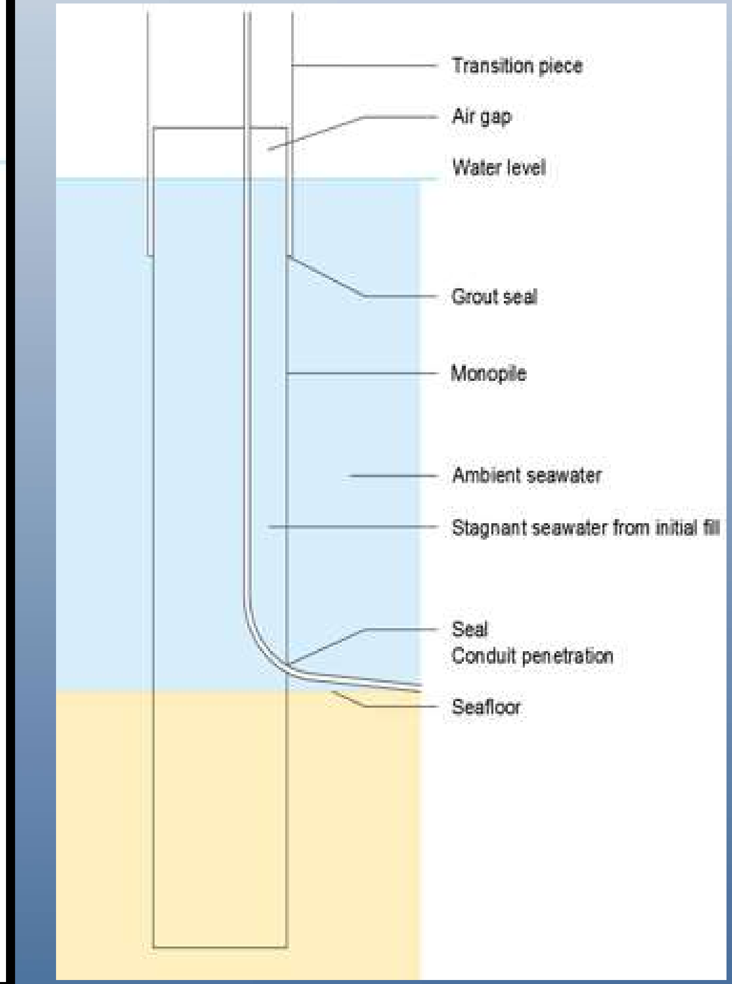
- A perforated structure will create an environment with more favorable corrosion mitigation, air quality, and water chemistry compared to the sealed structure.
- A perforated structure will create a habitat for marine life and recruit a diverse population of settled and mobile organisms.

# Experimental Design

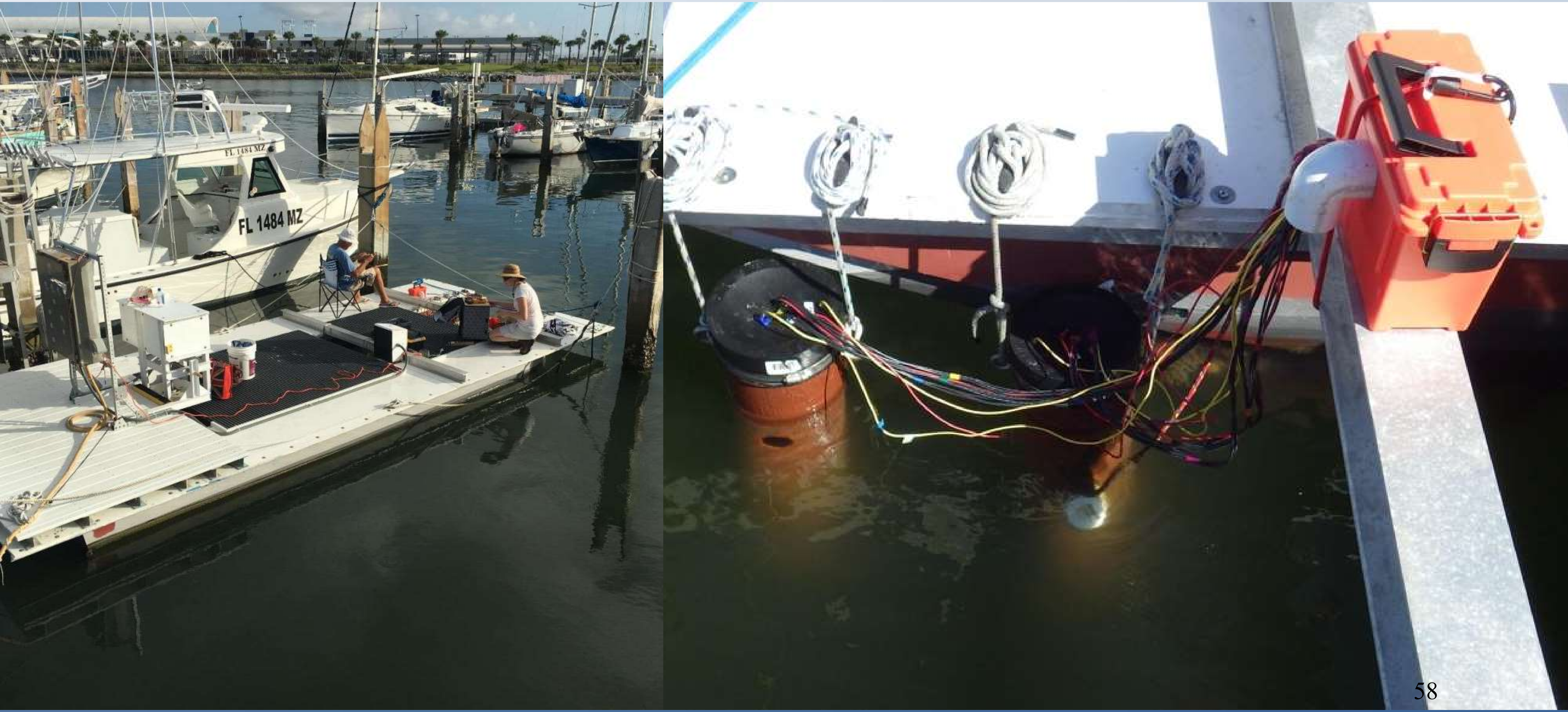
## 1M LONG 15CM Ø STEEL TEST PIPES



## FULL SCALE 5M Ø IN 20M DEEP WATER



# Test Site



# Measurements

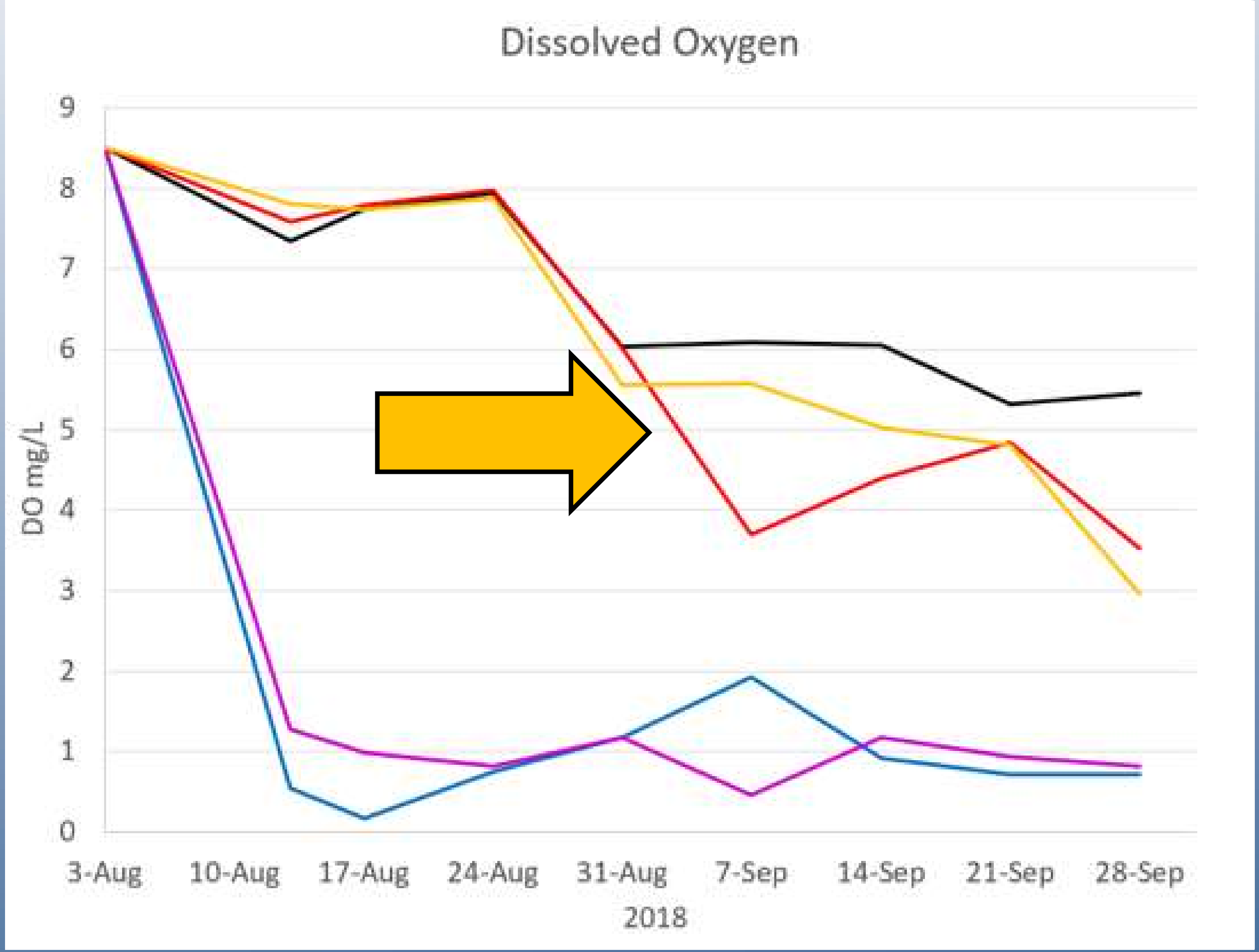
Weekly measurements

- Dissolved oxygen
- pH
- Cathodic protection
- Corrosion rates

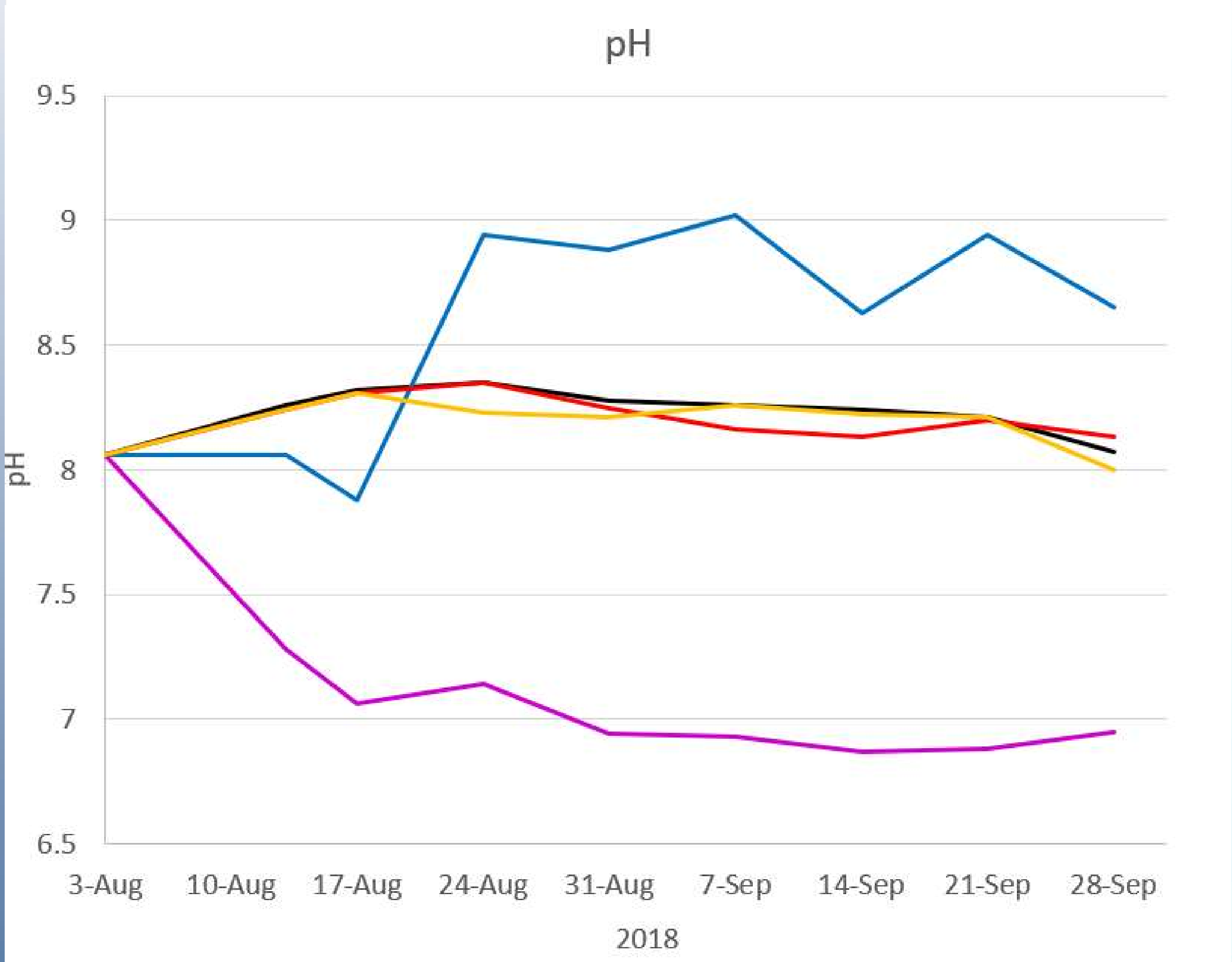
End of deployment

- Weight loss of steel
- Habitat observation

# Dissolved Oxygen



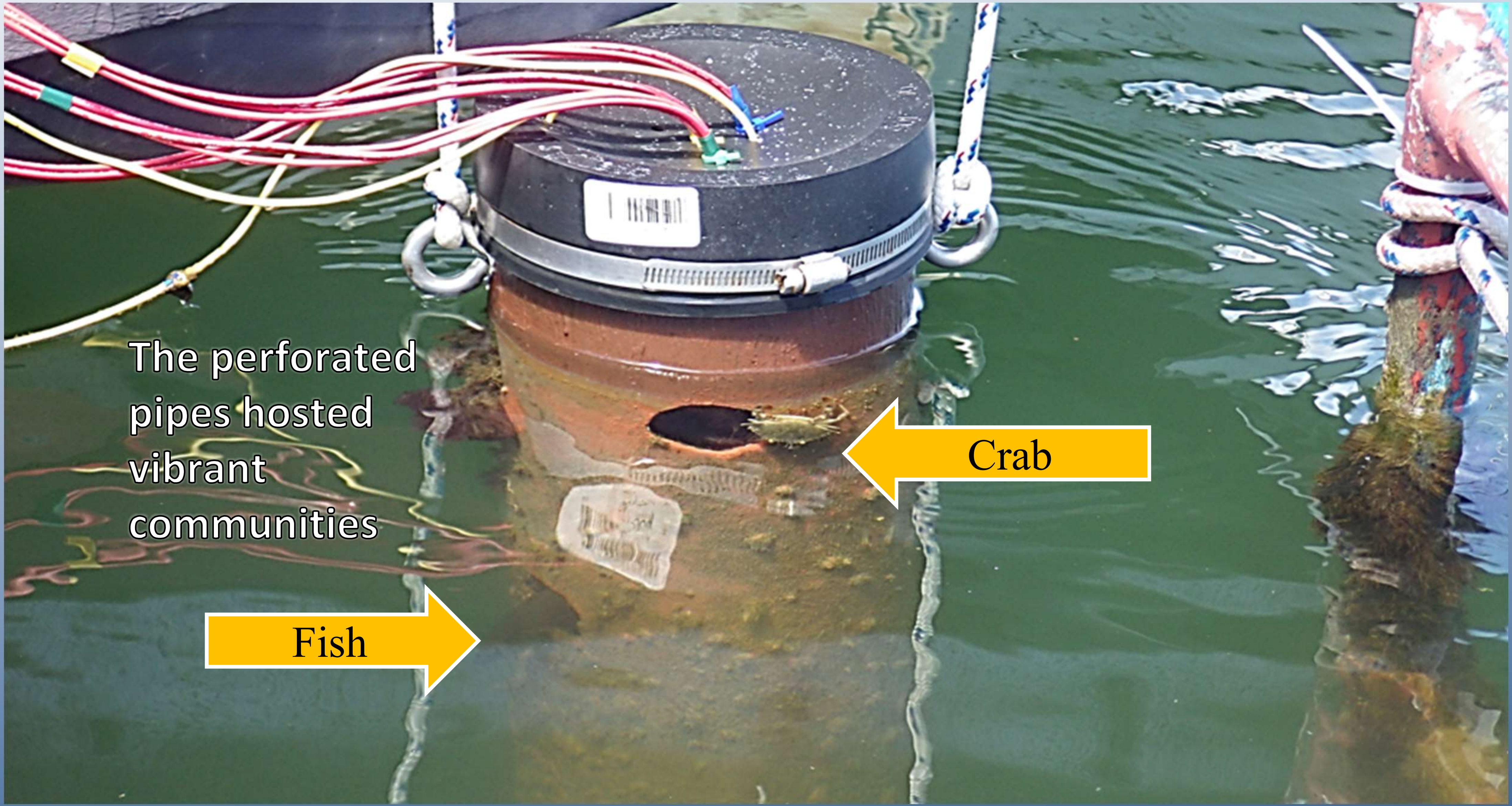
# pH


pH
9.5
9
8.5
8
7.5
7
6.5
pH
3-Aug
10-Aug
17-Aug
24-Aug
31-Aug
7-Sep
14-Sep
21-Sep
28-Sep
2018
Ambient
Sealed Freely Corroding
Sealed Zn
Perforated Freely Corroding
Perforated Zn


YSI
YSI
YSI

# Condition of the Steel at the End of the Test

# Habitat



The perforated pipes hosted vibrant communities

# Perforated Freely Corroding

# Perforated Freely Corroding

# Perforated Cathodically Protected

# Perforated Cathodically Protected

# Habitat

| | | Unprotected | w/ Zinc |
|---|---|---|---|
| Mobile Creatures | Schoolmaster snapper | 1 | 1 |
| | Frillfin goby | | 2 |
| | Blenny | | 2 |
| | Blue crabs | 5 | 2 |
| | Other *Calinectes* crabs | | 3 |
| | Daggerblade shrimp | | 18 |
| | Pink shrimp | | 2 |
| | Amphipods | X | X |
| Biofouling | Encrusting bryozoan | X | X |
| | Arborescent bryozoan | X | X |
| | Sauerkraut bryozoan | X | X |
| | Tubeworms | X | X |
| | Tunicates | X | X |
| | Barnacles (native & invasive) | X | X |
| | Oyster | | 1 |

# Conclusions

- Perforated monopile interior walls can more easily and predictably be protected from corrosion using cathodic protection.
- Cathodically protected perforated monopiles will enhance the ecology of a region by providing a sheltered space within which marine organisms prosper.
- Nature inclusive engineering offers opportunity to complement the local environment and provide ecosystem services

# 2.2. Biofouling Profiles

## Andrew Want, Heriot-Watt University

“Marine Ecosystem Considerations in the Design of Offshore Wind Support Structures”

# Biofouling Profiles

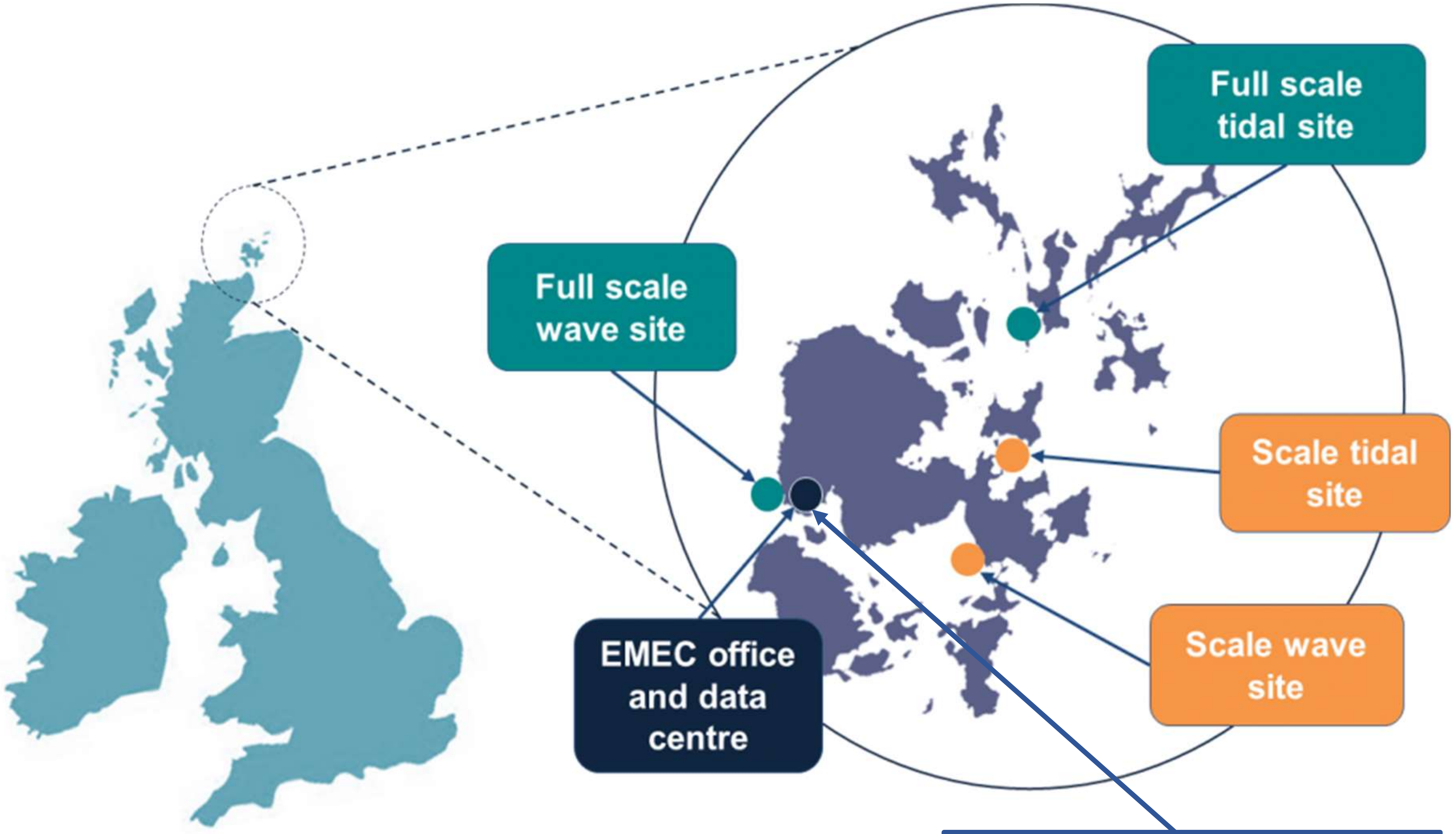

Image: A. Want


©Hywind Scotland


Image: A. Want

Dr Andrew Want – Heriot Watt University

16 May 2022



Full scale tidal site

Full scale wave site

Scale tidal site

Scale wave site

EMEC office and data centre

EMEC

THE EUROPEAN MARINE ENERGY CENTRE LTD

HERIOT WATT UNIVERSITY

ORKNEY CAMPUS

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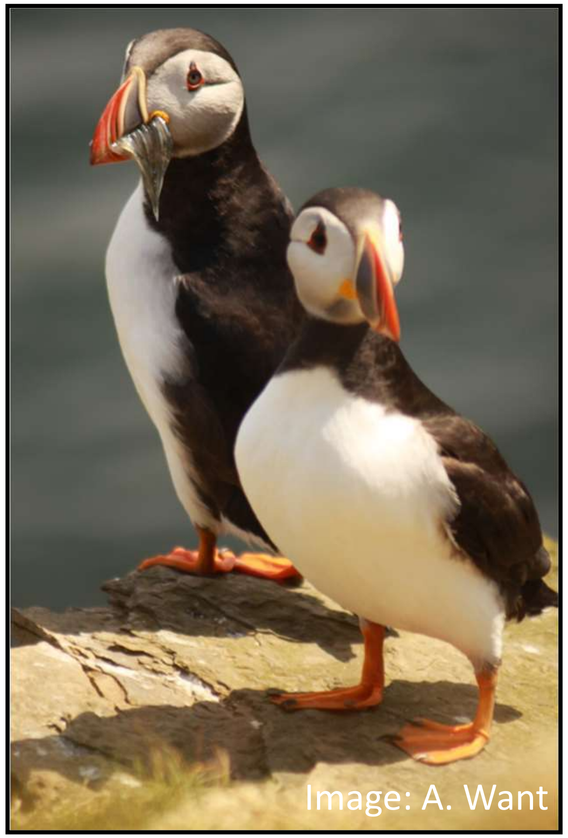


Image: A. Want

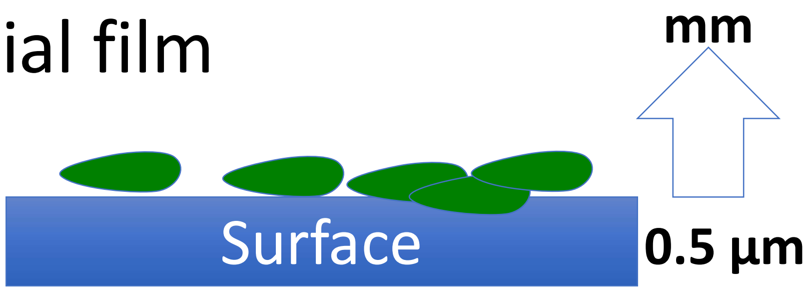
# Biofouling: the settlement and growth of organisms on submerged structures.

## Stages in Biofouling

1. Biofilm of organic chemicals = instantaneous
2. Bacterial Adhesion = <24 hours
3. Secondary Colonisers (spores and larvae) = <7 days
4. Tertiary Colonisers (macrofoulers) = 2-3 weeks

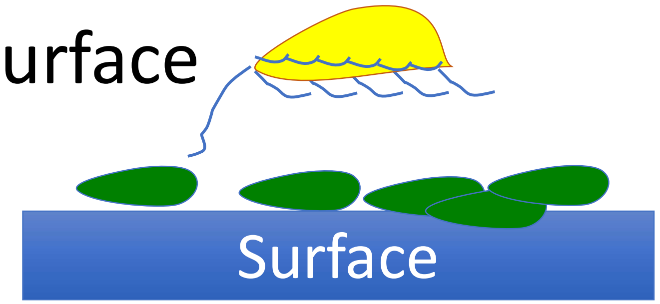
### Microfouling

- Attachment and formation of bacterial film



### Macrofouling

- Marine invertebrate larvae attracted to surface



Illustrations courtesy of Dr Mike Winson

# What is the problem?

- Accelerating corrosion of components: ↓survivability ↑costs
- Increased roughness: ↑drag
- Increased weight on mooring systems, cables: ↓performance
- Removal of fouling/antifouling strategies are expensive and require additional operational ‘down-time’: ↑costs
- Fouling of access areas: ↓safety
- Fouling of anodes and coatings: ↓cathodic protection ↑corrosion
- Ecological issues…

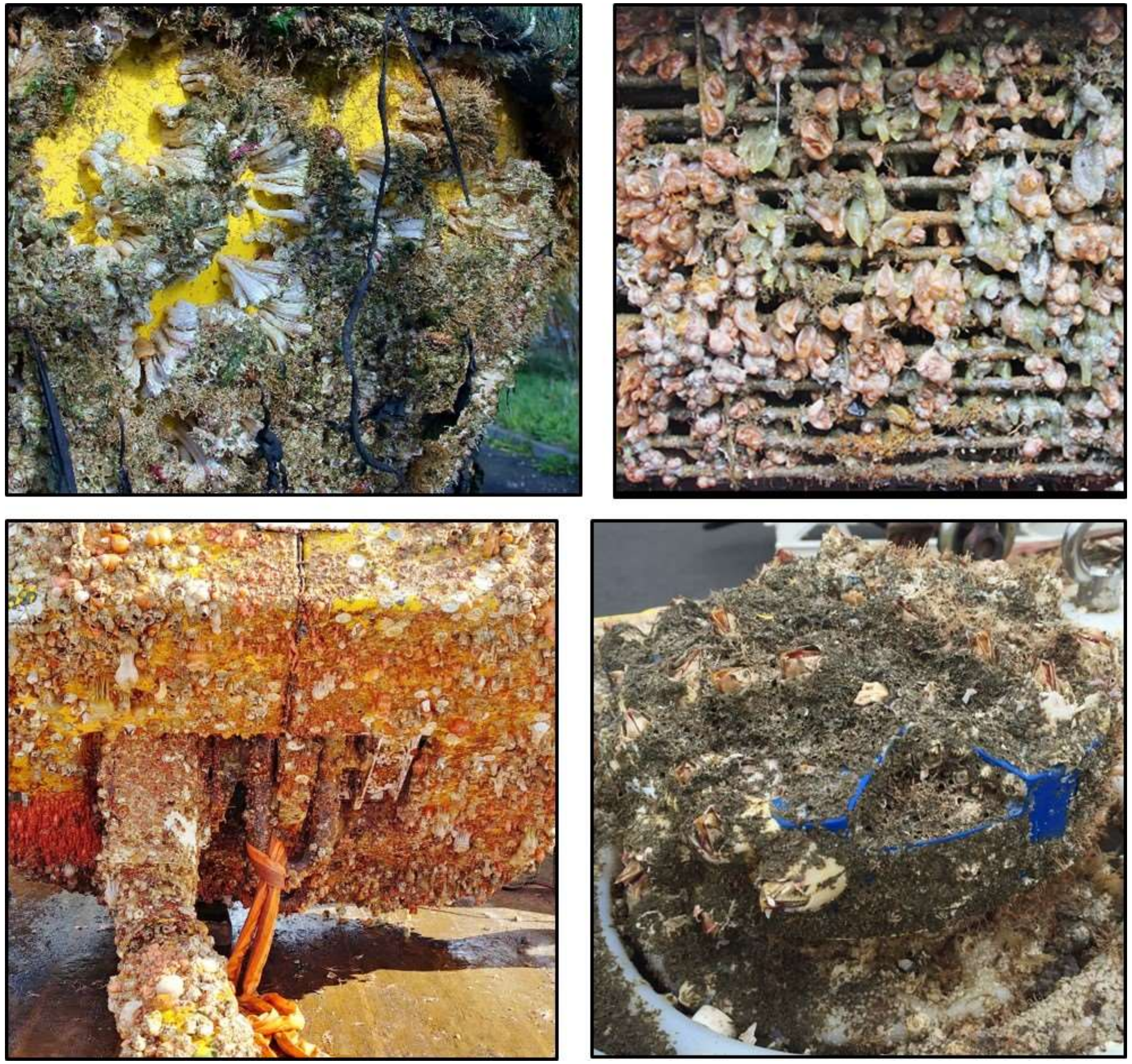

Image: A. Want


Image: A. Want

# Is this a new problem?

***Yes***, there are several issues unique to the Offshore Renewable Energy (ORE) sector:

- New components/materials used in the sector
- Devices are being placed in poorly understood habitats
- Narrow diameter structures not used in O&G sector, e.g. dynamic subsea cables, mooring systems
- Increased use of sensor technologies to determine performance and resource assessment



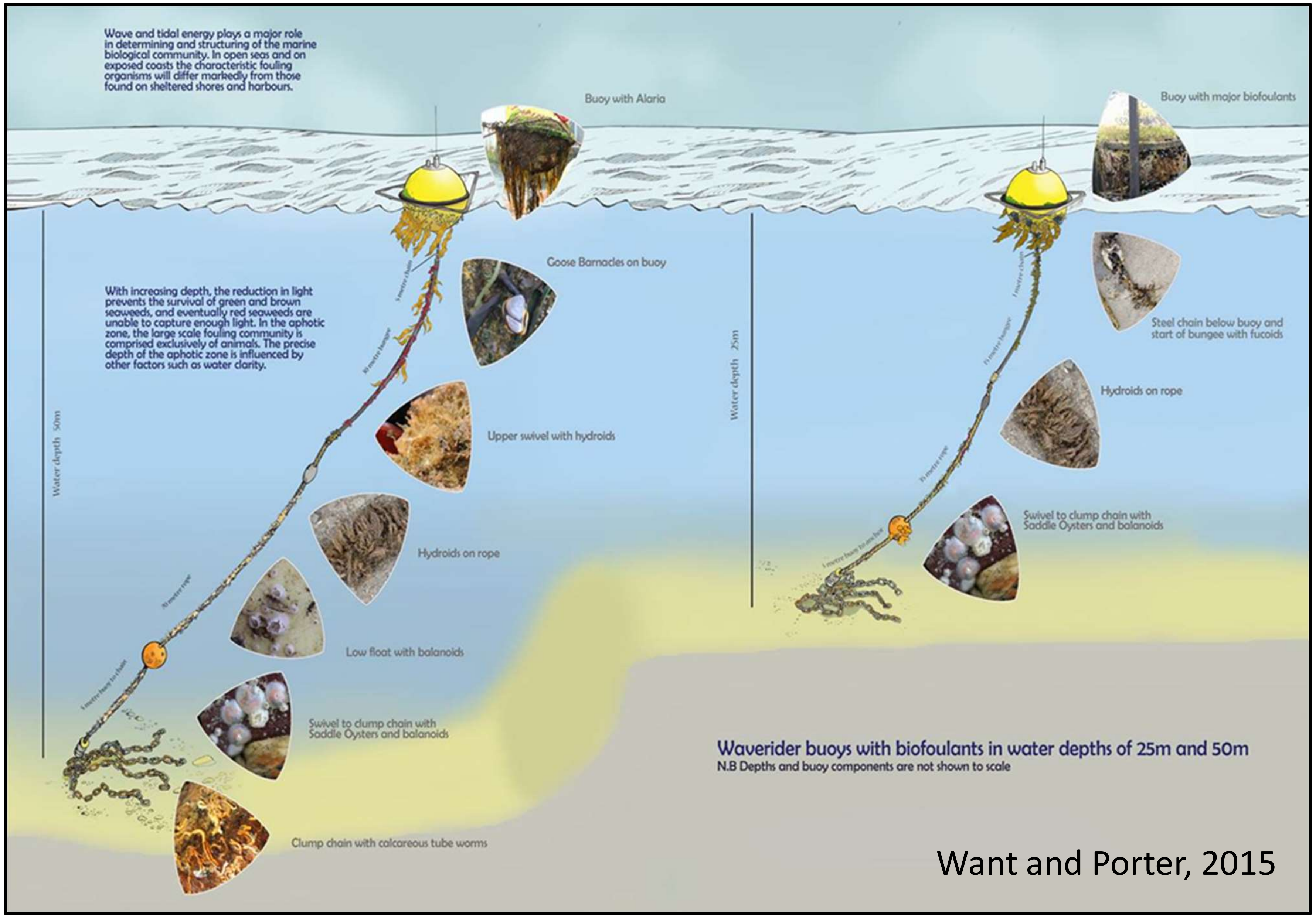
# What factors effect biofouling?

Physical factors

- Depth, e.g. photic energy
- Temperature
- Substrate type
- Hydrological processes,
  - e.g. turbidity, nutrients, larvae
- Hydrodynamic conditions,
  - e.g. currents, tides, waves
- Water chemistry,
  - e.g. oxygenation, salinity
- Distance from land
- Distance from ports
- Others

Biological factors

- Competition
- Seasonality
- Successional processes



Wave and tidal energy plays a major role in determining and structuring of the marine biological community. In open seas and on exposed coasts the characteristic fouling organisms will differ markedly from those found on sheltered shores and harbours.

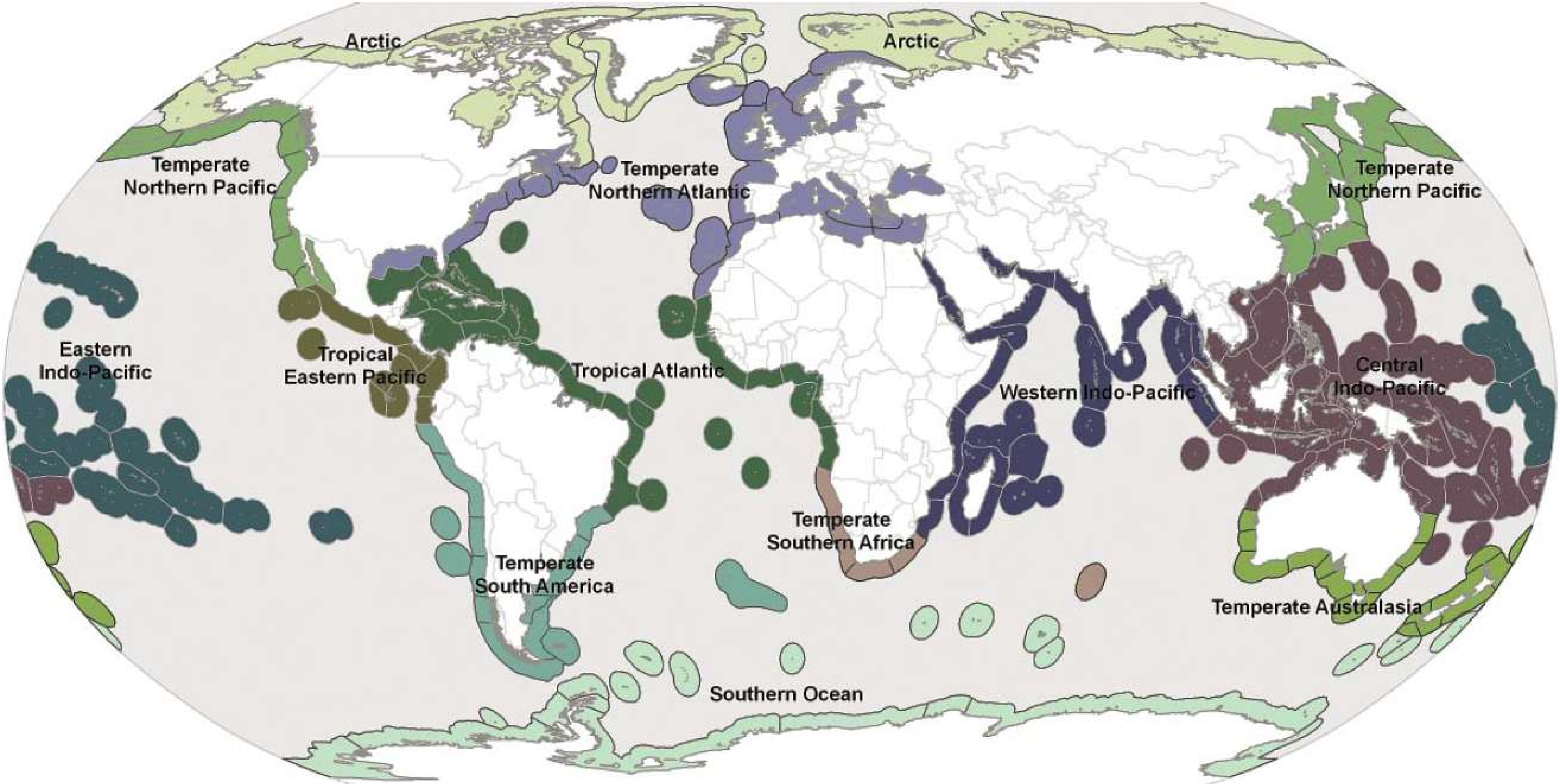
With increasing depth, the reduction in light prevents the survival of green and brown seaweeds, and eventually red seaweeds are unable to capture enough light. In the aphotic zone, the large scale fouling community is comprised exclusively of animals. The precise depth of the aphotic zone is influenced by other factors such as water clarity.

Waverider buoys with biofoulants in water depths of 25m and 50m

N.B Depths and buoy components are not shown to scale

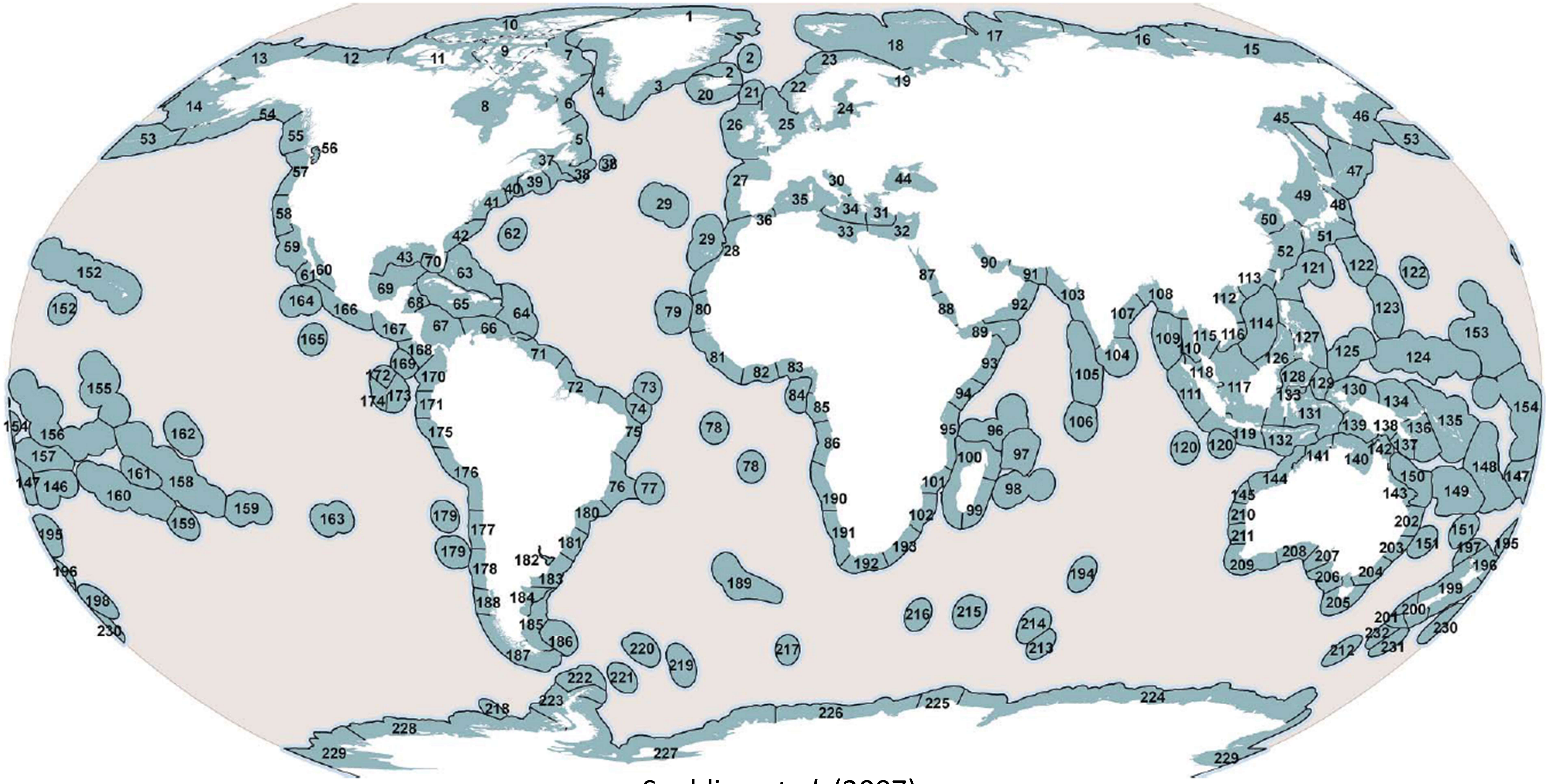
Want and Porter, 2015

# Marine Ecoregions



Spalding *et al.* (2007)

# Marine Ecoregions



Spalding *et al.* (2007)

# Major Macrofouling Groups – North Sea

Seaweeds
- Reds
- Browns
- Greens

Porifera (sponges)

Cnidaria
- Hydroids
- Sea anemones
- ‘Soft’ corals
- ‘Hard’ corals

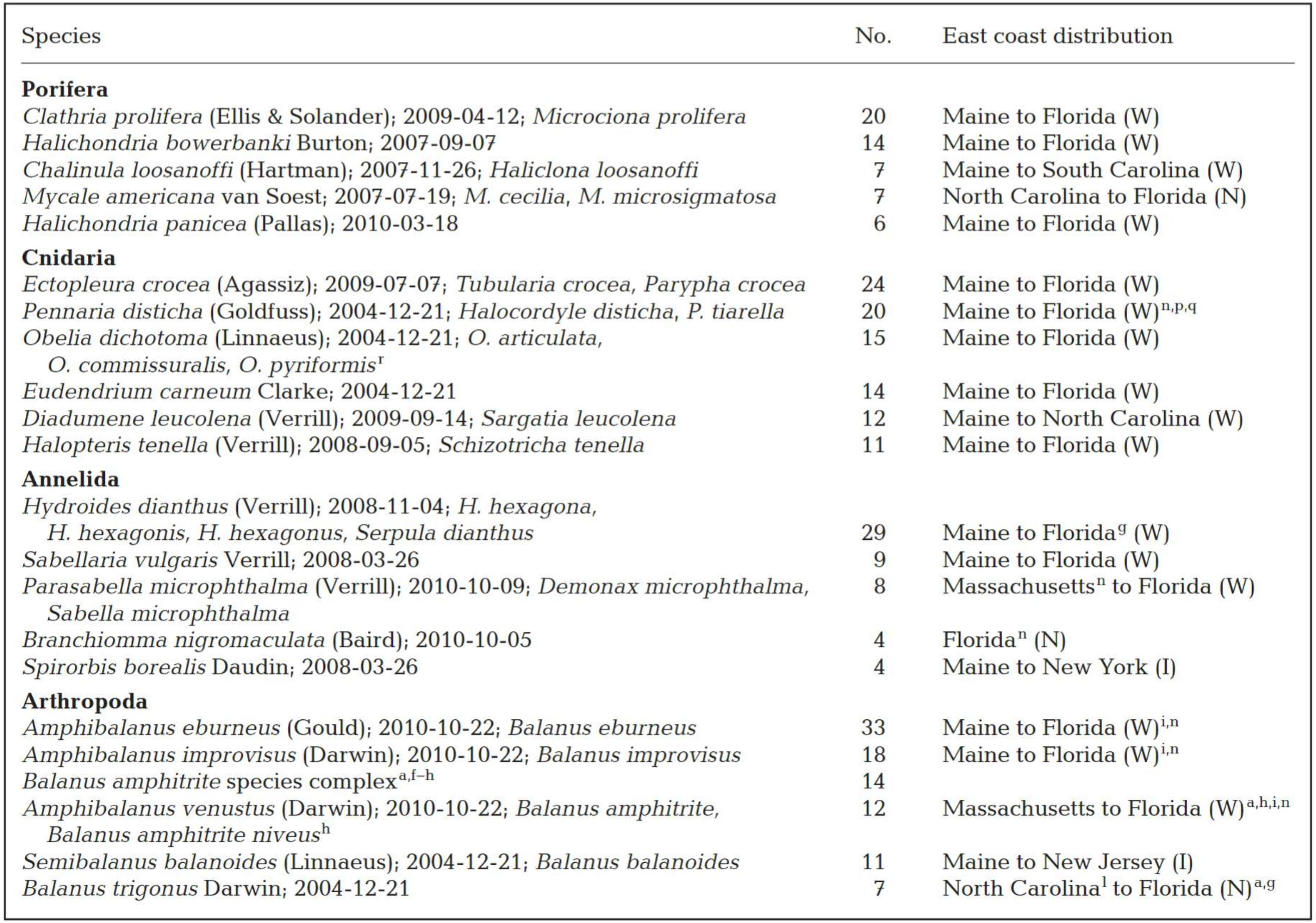
Crustacea
- Barnacles
- Amphipods

Bryozoa

Mollusca
- Mussels
- Saddle oysters

Chordata
- Solitary sea squirts
- Colonial sea squirts

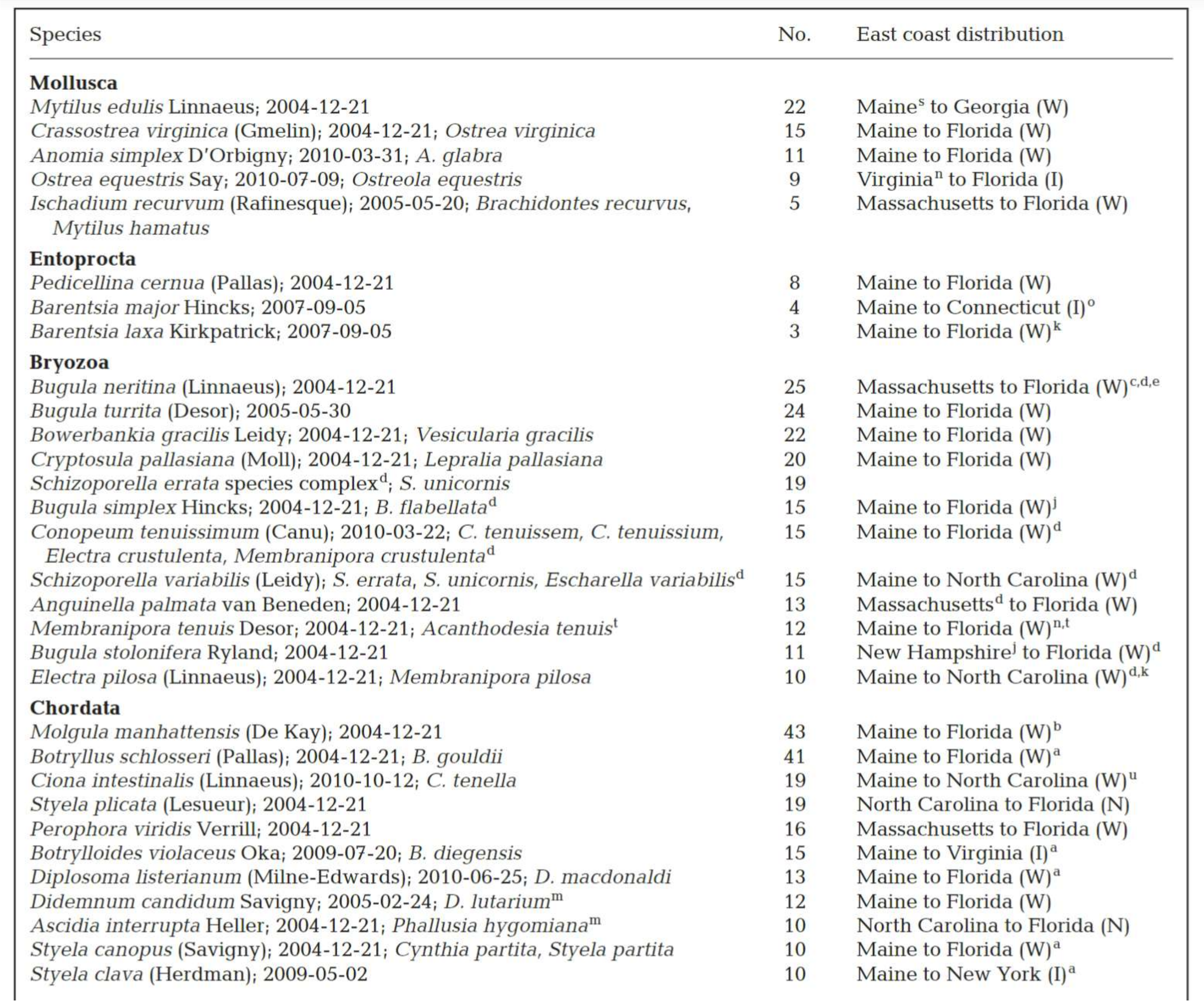
# Major Macrofouling Groups: NW Atlantic



| Species | No. | East coast distribution |
|---|---|---|
| **Porifera** | | |
| *Clathria prolifera* (Ellis & Solander); 2009-04-12; *Microciona prolifera* | 20 | Maine to Florida (W) |
| *Halichondria bowerbanki* Burton; 2007-09-07 | 14 | Maine to Florida (W) |
| *Chalinula loosanoffi* (Hartman); 2007-11-26; *Haliclona loosanoffi* | 7 | Maine to South Carolina (W) |
| *Mycale americana* van Soest; 2007-07-19; *M. cecilia, M. microsigmatosa* | 7 | North Carolina to Florida (N) |
| *Halichondria panicea* (Pallas); 2010-03-18 | 6 | Maine to Florida (W) |
| **Cnidaria** | | |
| *Ectopleura crocea* (Agassiz); 2009-07-07; *Tubularia crocea, Parypha crocea* | 24 | Maine to Florida (W) |
| *Pennaria disticha* (Goldfuss); 2004-12-21; *Halocordyle disticha, P. tiarella* | 20 | Maine to Florida (W)[n,p,q] |
| *Obelia dichotoma* (Linnaeus); 2004-12-21; *O. articulata, O. commissuralis, O. pyriformis*[r] | 15 | Maine to Florida (W) |
| *Eudendrium carneum* Clarke; 2004-12-21 | 14 | Maine to Florida (W) |
| *Diadumene leucolena* (Verrill); 2009-09-14; *Sargatia leucolena* | 12 | Maine to North Carolina (W) |
| *Halopteris tenella* (Verrill); 2008-09-05; *Schizotricha tenella* | 11 | Maine to Florida (W) |
| **Annelida** | | |
| *Hydroides dianthus* (Verrill); 2008-11-04; *H. hexagona, H. hexagonis, H. hexagonus, Serpula dianthus* | 29 | Maine to Florida[g] (W) |
| *Sabellaria vulgaris* Verrill; 2008-03-26 | 9 | Maine to Florida (W) |
| *Parasabella microphthalma* (Verrill); 2010-10-09; *Demonax microphthalma, Sabella microphthalma* | 8 | Massachusetts[n] to Florida (W) |
| *Branchiomma nigromaculata* (Baird); 2010-10-05 | 4 | Florida[n] (N) |
| *Spirorbis borealis* Daudin; 2008-03-26 | 4 | Maine to New York (I) |
| **Arthropoda** | | |
| *Amphibalanus eburneus* (Gould); 2010-10-22; *Balanus eburneus* | 33 | Maine to Florida (W)[i,n] |
| *Amphibalanus improvisus* (Darwin); 2010-10-22; *Balanus improvisus* | 18 | Maine to Florida (W)[i,n] |
| *Balanus amphitrite* species complex[a,f–h] | 14 | |
| *Amphibalanus venustus* (Darwin); 2010-10-22; *Balanus amphitrite, Balanus amphitrite niveus*[h] | 12 | Massachusetts to Florida (W)[a,h,i,n] |
| *Semibalanus balanoides* (Linnaeus); 2004-12-21; *Balanus balanoides* | 11 | Maine to New Jersey (I) |
| *Balanus trigonus* Darwin; 2004-12-21 | 7 | North Carolina[l] to Florida (N)[a,g] |

Karlson & Osman 2012

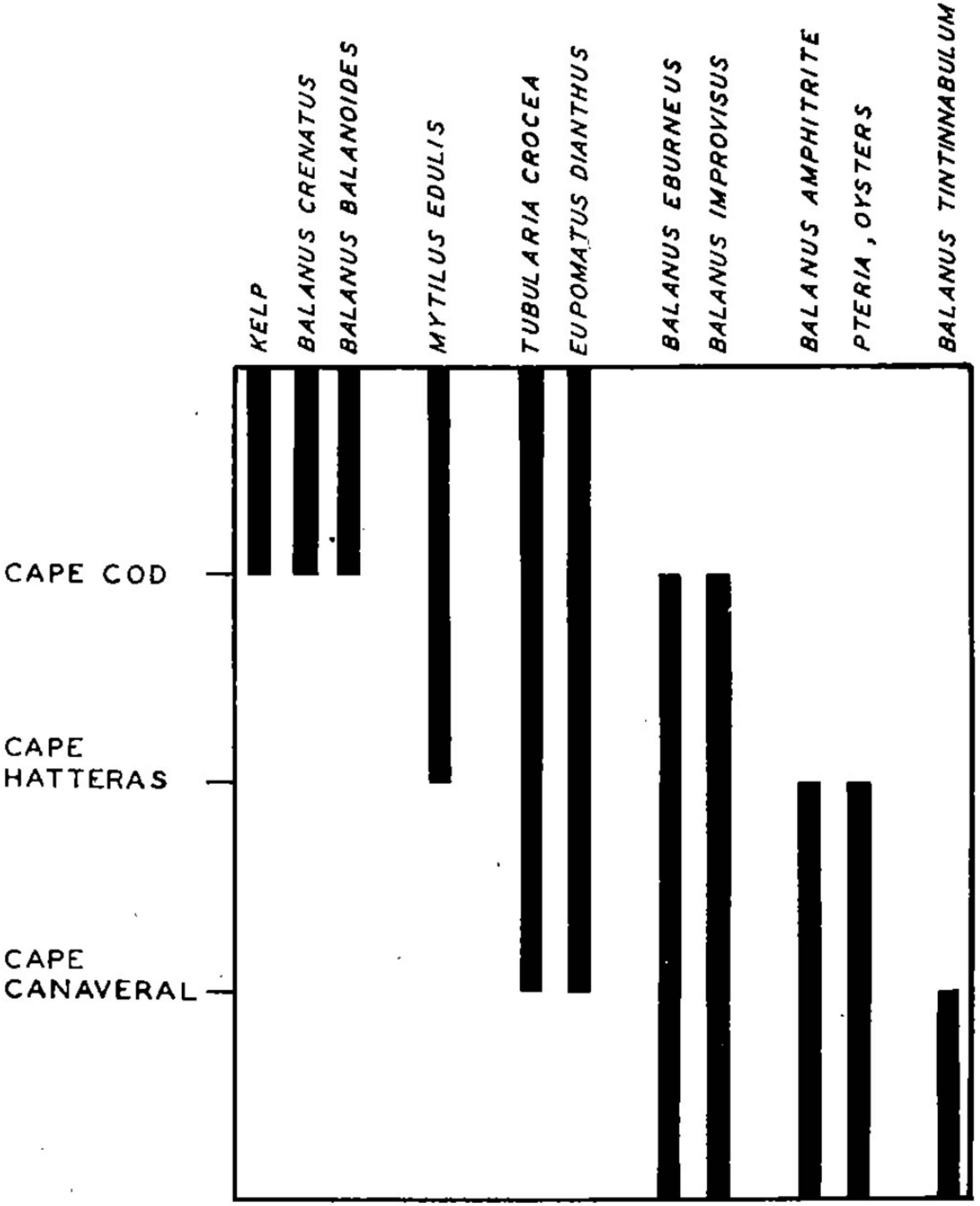
# Major Macrofouling Groups: NW Atlantic



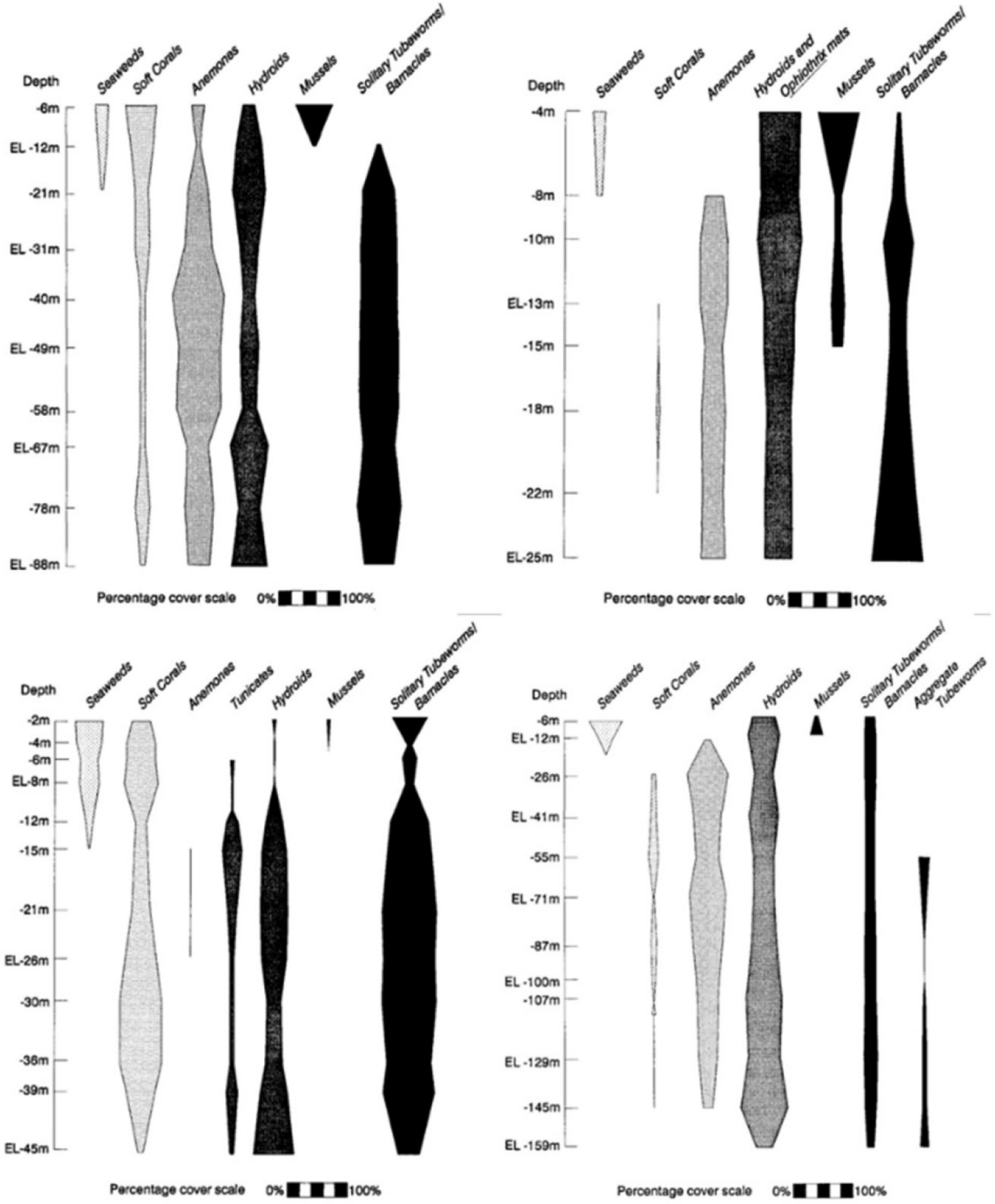
| Species | No. | East coast distribution |
|---|---|---|
| **Mollusca** | | |
| *Mytilus edulis* Linnaeus; 2004-12-21 | 22 | Maine[s] to Georgia (W) |
| *Crassostrea virginica* (Gmelin); 2004-12-21; *Ostrea virginica* | 15 | Maine to Florida (W) |
| *Anomia simplex* D'Orbigny; 2010-03-31; *A. glabra* | 11 | Maine to Florida (W) |
| *Ostrea equestris* Say; 2010-07-09; *Ostreola equestris* | 9 | Virginia[n] to Florida (I) |
| *Ischadium recurvum* (Rafinesque); 2005-05-20; *Brachidontes recurvus, Mytilus hamatus* | 5 | Massachusetts to Florida (W) |
| **Entoprocta** | | |
| *Pedicellina cernua* (Pallas); 2004-12-21 | 8 | Maine to Florida (W) |
| *Barentsia major* Hincks; 2007-09-05 | 4 | Maine to Connecticut (I)[o] |
| *Barentsia laxa* Kirkpatrick; 2007-09-05 | 3 | Maine to Florida (W)[k] |
| **Bryozoa** | | |
| *Bugula neritina* (Linnaeus); 2004-12-21 | 25 | Massachusetts to Florida (W)[c,d,e] |
| *Bugula turrita* (Desor); 2005-05-30 | 24 | Maine to Florida (W) |
| *Bowerbankia gracilis* Leidy; 2004-12-21; *Vesicularia gracilis* | 22 | Maine to Florida (W) |
| *Cryptosula pallasiana* (Moll); 2004-12-21; *Lepralia pallasiana* | 20 | Maine to Florida (W) |
| *Schizoporella errata* species complex[d]; *S. unicornis* | 19 | |
| *Bugula simplex* Hincks; 2004-12-21; *B. flabellata*[d] | 15 | Maine to Florida (W)[j] |
| *Conopeum tenuissimum* (Canu); 2010-03-22; *C. tenuissem, C. tenuissium, Electra crustulenta, Membranipora crustulenta*[d] | 15 | Maine to Florida (W)[d] |
| *Schizoporella variabilis* (Leidy); *S. errata, S. unicornis, Escharella variabilis*[d] | 15 | Maine to North Carolina (W)[d] |
| *Anguinella palmata* van Beneden; 2004-12-21 | 13 | Massachusetts[d] to Florida (W) |
| *Membranipora tenuis* Desor; 2004-12-21; *Acanthodesia tenuis*[t] | 12 | Maine to Florida (W)[n,t] |
| *Bugula stolonifera* Ryland; 2004-12-21 | 11 | New Hampshire[j] to Florida (W)[d] |
| *Electra pilosa* (Linnaeus); 2004-12-21; *Membranipora pilosa* | 10 | Maine to North Carolina (W)[d,k] |
| **Chordata** | | |
| *Molgula manhattensis* (De Kay); 2004-12-21 | 43 | Maine to Florida (W)[b] |
| *Botryllus schlosseri* (Pallas); 2004-12-21; *B. gouldii* | 41 | Maine to Florida (W)[a] |
| *Ciona intestinalis* (Linnaeus); 2010-10-12; *C. tenella* | 19 | Maine to North Carolina (W)[u] |
| *Styela plicata* (Lesueur); 2004-12-21 | 19 | North Carolina to Florida (N) |
| *Perophora viridis* Verrill; 2004-12-21 | 16 | Massachusetts to Florida (W) |
| *Botrylloides violaceus* Oka; 2009-07-20; *B. diegensis* | 15 | Maine to Virginia (I)[a] |
| *Diplosoma listerianum* (Milne-Edwards); 2010-06-25; *D. macdonaldi* | 13 | Maine to Florida (W)[a] |
| *Didemnum candidum* Savigny; 2005-02-24; *D. lutarium*[m] | 12 | Maine to Florida (W) |
| *Ascidia interrupta* Heller; 2004-12-21; *Phallusia hygomiana*[m] | 10 | North Carolina to Florida (N) |
| *Styela canopus* (Savigny); 2004-12-21; *Cynthia partita, Styela partita* | 10 | Maine to Florida (W)[a] |
| *Styela clava* (Herdman); 2009-05-02 | 10 | Maine to New York (I)[a] |

Karlson & Osman 2012

# Latitudinal gradient:



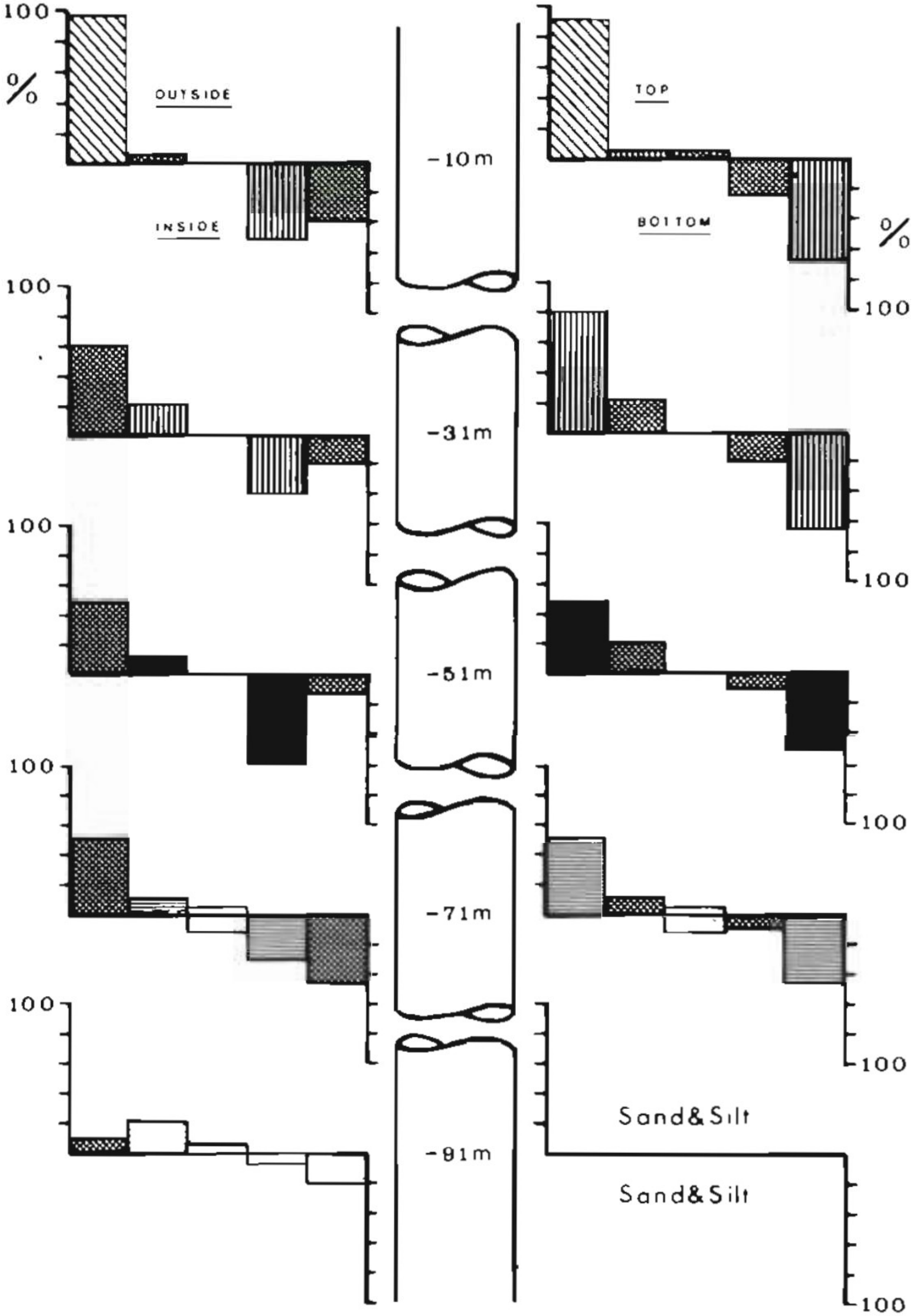
Woods Hole Oceanographic Institution, United States. Navy Dept. Bureau of Ships, "Marine fouling and its prevention", 1952.



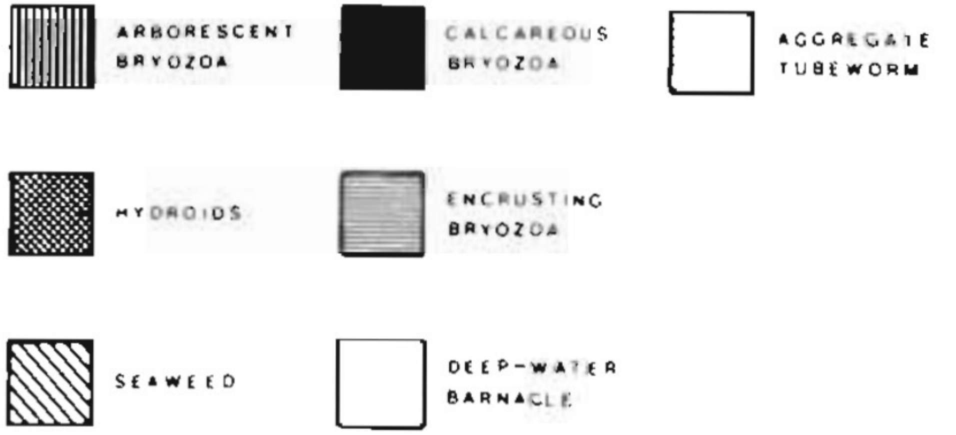
# Depth gradient:

Change in percent cover of fouling organisms on jackets with depth: (Top left) Claymore A; (Top right) West Sole AP; (Bottom left) Beatrice AD; (Bottom right) Heather A
-Sell, 1992.

# Depth gradient:



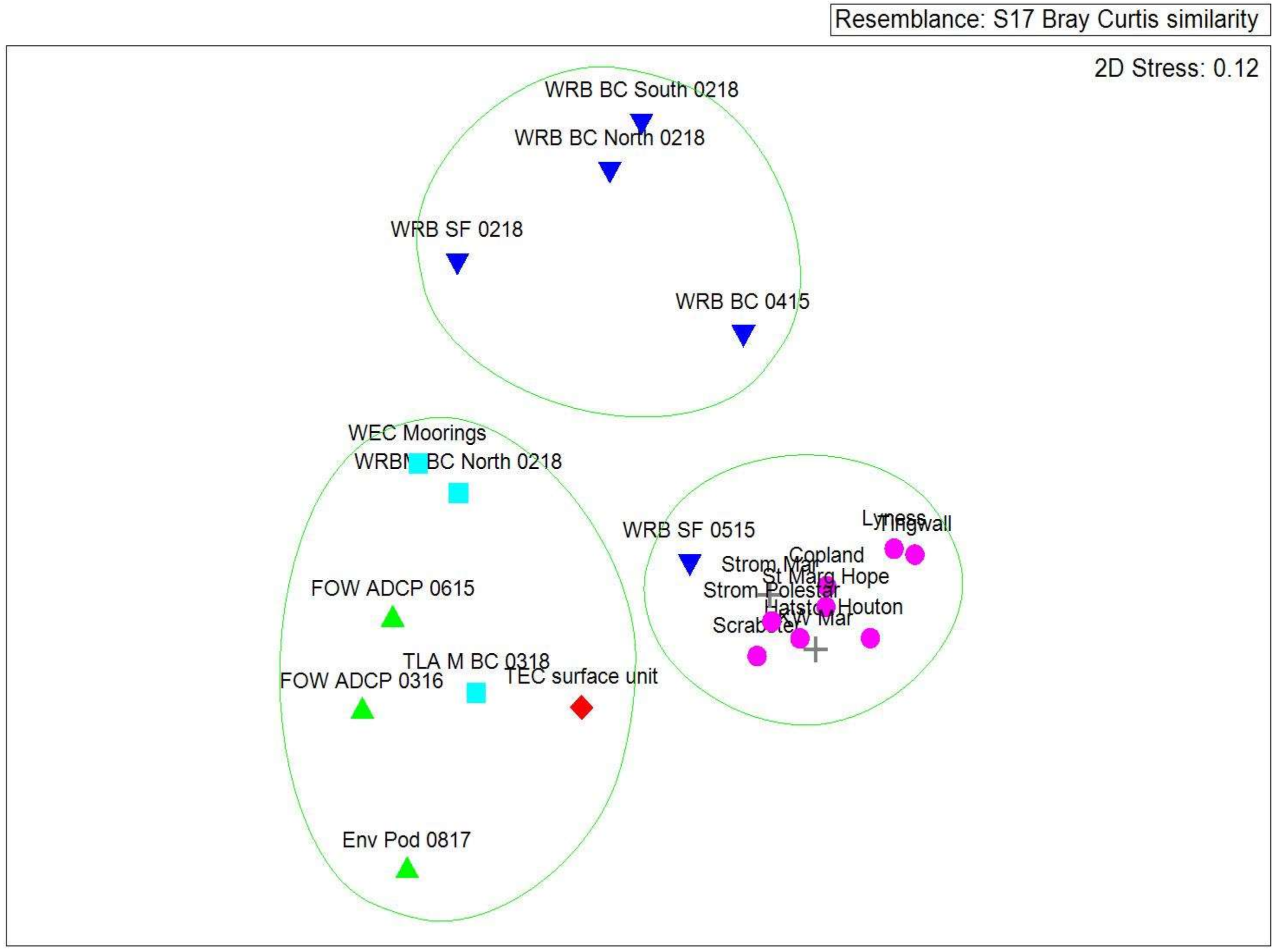
Estimated percentage cover of marine growth on a Montrose jacket, North Sea -Forteath *et al*. 1982



# Hydrodynamic gradient:

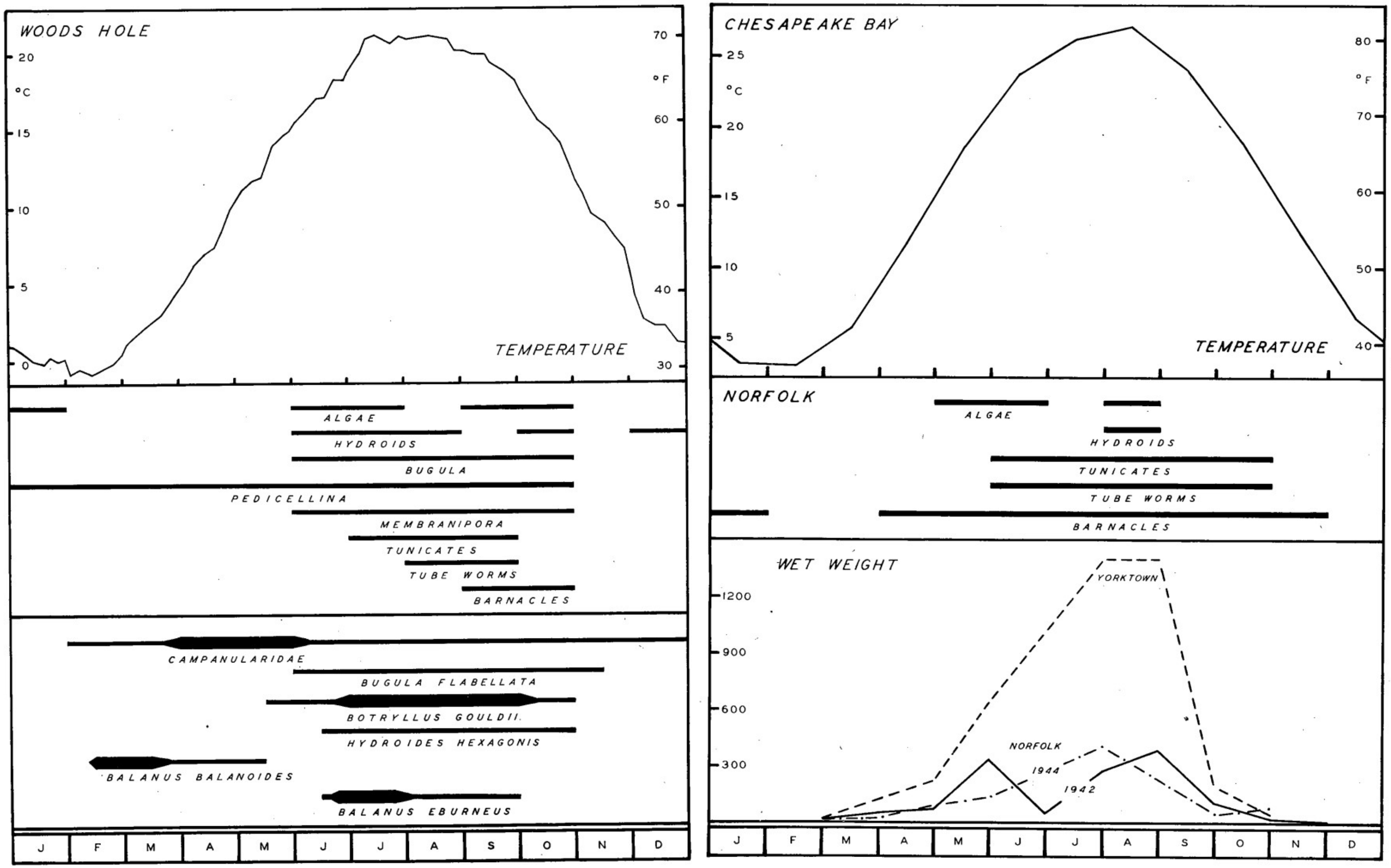
BioFREE

- 200+ species recorded
- 7 INNS (in harbours/marinas)
- MDS plots differences in species suites, between locations



**Want, A.**, Bell, M.C., Harris, R.E., Hull, M.Q., Long, C.R. and Porter, J.S. (2021). Sea-trial verification of a novel system for monitoring biofouling and testing anti-fouling coatings in highly energetic environments targeted by the marine renewable energy industry. *Biofouling*. DOI: 10.1080/08927014.2021.1928091

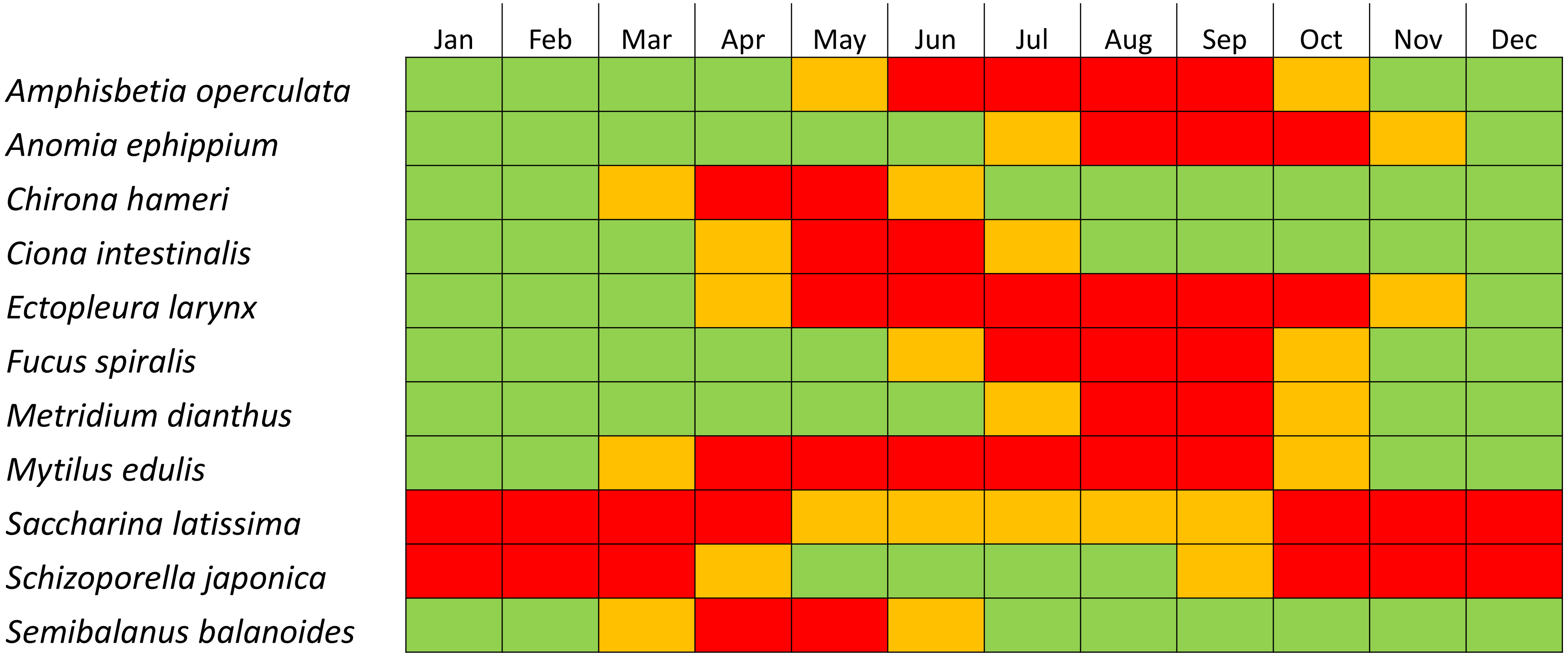
# Seasonality



Woods Hole Oceanographic Institution, United States. Navy Dept. Bureau of Ships, "Marine fouling and its prevention", 1952.

# Seasonality and Succession:

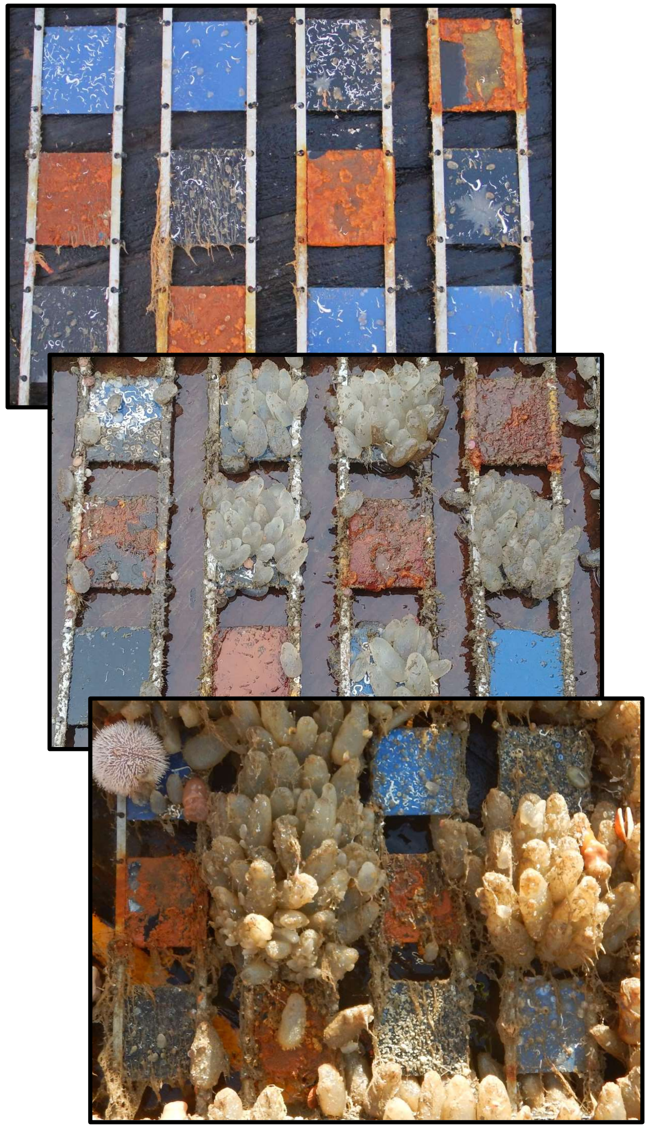
- Evidence gathered has provided examples of profound levels of fouling occurring over a relatively short period of time, depending on seasonality and succession
- Marked seasonality of fouling suggest that scheduling deployment and maintenance operations in a targeted manner may be an effective means to minimise fouling impacts and mitigate risk of invasive species



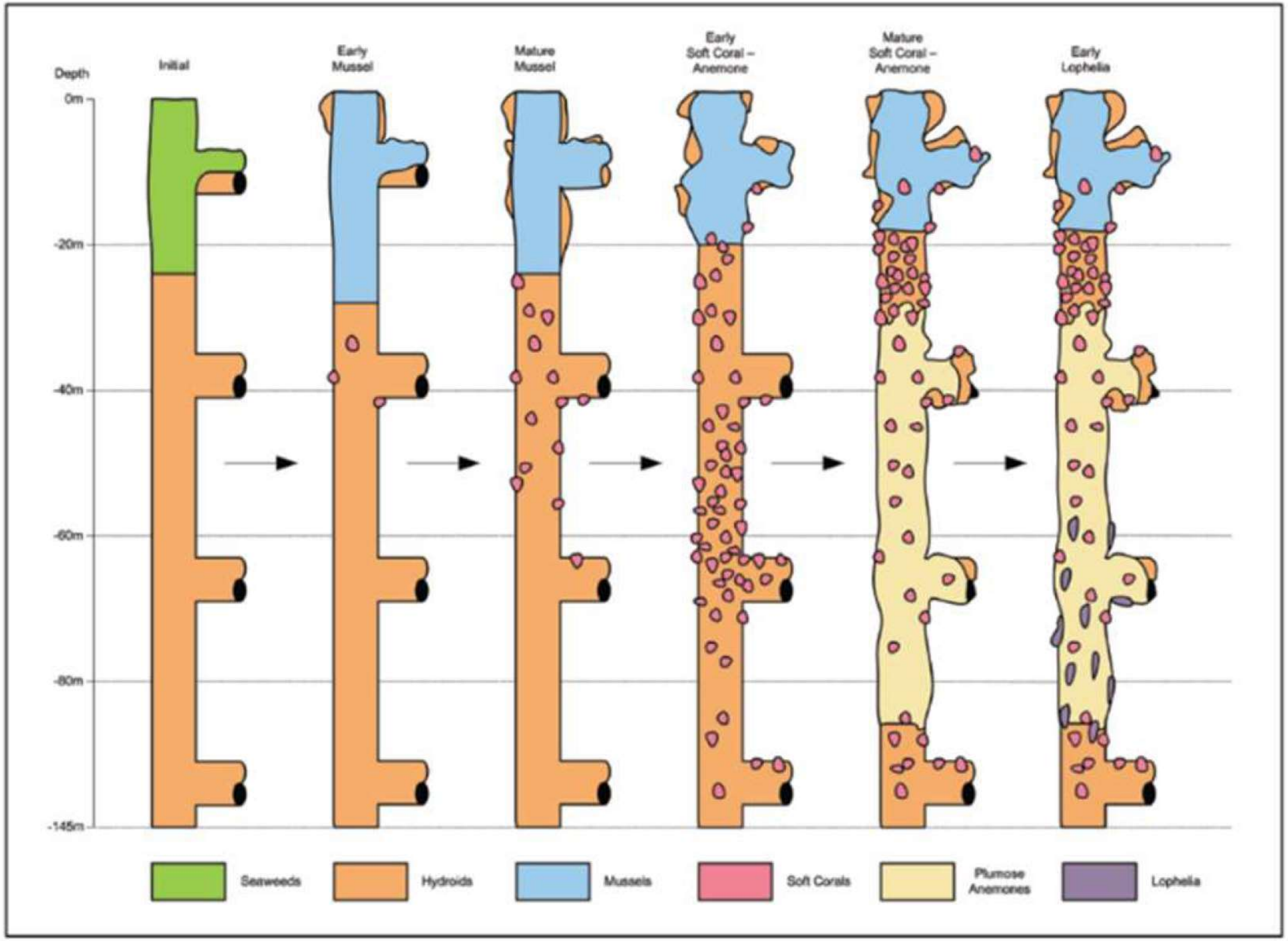
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Amphisbetia operculata* | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 |
| *Anomia ephippium* | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 |
| *Chirona hameri* | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| *Ciona intestinalis* | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| *Ectopleura larynx* | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 |
| *Fucus spiralis* | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 |
| *Metridium dianthus* | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 |
| *Mytilus edulis* | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 |
| *Saccharina latissima* | 🟥 | 🟥 | 🟥 | 🟥 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟥 | 🟥 | 🟥 |
| *Schizoporella japonica* | 🟥 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟥 |
| *Semibalanus balanoides* | 🟩 | 🟩 | 🟧 | 🟥 | 🟥 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

Periods of settlement associated with major fouling organisms at ORE test sites in Orkney. Months in red indicate the highest recognised settlement season, orange months are of intermediate concern, and green months are of least concern. Table updated from Want *et al*., 2017.

# Successional processes



Oct 2018; Jan 2019; Sept 2019 (Want *et al*. 2021)



(Sell, 1992)

# Impacts revisited:

DNV·GL

STANDARD

DNVGL-ST-0437 Edition November 2016

**Loads and site conditions for wind turbines**

"Unless more accurate data are available, the density of the marine growth may be set equal to 1325 kg/m$^3$."

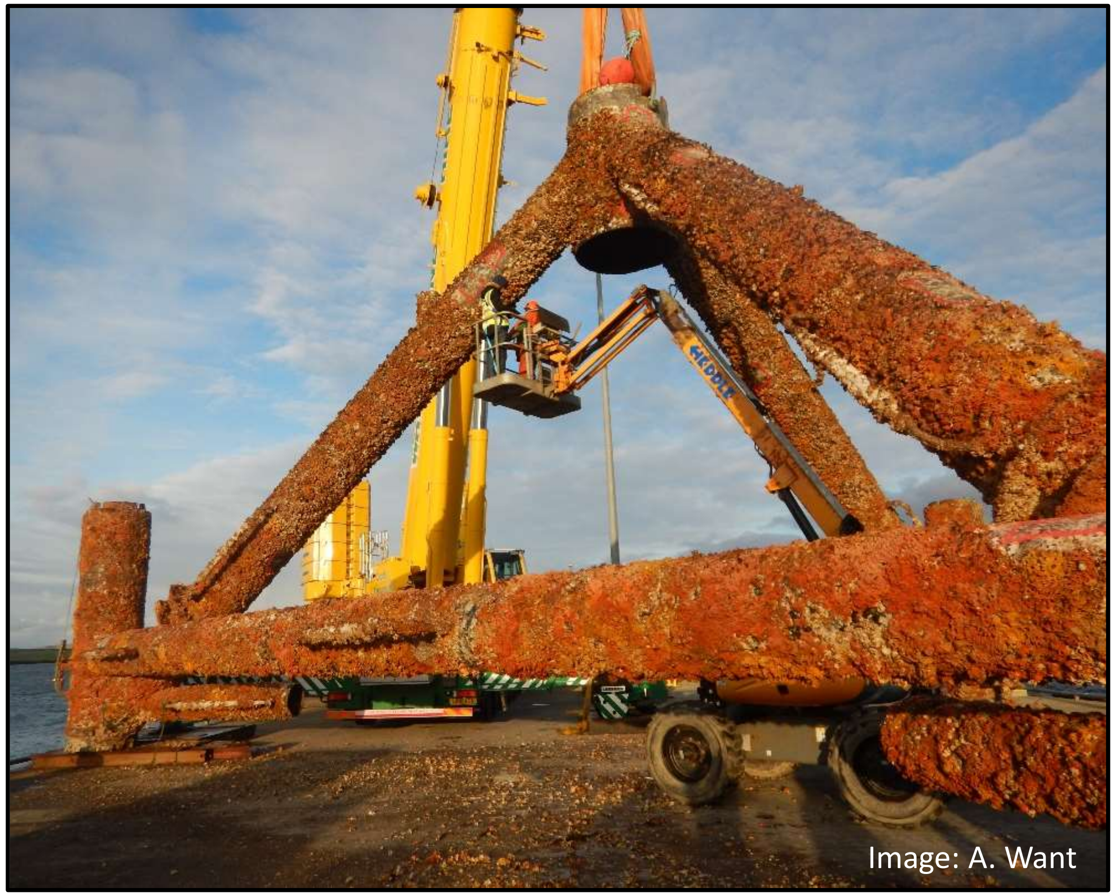
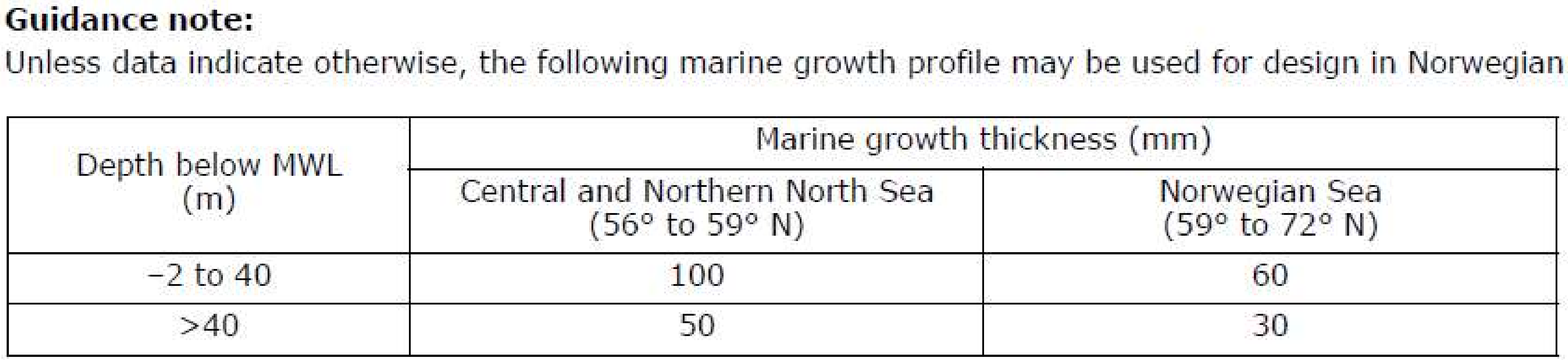


Image: A. Want



**Guidance note:**

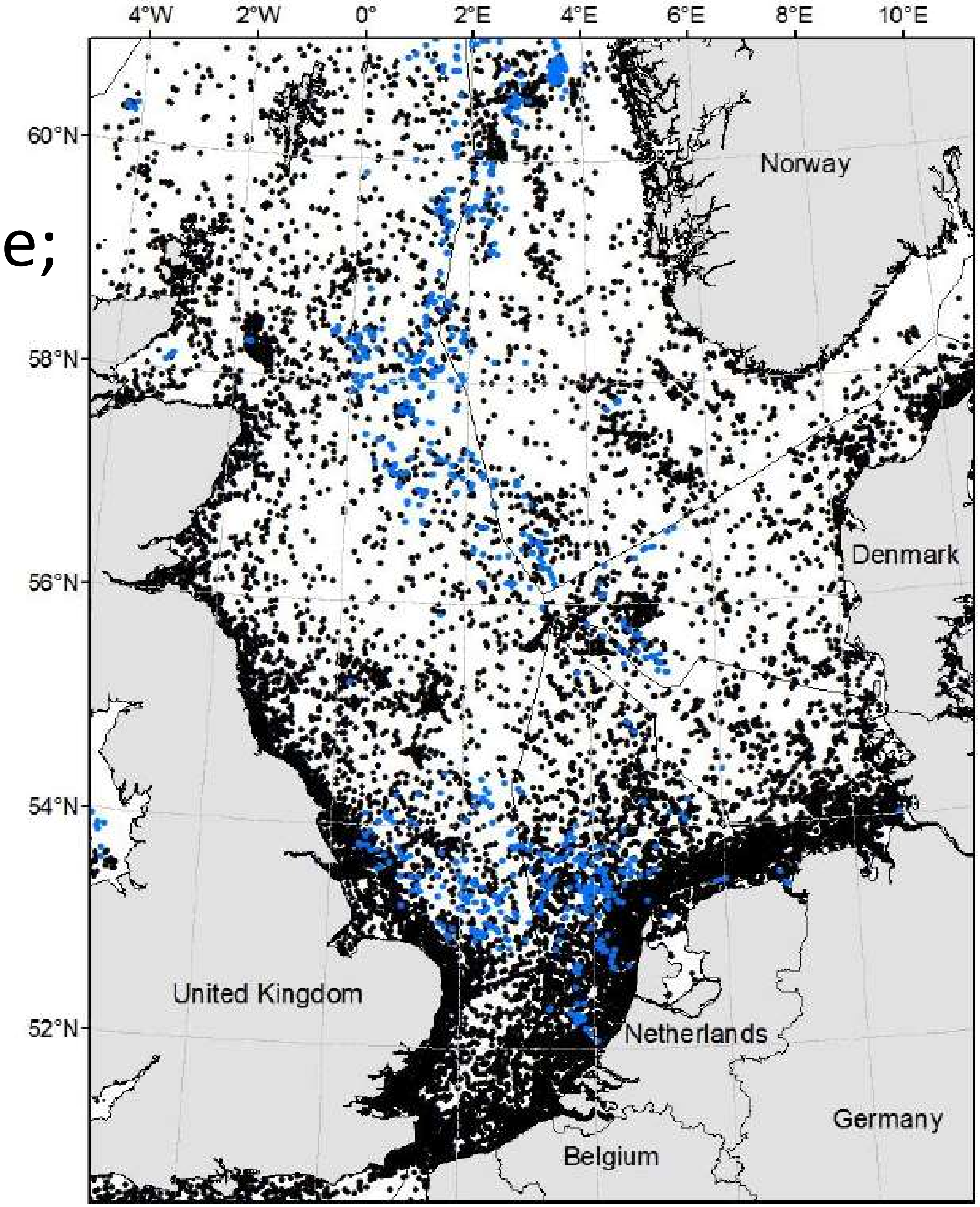
Unless data indicate otherwise, the following marine growth profile may be used for design in Norwegian and UK waters:

| Depth below MWL (m) | Marine growth thickness (mm) | |
|---|---|---|
| | Central and Northern North Sea (56° to 59° N) | Norwegian Sea (59° to 72° N) |
| −2 to 40 | 100 | 60 |
| >40 | 50 | 30 |

# What are the ecological impacts of substrate/habitat provision?

- Enhanced biodiversity: more and varied substrate; formation of biogenic reef/turf communities
- Devices may create ‘stepping stones’, facilitating population connectivity; ‘good’ vs ‘bad’?
- Service vessels may also increase risk of transfer of invasive, non-native species (INNS), i.e. biosecurity


Image: O. Dugornay - IFREMER



North Sea wrecks and O&G Installations
From: Coolen *et al*. 2019

# Invasive Non-native Species (INNS): Orkney


Image: A. Want


Image: A. Want


Image: Kate Willis

- *Corella eumyota* – Kirkwall Marina
- *Schizoporella japonica* – Hatston Pier
- *Caprella mutica* – Stromness Marina
- … and several others

Note: no INNS have been recorded at full-scale ORE sites in Orkney…

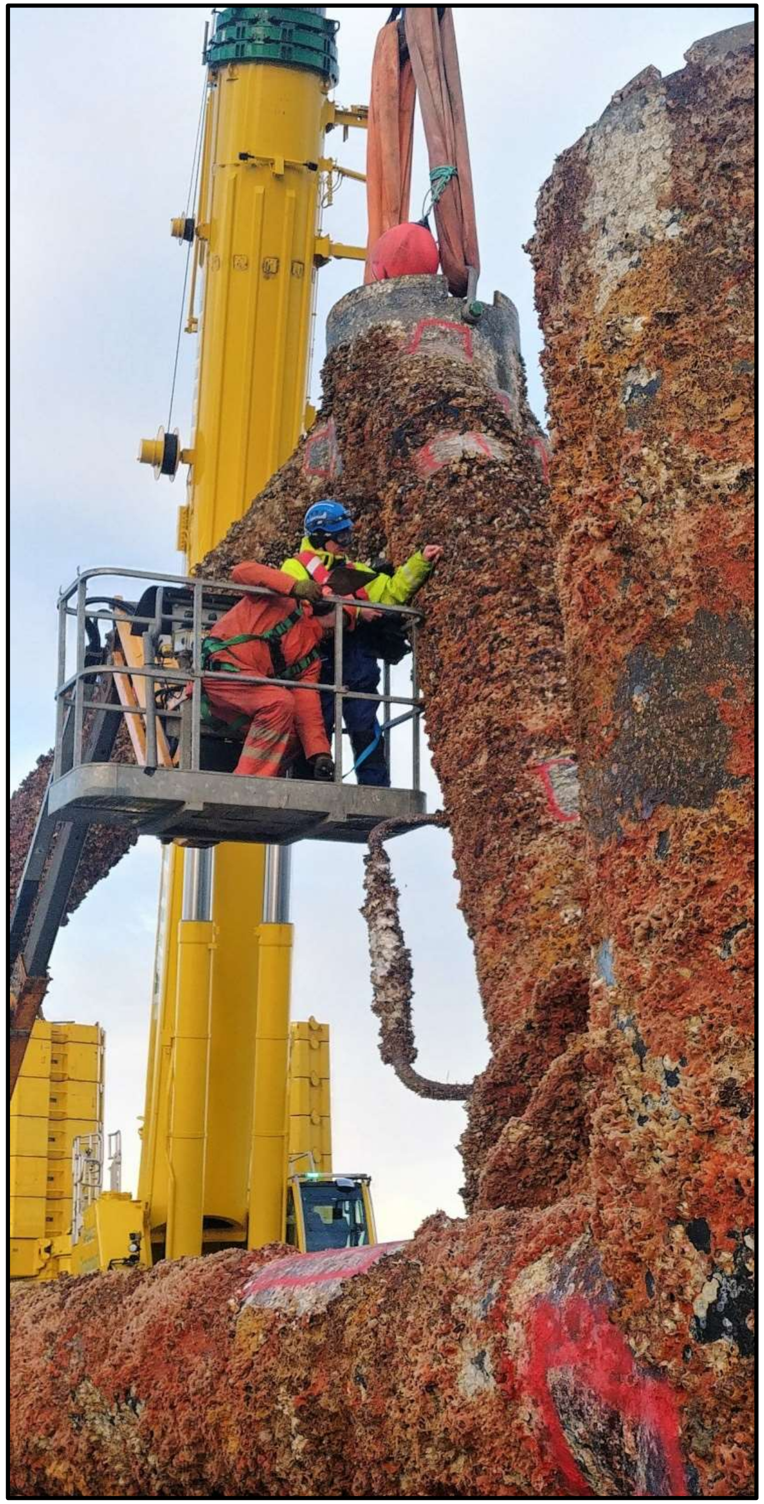
Knowledge gaps exist concerning the fouling communities:

- Energy-rich locations targeted by ORE
- Materials and 'niche' areas associated with novel technologies
- Biofouling characterisation of less studied waters throughout the globe
- Overall risk assessment of the potential role of ORE in INNS transmission

GloFouling PARTNERSHIPS

Questions?

a.want@hw.ac.uk



# 2.3. Internal Chemistry in Monopiles

## Niek Briunsma and Stefan Jansen (Deltares)

Deltares

# Deltares in offshore wind

## Corrosion Protection and water and air replenishment

Niek Bruinsma

# Corrosion in offshore wind: Mitigation inside offshore structures

- Coatings
- internal cathodic protection systems
  - Sacrificial anodes (Zink or Aluminum alloy SACP)
  - Impressed Current Corrosion Protection (ICCP)

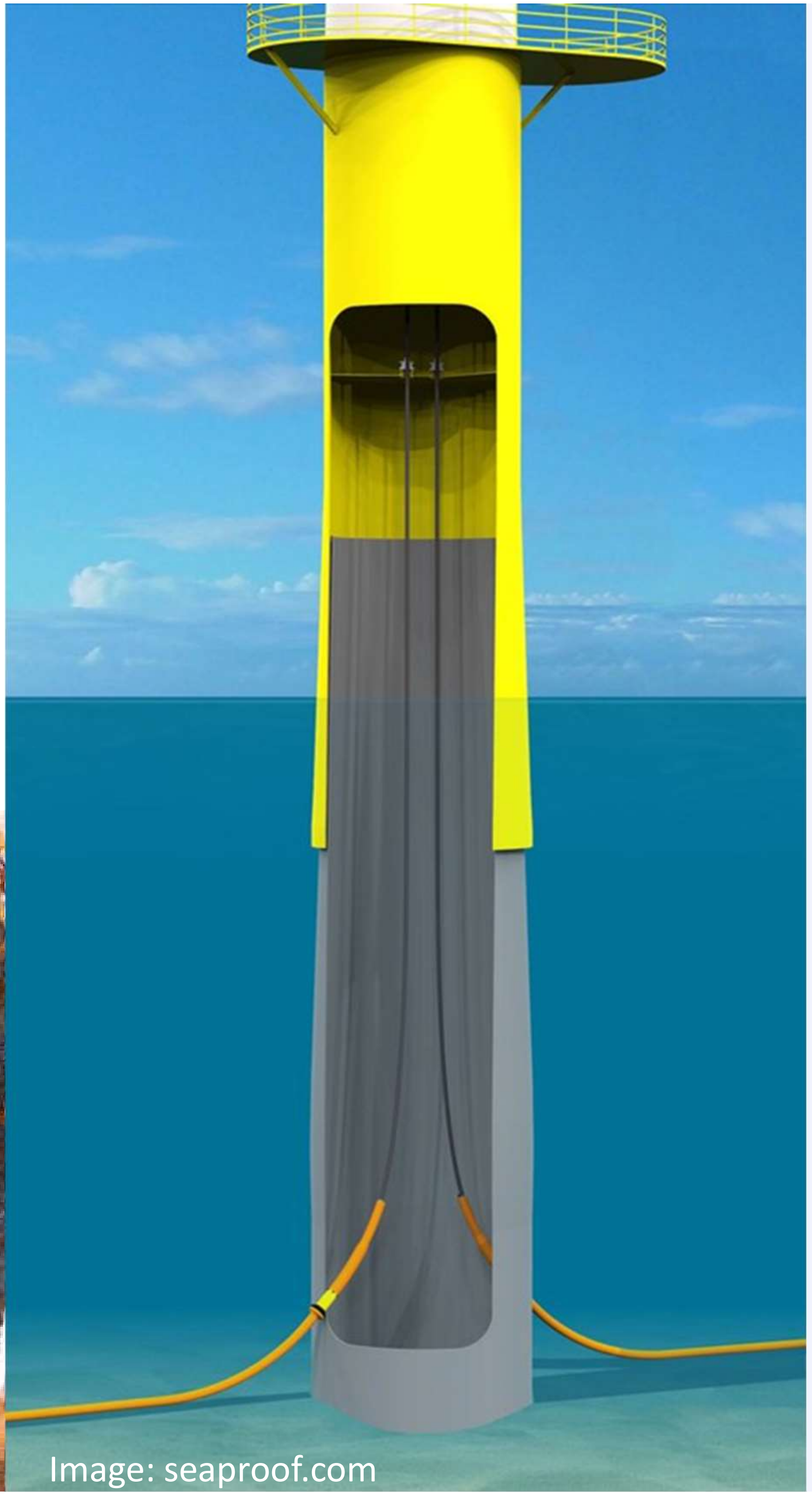


Image: seaproof.com

# Corrosion in offshore wind: Mitigation inside offshore structures

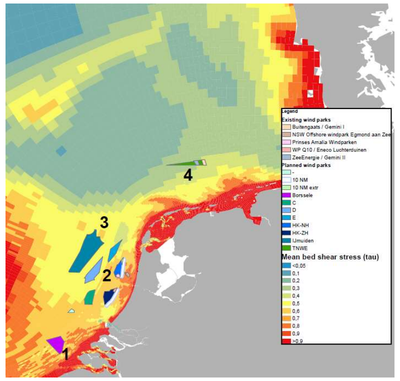
- Coatings
- internal cathodic protection systems
  - Sacrificial anodes (Zink or Aluminum alloy SACP)
  - Impressed Current Corrosion Protection (ICCP)

**Can we make this into a Nature Inclusive Design?**

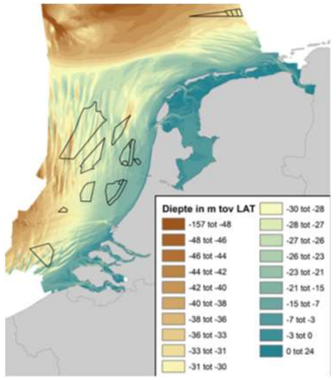
  - limitation of large-scale impacts (e.g. noise)
  - historical species restoration (e.g. oysters in North Sea)
  - biodiversity enhancement (e.g. increase in biomass)

Model/measuer: sediment composition, historic species concentrations, oxygen levels and depletion periods, predators, food availability, flow velocity/direction, species competition, etc…

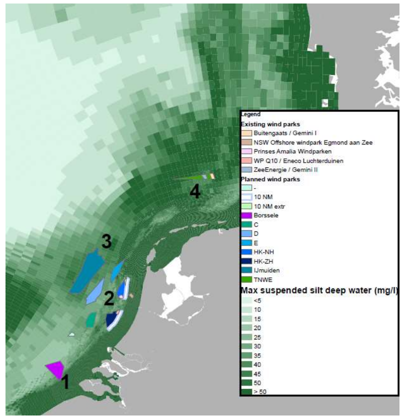
bed shear stress



water depth

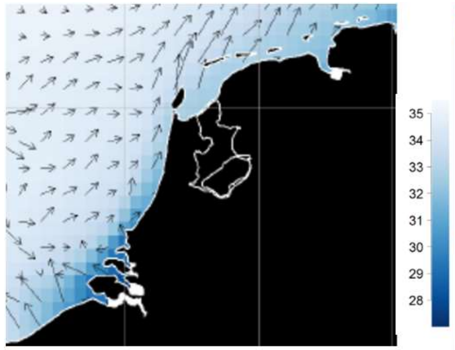


SPM

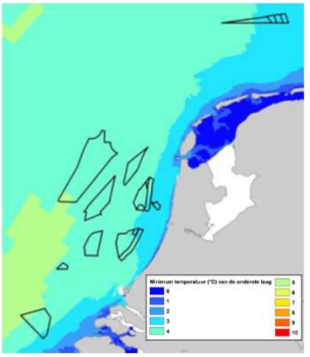


area use

salinity



temperature



# Corrosion protection systems inside monopiles

## Internal cathodic protection side effects:

- SACP: Zn or Al emissions
- ICCP: pH drop & gas formation (e.g., chlorine, bromine)

| Element | Typical Composition Open Sea Water 35% Salinity (ppm) [2]. | Typical Composition Open Sea Water Outside Nearby monopile (ppm) | Composition in trial position Internal Surface (ppm) |
|---|---|---|---|
| Chloride ($Cl^-$) | 19,353 | 17,900 | 18,700 |
| Sodium ($Na^+$) | 10,760 | 10,250 | 10,100 |
| Sulfate ($SO_4^{2-}$) | 2,712 | 2,830 | 2,440 |
| Magnesium ($Mg^{2+}$) | 1,294 | 983 | 1,210 |
| Calcium ($Ca^{2+}$) | 413 | 469 | 566 |
| Potassium ($K^+$) | 367 | 650 | 506 |
| Bicarbonate($HCO_3^-$) | 142 | 154 | 55 |
| Strontium ($Sr^{2+}$) | 8 | Not Measured | Not Measured |
| Bromide ($Br^-$) | 67 | 71.6 | 64 |
| Borate ($BO_3^{3-}$) | 4 | Not Measured | Not Measured |
| Fluoride ($F^-$) | 1 | 1 | ND |
| Conductivity $mScm^{-1}$ 25°C | 47.8 | 53.0 | 52.2 |
| pH | 8.1 to 8.3 | 8.0 | 8.0 |
| Total Dissolved Solids | 35,000 | Not Measured | Not Measured |

Delwiche, 2017

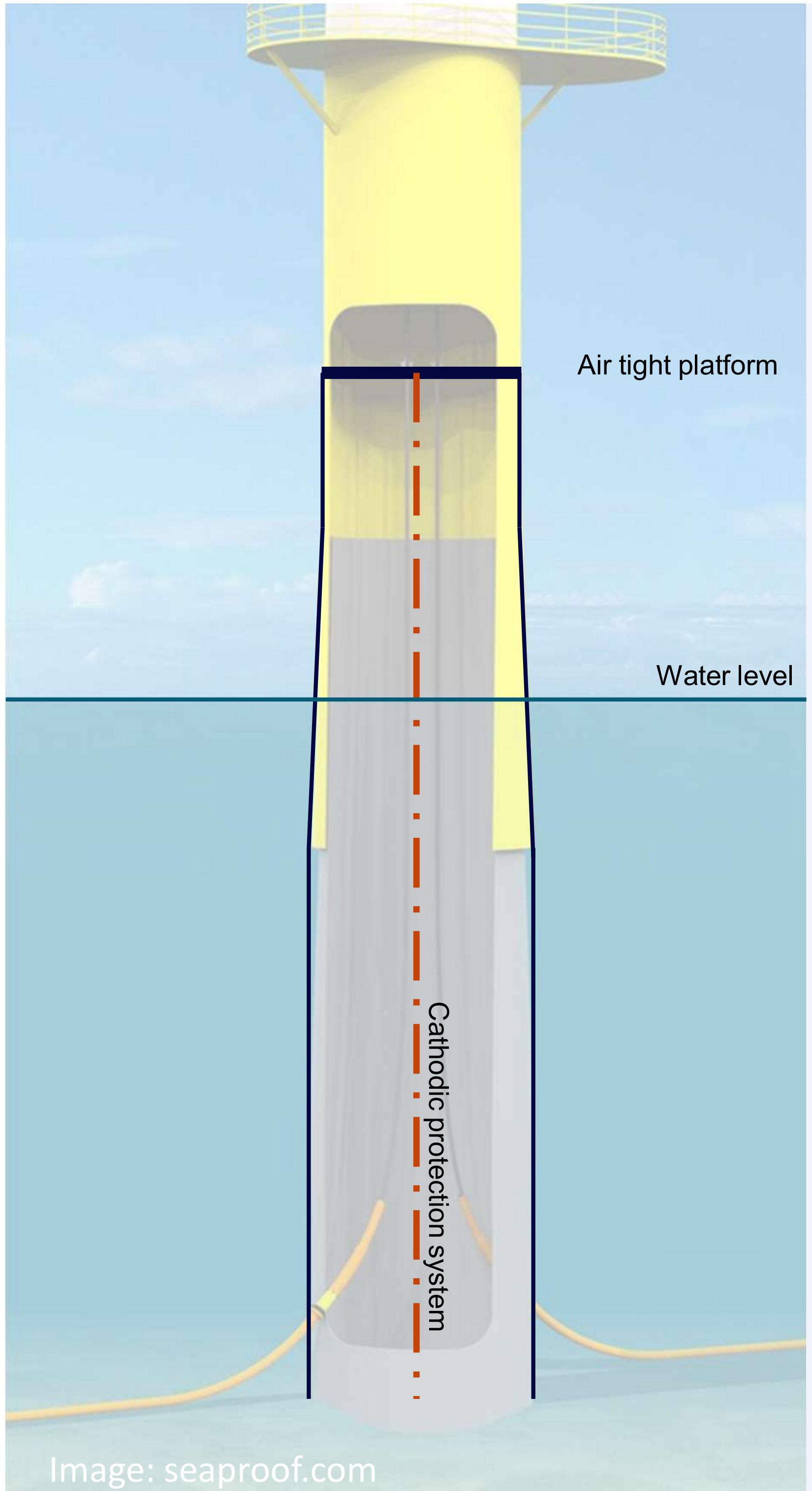


Image: seaproof.com

# Corrosion protection systems inside monopiles

**Internal cathodic protection side effects:**

- SACP: Zn or Al emissions
- ICCP: pH drop & gas formation (e.g., chlorine, bromine)

*Obtaining local measurement data can be a challenge*

**Oxygen** → ‘Closed’ interior: depletion of oxygen? Potential consumption near seafloor or local anaerobic niches

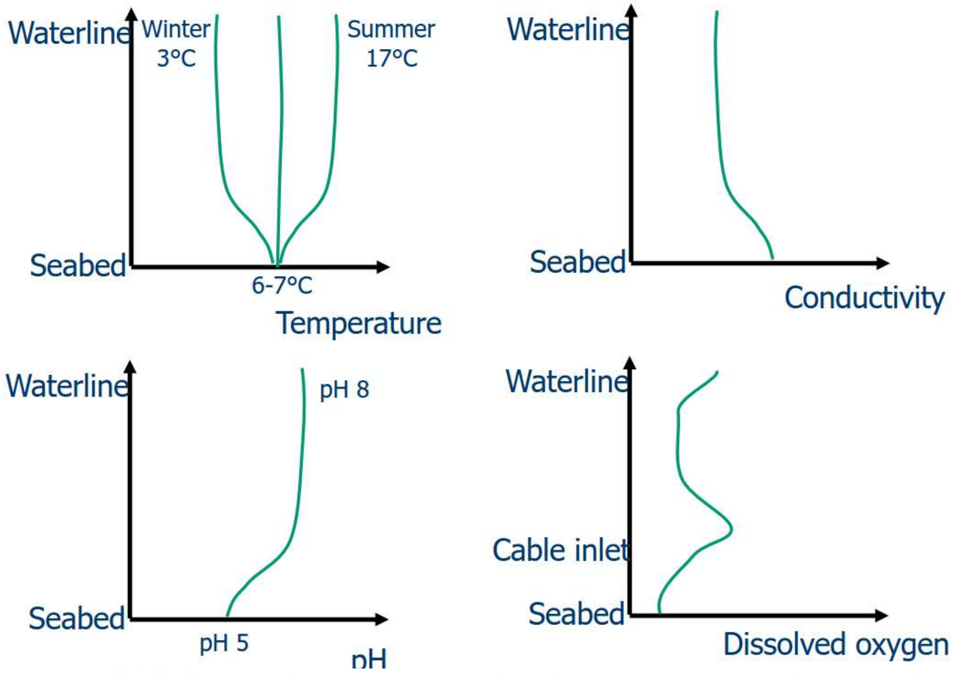
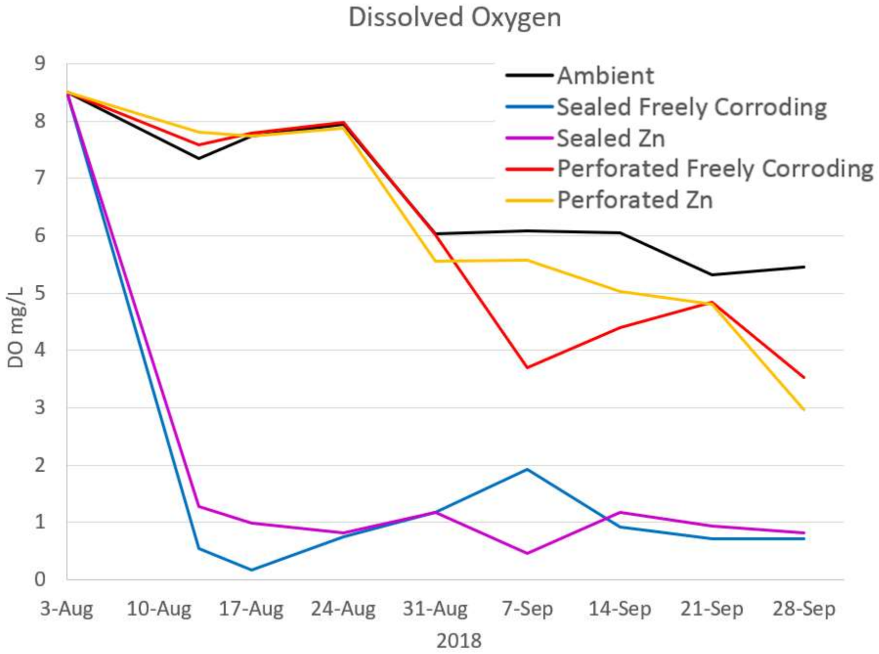


**FIGURE 13:** Trends observed using a drop-cell rack for environmental monitoring inside monopiles.

Mathiesen, 2015



Maher Monica M. Geoffrey Swain (2019) Corrosion control and ecosystem enhancement for offshore monopiles, Materials Performance. pp. 28-33, August 2019

# Microbiology inside monopiles

- Different niches:
    - Aerobic/anaerobic
    - Seawater/sediment/sand
    - Steel surface
- Sulphate reducers, methanogens, sulphur oxidizers, iron oxiders, algae, etc, etc…

*Biofilm from steel coupon from laboratory seawater reactor*

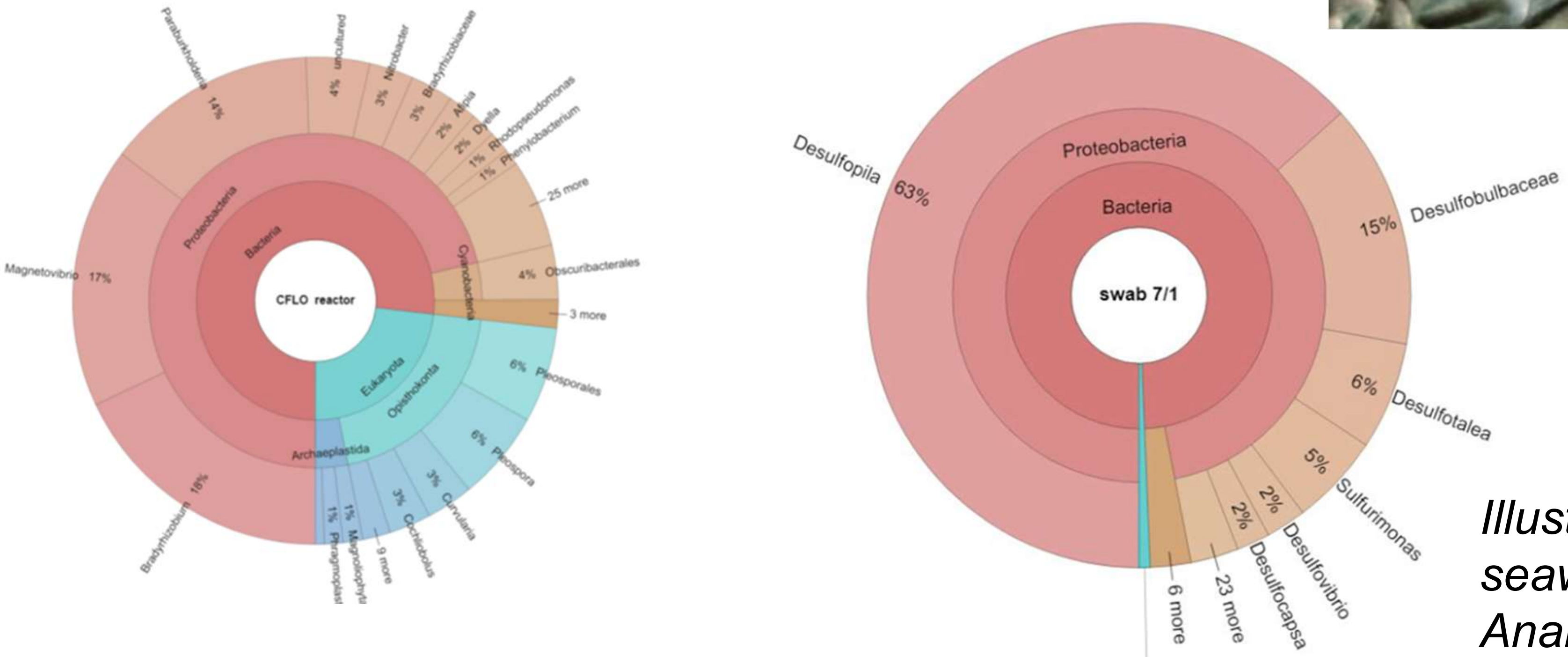


*Illustration of microbiological diversity in seawater reactor and biofilm. (Microbial Analysis)*

# Water and air replenishment systems

**Replenishment of air and water:**

- Air and water replenishment holes
- Unsteady marine environment (waves, tide, current)
- Enclosed water (internal free surface elevation)
- Biological activity (effect of marine growth)

➢ *Optimize through replenishment and water quality modelling*

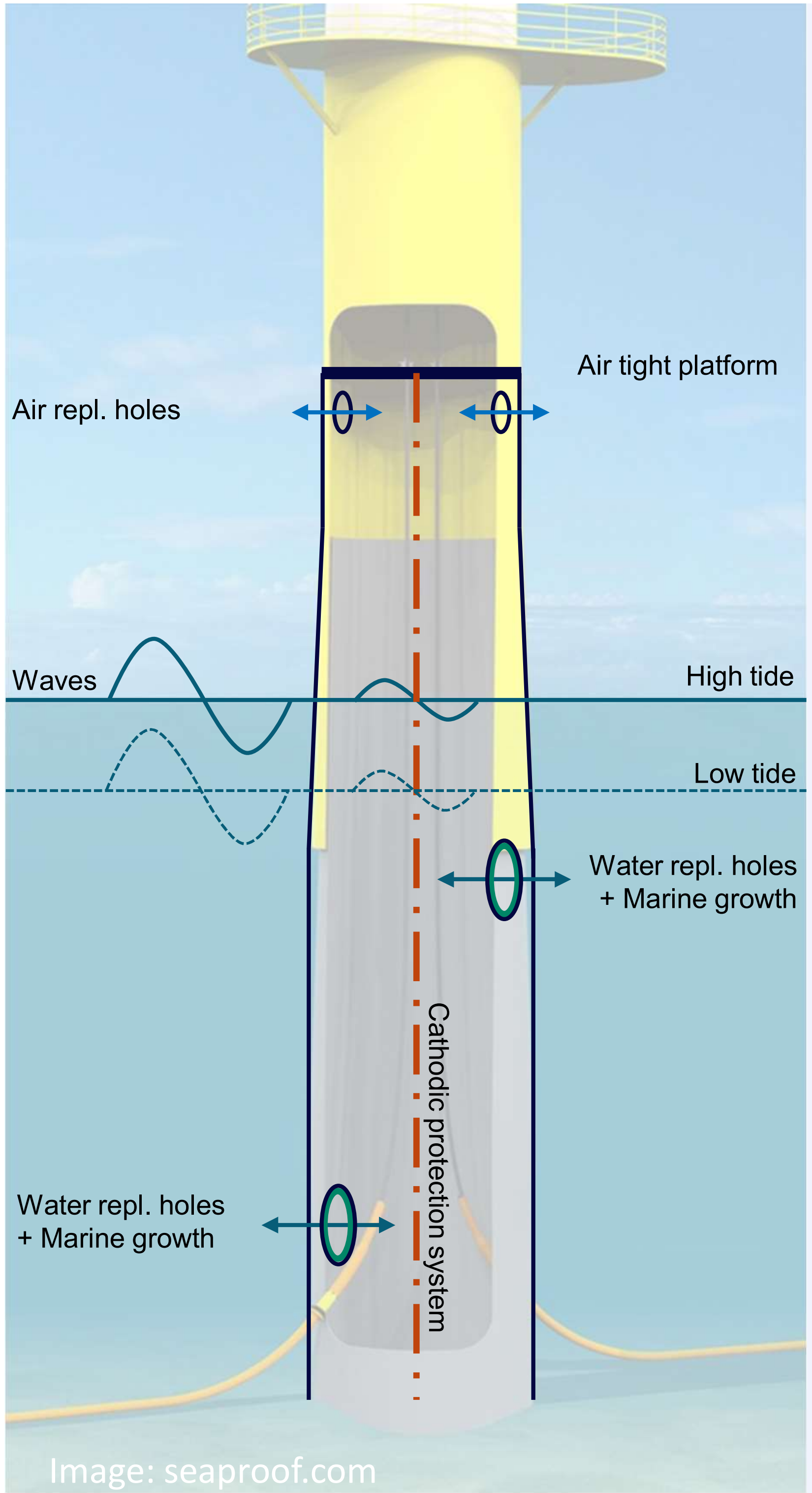
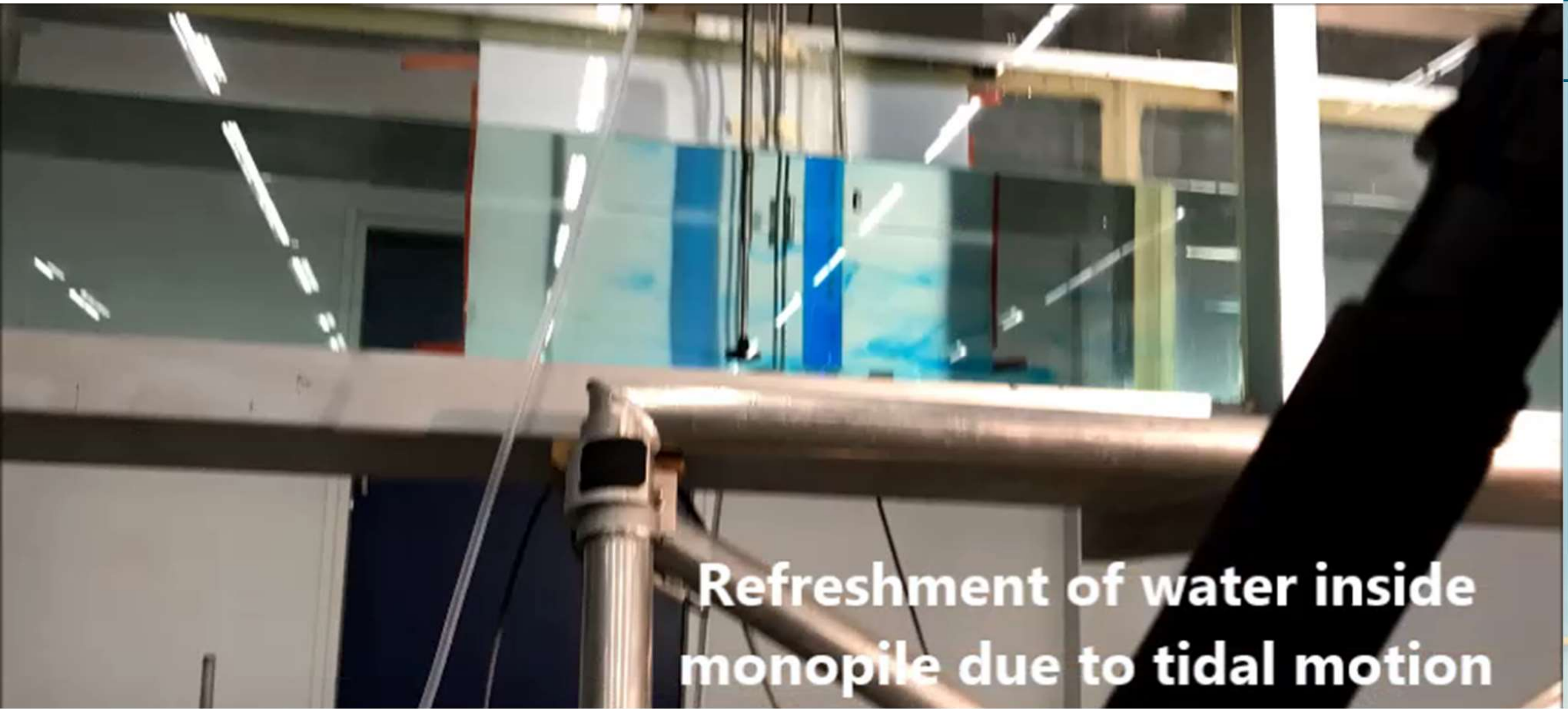


Image: seaproof.com

Deltares

# Modelling optimisation CP systems: hydrodynamics

- Water replenishment from waves and tide
- Internal wave response
- Flow velocities and mixing
- Investigate the effect of marine growth



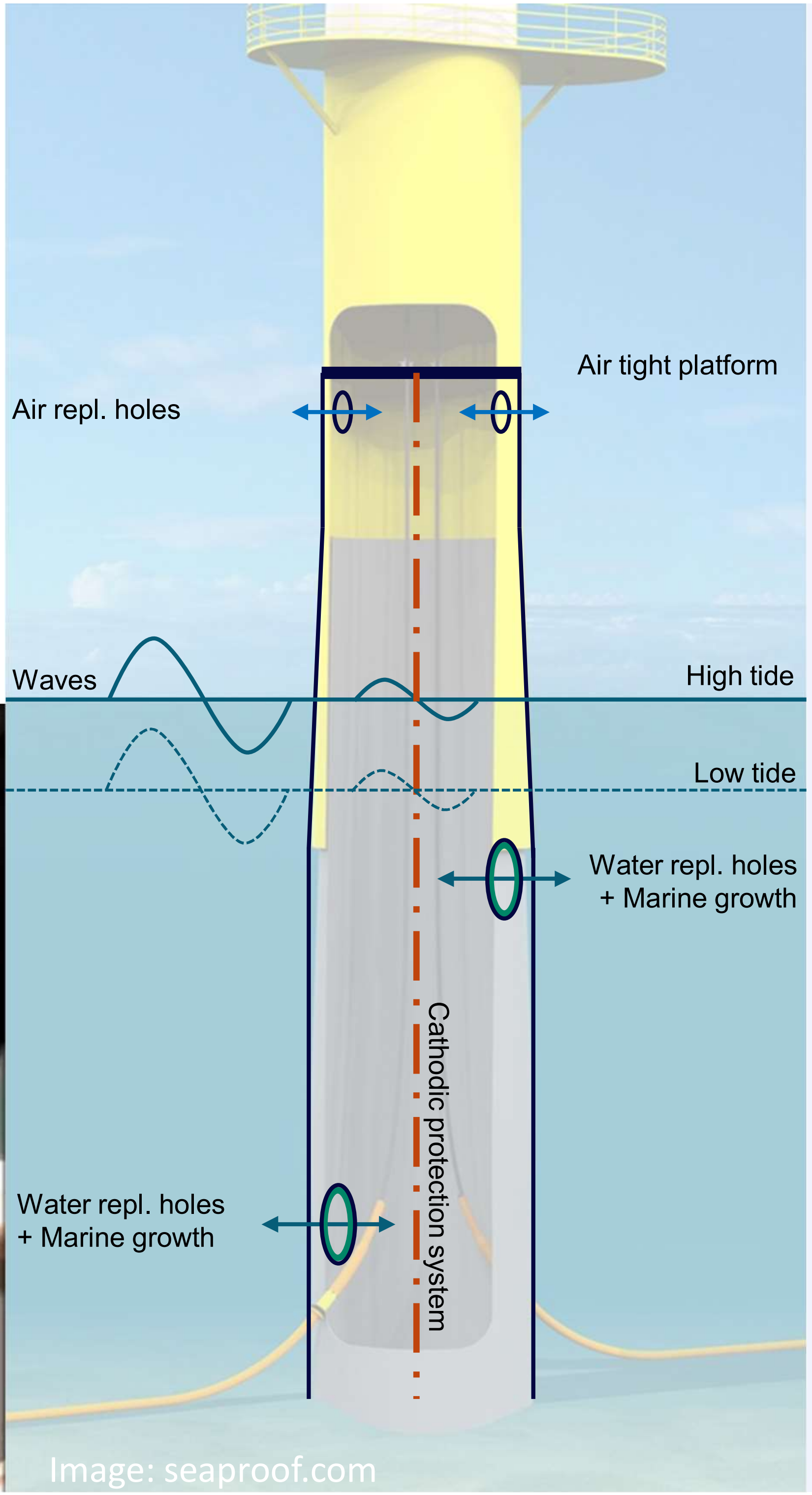
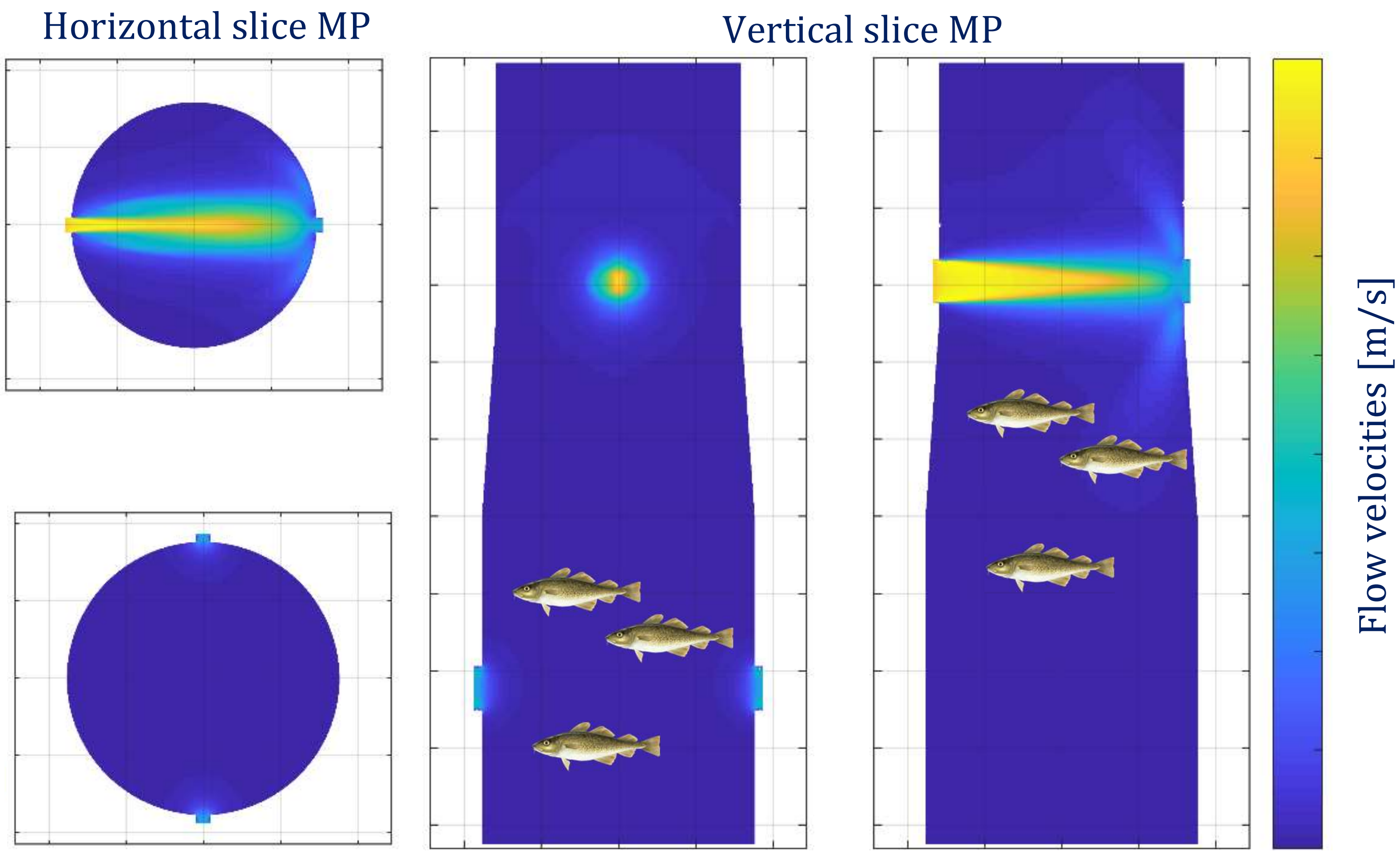
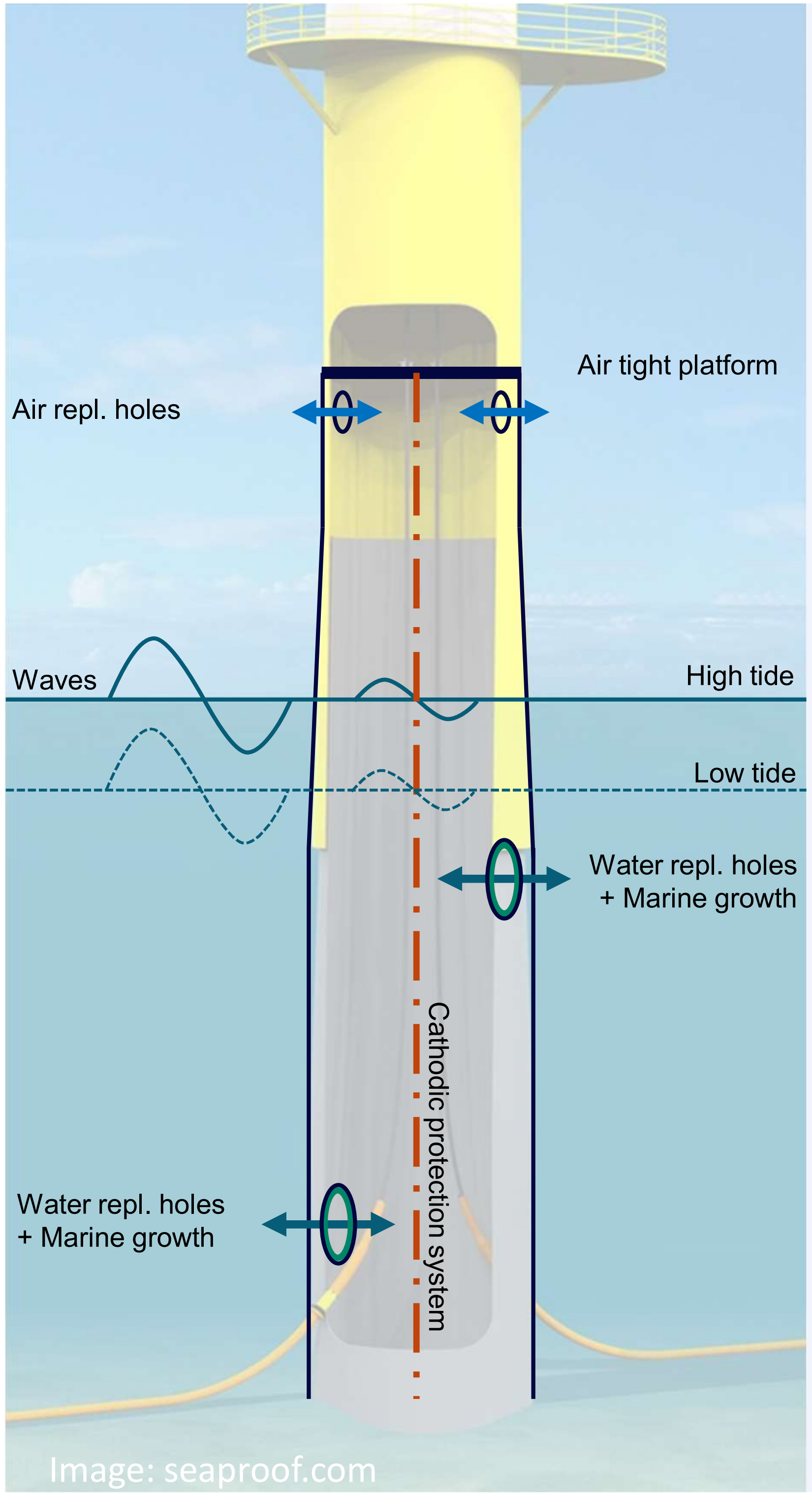


Image: seaproof.com

# Modelling optimisation CP systems: Detailed CFD modelling

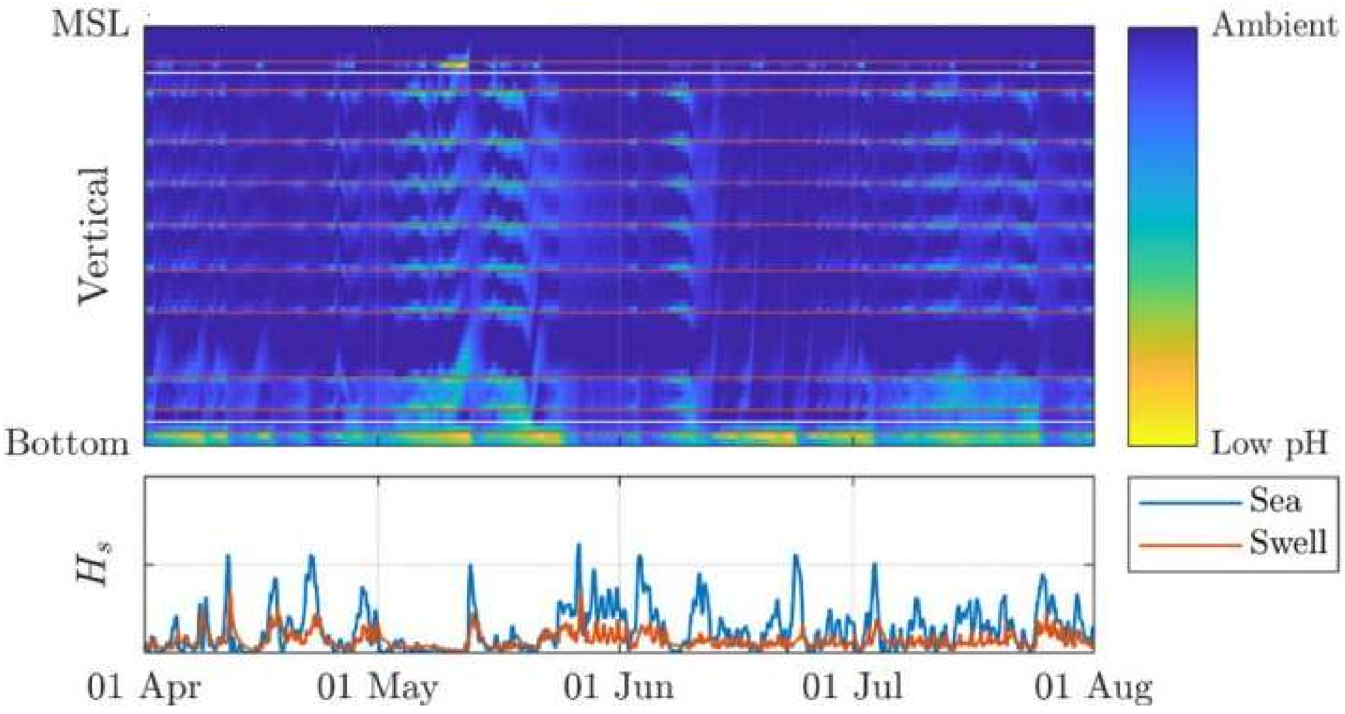
- Investigation of flow velocities through holes → jet flows
  - Inside water column and the air volume





# Modelling optimisation CP systems: Water quality model - DELWAQ

- DELWAQ: Deltares in-house water quality model, for detailed investigations of the water chemistry:
  - pH, dissolved oxygen, etc.
  - The effect of the hydrodynamic forcing
  - Location of water replenishment holes and of CP anodes.



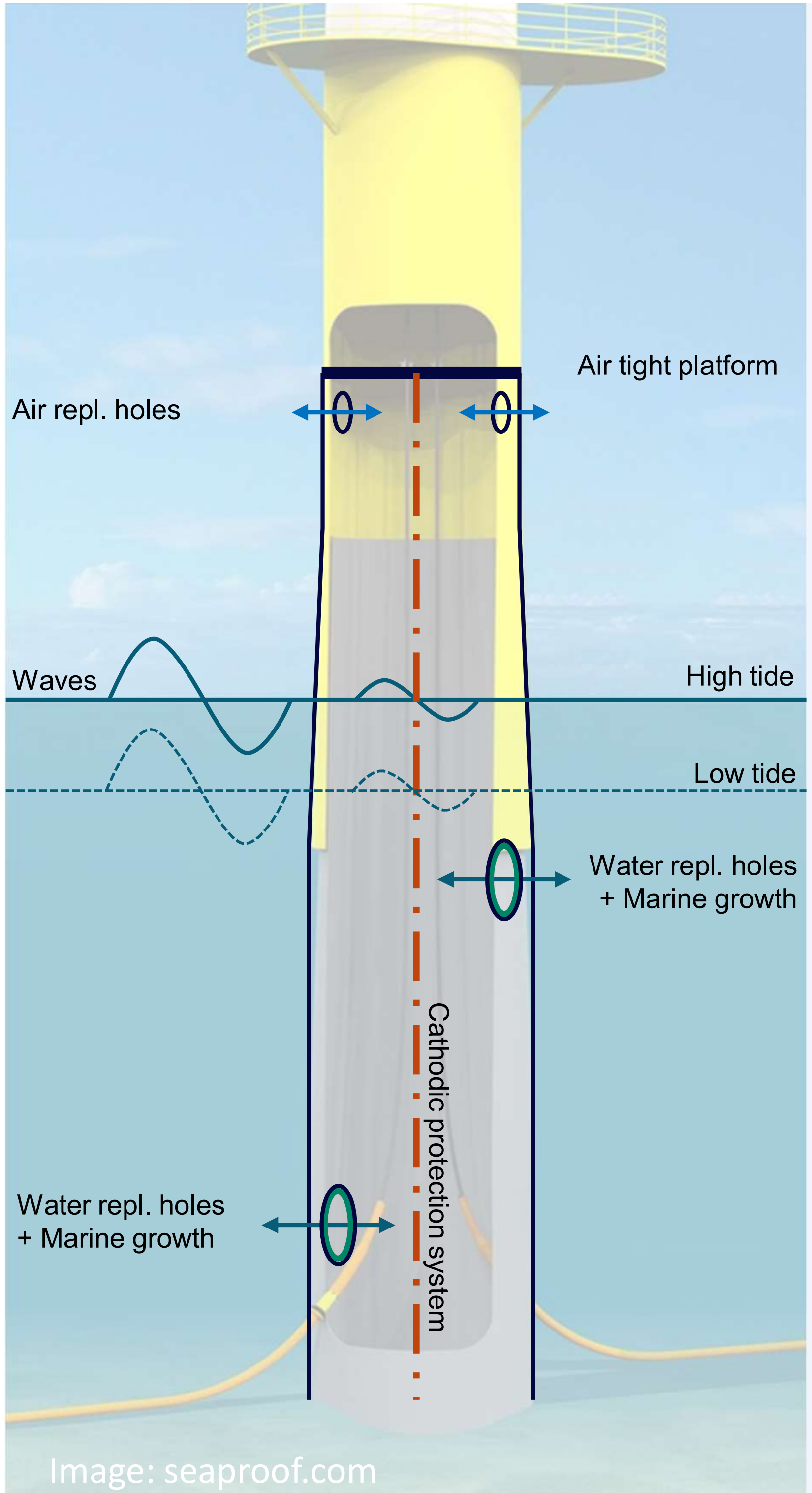


Image: seaproof.com

Deltares

# Modelling optimisation CP systems: Water quality model - DELWAQ

- DELWAQ: Deltares in-house water quality model, for detailed investigations of the water chemistry:
  - pH, *dissolved oxygen*, etc.
  - The effect of the hydrodynamic forcing
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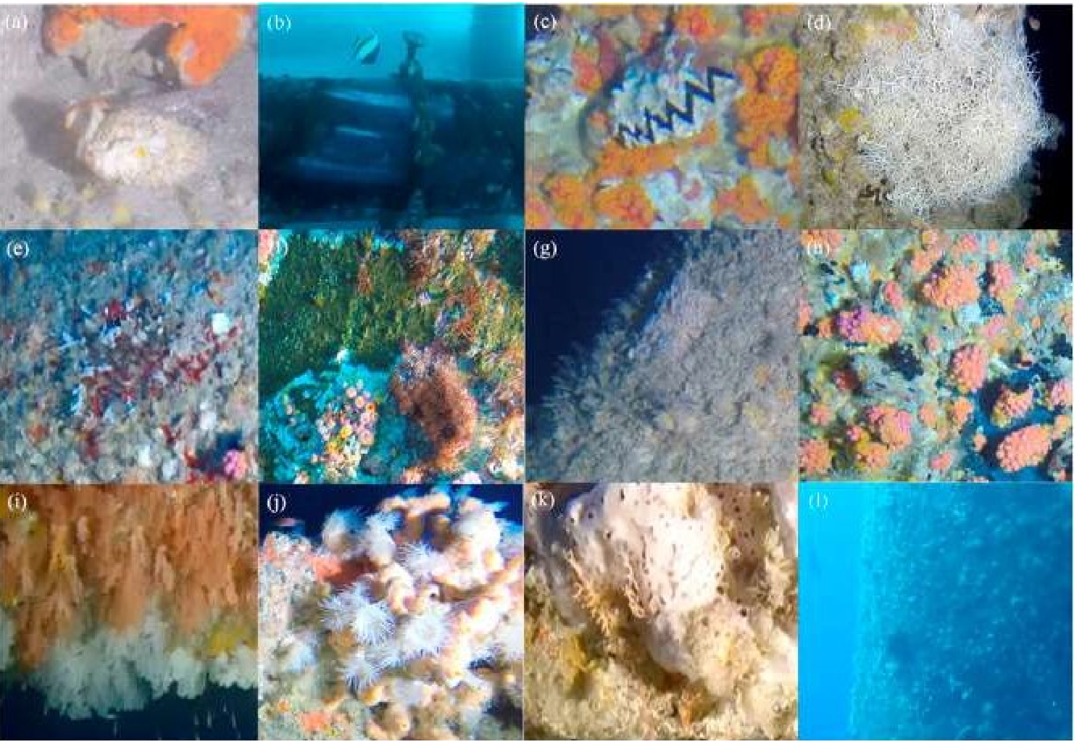


*Oxygen – variable over time*

- affected by marine growth clogging up holes
- Oxygen demand inside
  - Species biomass and composition will change over time (i.e. oxygen uptake varies)
  - Build-up of organic material → increased oxygen demand bacteria

*Image: McLean et al 2019*

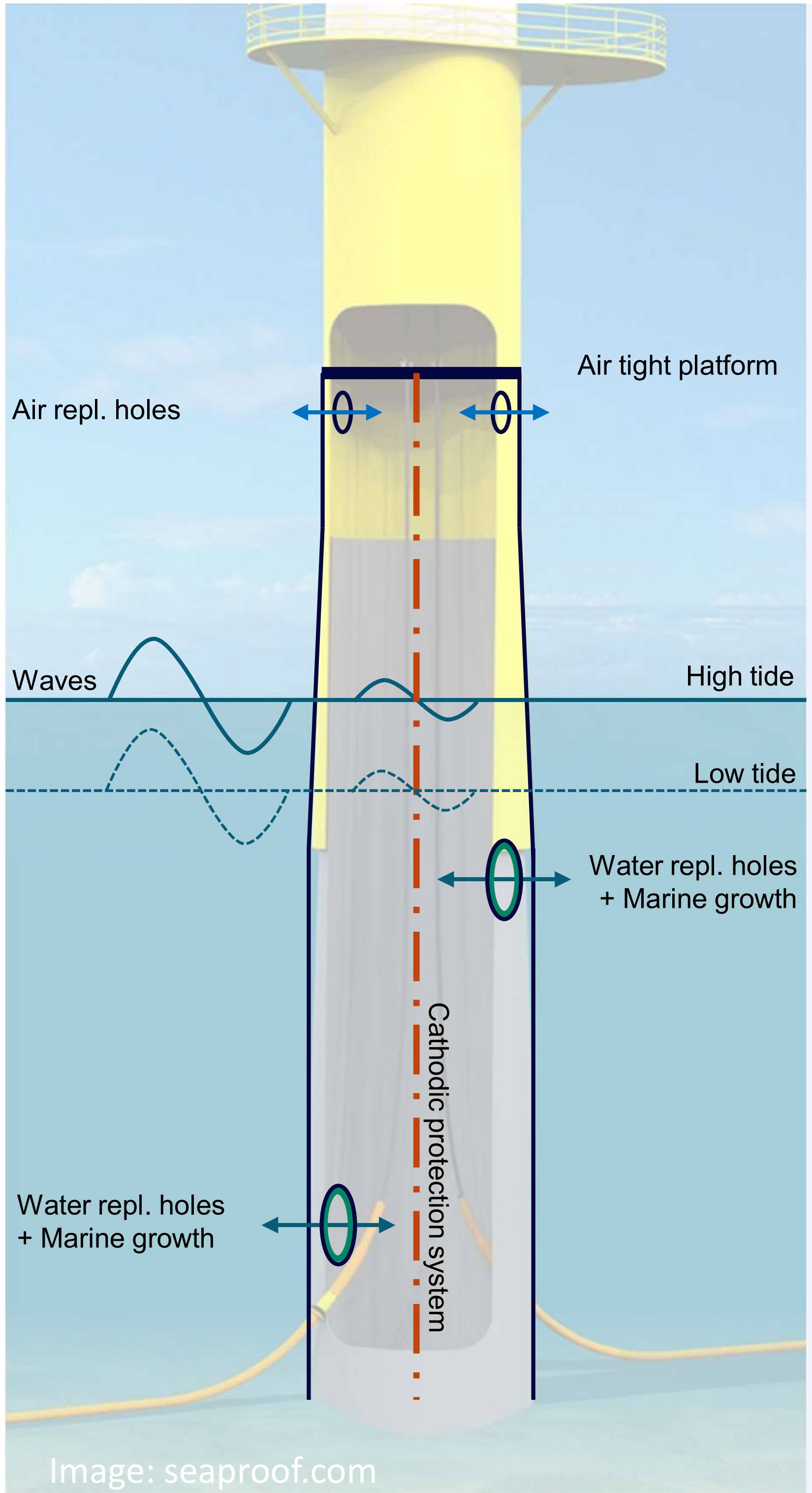


Image: seaproof.com

# Discussion and next steps

**What do we have**

- Water and air replenishment model (validated with model experiments)
- Water quality model (DELWAQ)

**What do we know**

- Water and air replenishment and resulting pH and gas concentration
- Velocities in air and water replenishment holes and pressure buildup
- There are opportunities for system optimization and retrofitting

**What would we like to improve**

- *Field validation of the hydrodynamic and water quality models*
- *Field measurements of marine habitat and effect of marine growth*
- ICCP effectiveness in different environmental conditions and optimizing power consumption
- Risk mitigation by further optimizing the ICCP and water replenishment systems

# Thank you for your attention!

Niek.bruinsma@deltares.nl

# 2.4. Interactions between Marine Growth and Internal Water Chemistry

Geoff Swain (Florida Tech.)

Center for Corrosion
and
Biofouling Control

# Managing the Interactions between Marine Growth and Internal Water Chemistry

Geoff Swain, Caglar Erdogan and Monica Maher

## How do we perceive marine growths and associated fauna?

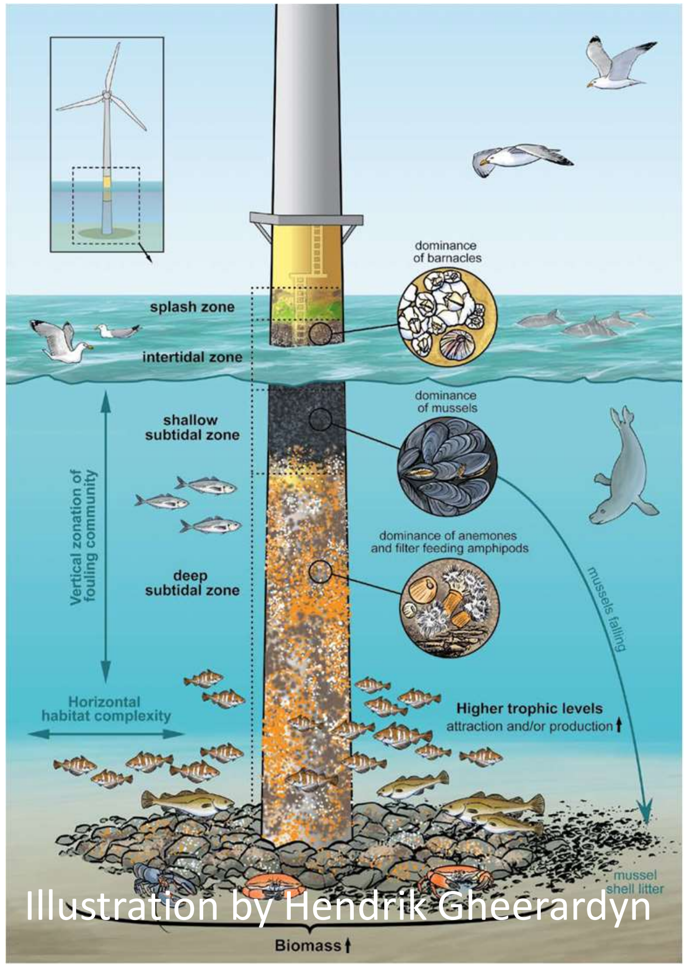


Illustration by Hendrik Gheerardyn

- Biofouling:
  - Design to reduce and control
- Ecology
  - Design to enhance and nurture
- Mariculture
  - Design to be species specific

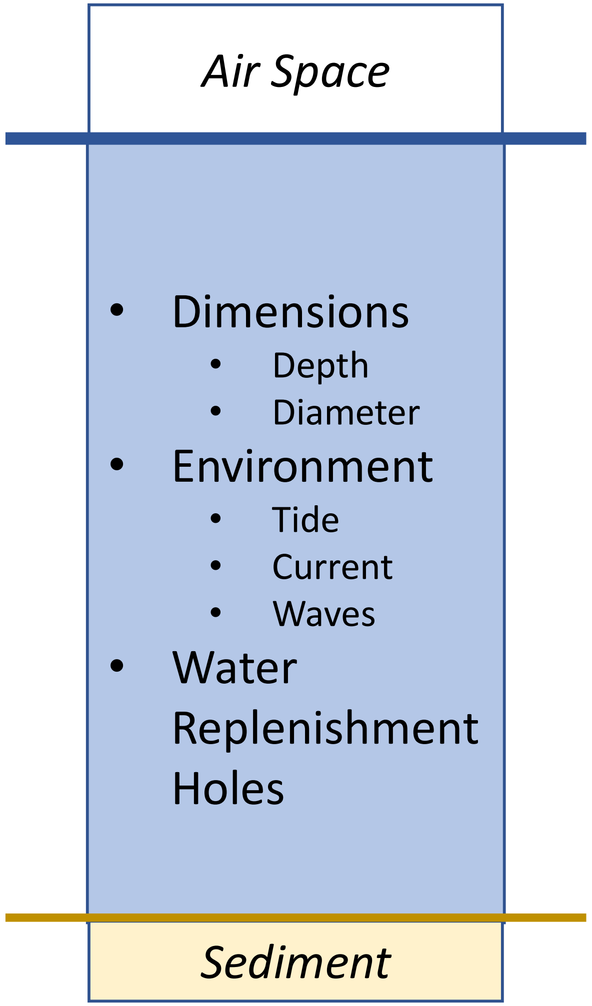

*Mytilus edulis*


*Lophelia pertusa*


*Mytilus edulis*

# Factors that Influence the Internal Space

- Monopile

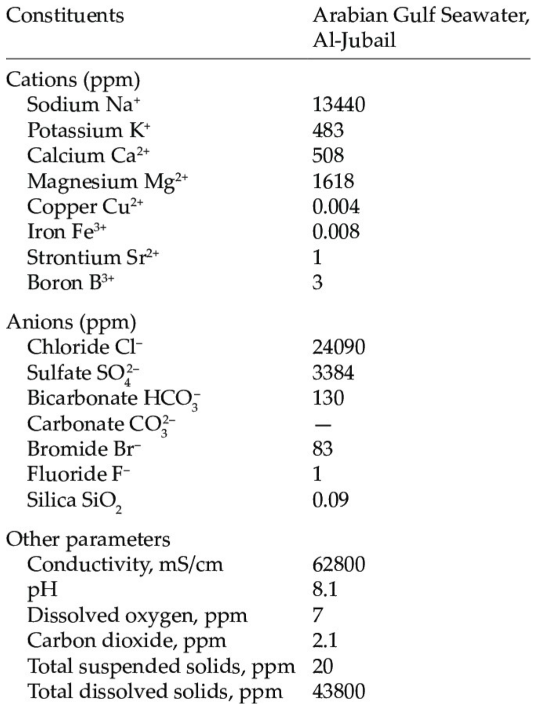


*Air Space*

- Dimensions
    - Depth
    - Diameter
- Environment
    - Tide
    - Current
    - Waves
- Water Replenishment Holes

*Sediment*

- Chemistry

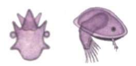


| Constituents | Arabian Gulf Seawater, Al-Jubail |
|---|---|
| Cations (ppm) | |
| Sodium $Na^+$ | 13440 |
| Potassium $K^+$ | 483 |
| Calcium $Ca^{2+}$ | 508 |
| Magnesium $Mg^{2+}$ | 1618 |
| Copper $Cu^{2+}$ | 0.004 |
| Iron $Fe^{3+}$ | 0.008 |
| Strontium $Sr^{2+}$ | 1 |
| Boron $B^{3+}$ | 3 |
| Anions (ppm) | |
| Chloride $Cl^-$ | 24090 |
| Sulfate $SO_4^{2-}$ | 3384 |
| Bicarbonate $HCO_3^-$ | 130 |
| Carbonate $CO_3^{2-}$ | — |
| Bromide $Br^-$ | 83 |
| Fluoride $F^-$ | 1 |
| Silica $SiO_2$ | 0.09 |
| Other parameters | |
| Conductivity, mS/cm | 62800 |
| pH | 8.1 |
| Dissolved oxygen, ppm | 7 |
| Carbon dioxide, ppm | 2.1 |
| Total suspended solids, ppm | 20 |
| Total dissolved solids, ppm | 43800 |

- Biology

Location

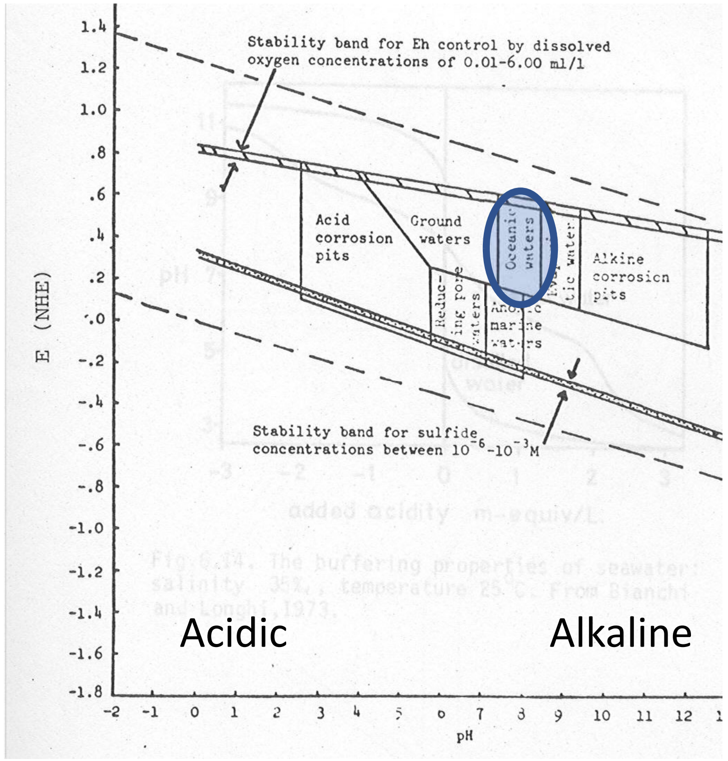
Season

| **Time** | **Event** | **Illustration** |
|---|---|---|
| Minutes | Organic Films |  |
| Hours | Bacteria |  |
| Days | Diatoms<br>Low Form Algae |  |
| Weeks | Macroalgae<br>Barnacles,<br>Bryozoans,<br>Tubeworms, |  |
| Months | Mussels,<br>Oysters,<br>Sponges<br>Kelp |  |

- Corrosion

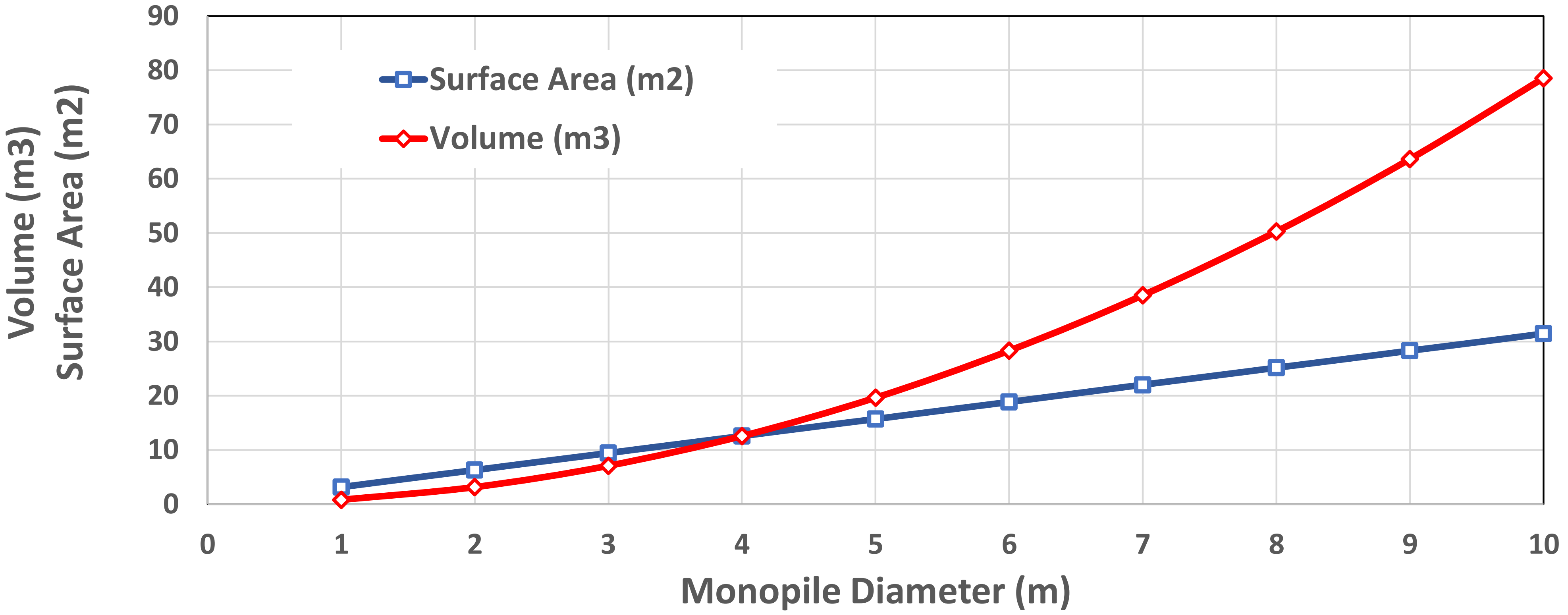
Coatings

Cathodic Protection



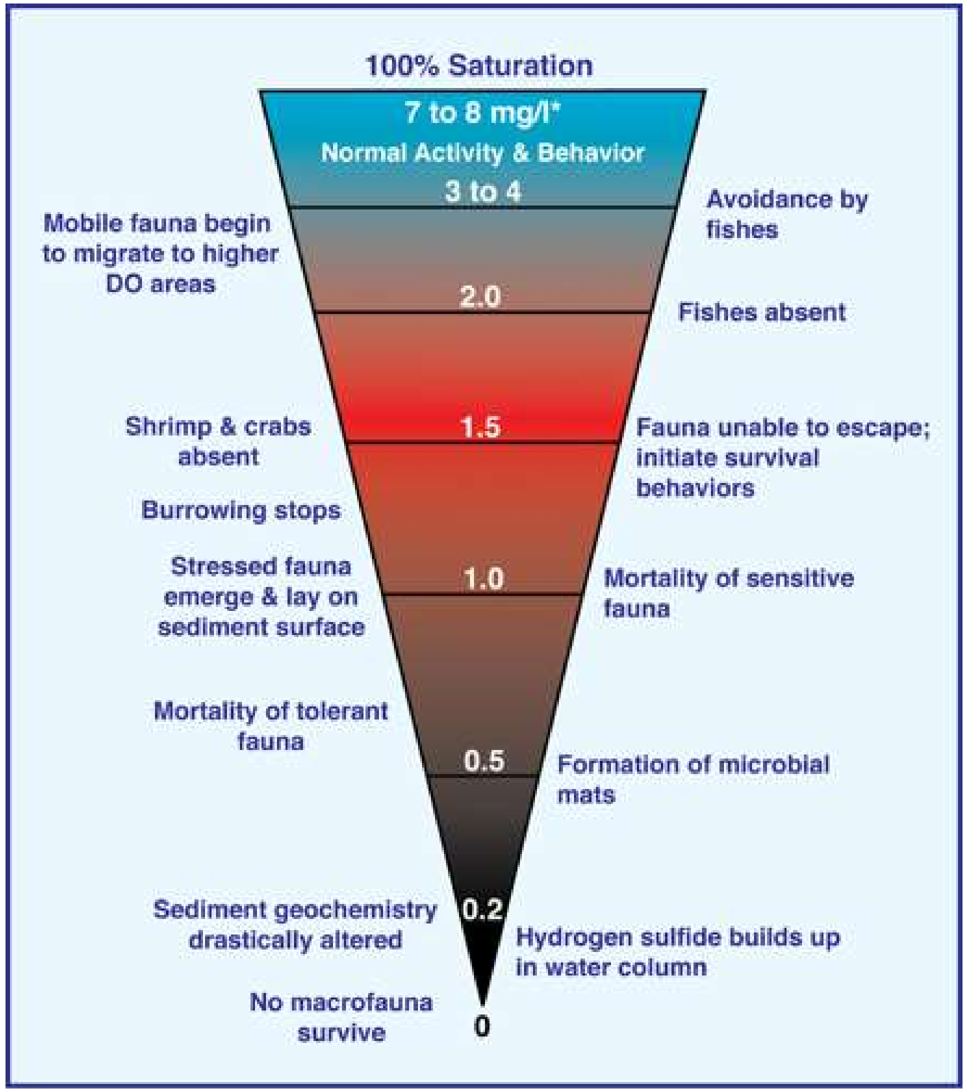
# Monopile Internal Space

## Volume to Surface Area for Increasing Diameters per Meter Length Monopile



- Large Diameter Monopiles have a larger volume to surface area ratio.
- Oxygen depletion will be slower for large diameter piles.

# Dissolved Oxygen and Biology



100% Saturation

7 to 8 mg/l*

Normal Activity & Behavior

3 to 4

Mobile fauna begin to migrate to higher DO areas

Avoidance by fishes

2.0

Fishes absent

Shrimp & crabs absent

1.5

Fauna unable to escape; initiate survival behaviors

Burrowing stops

Stressed fauna emerge & lay on sediment surface

1.0

Mortality of sensitive fauna

Mortality of tolerant fauna

0.5

Formation of microbial mats

Sediment geochemistry drastically altered

0.2

Hydrogen sulfide builds up in water column

No macrofauna survive

0

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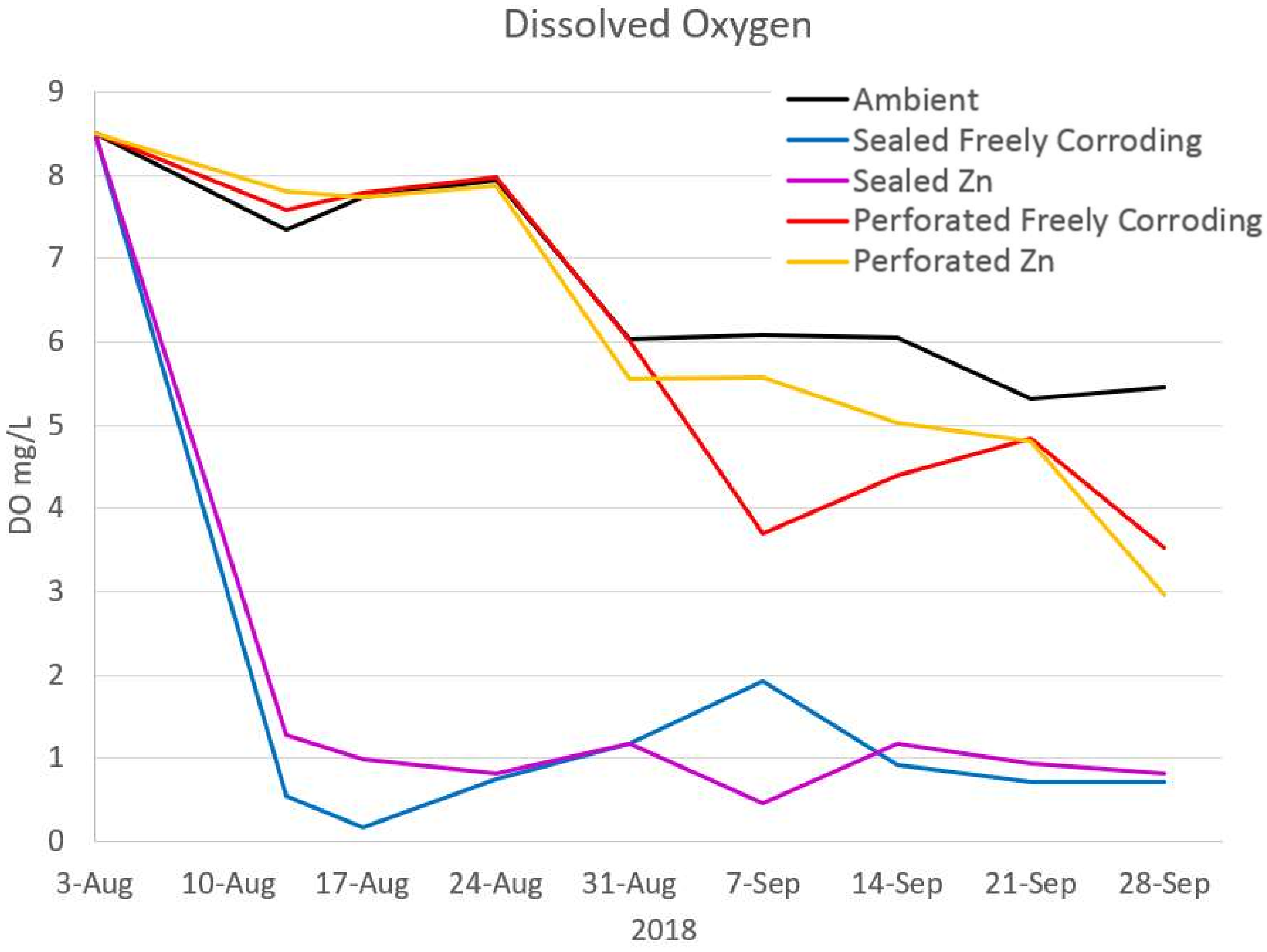


# *Oxygen Requirements for Mytilus edulis*

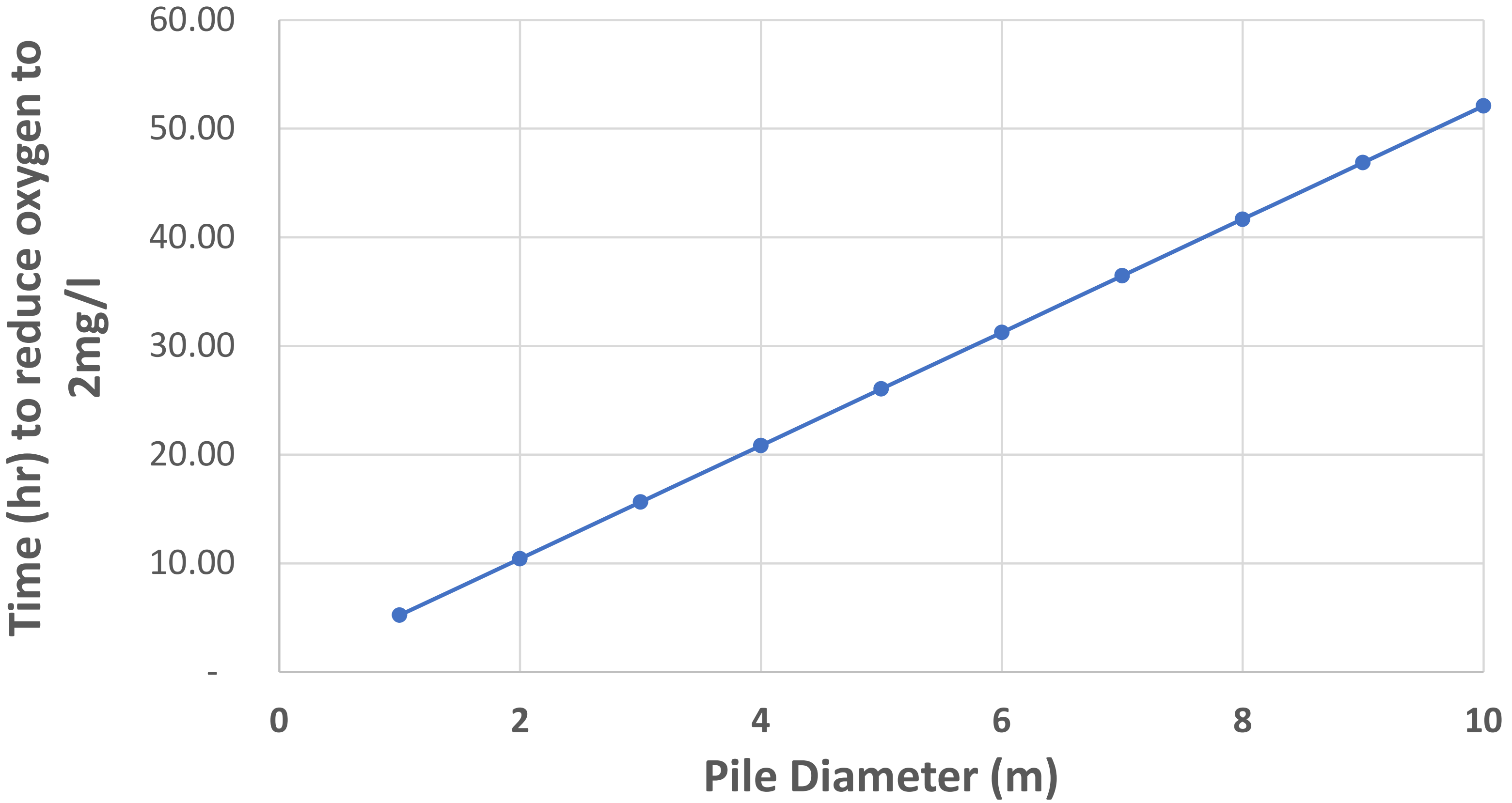
## Time to reduce Oxygen to 2mg/l due to Respiration

### Closed Monopile

Oxygen Conc (mg/l)
7.00

Mussel Respiration (mg/hr)
0.60

Mussel Density (#/m2)
400.00



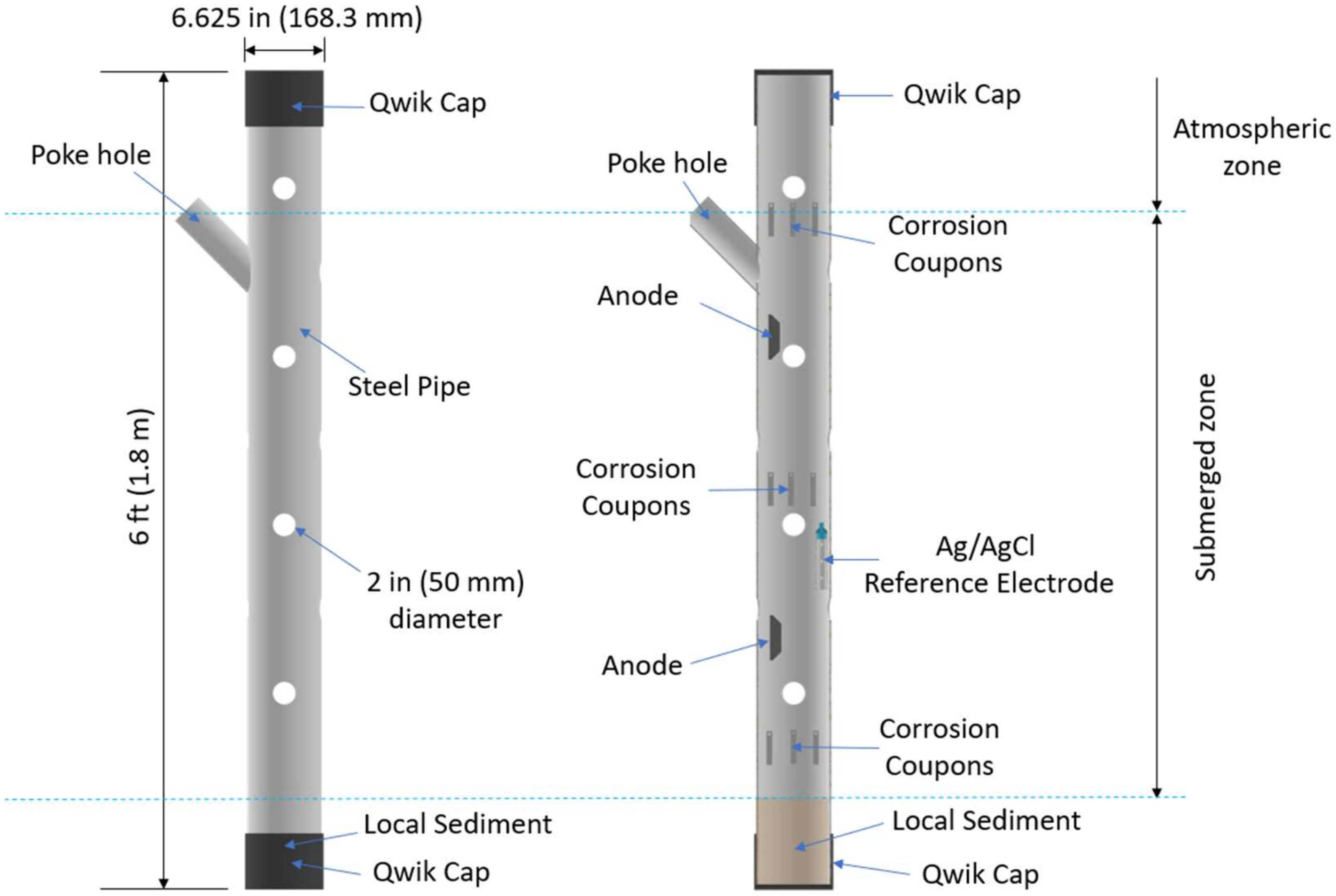
- Large Diameter Monopiles will be more supportive of a stable ecosystem

# What are the Data Requirements for Models to Manage the Internal Space?

## Cathodic Protection, Corrosion and Biofouling Field Study, 2022 Tufts, WHOI, FIT

Dan Kuchma, John DeFrancisci, Guodong Feng,
Colleen Hansel, Lina Taenzer, Loretta Robinson,
Geoff Swain, Caglar Erdogan

- Measuring the impact of perforations on CP, corrosion and biofouling
- Measuring the impact of coatings on CP, corrosion and biofouling
- Measuring the impact of biology on conditions in the pipe and CP



# Supporting Marine Ecosystems Through Nature-Inclusive Design

## Final Agenda (Times are in U.S. East Coast Time)

10:00 – 10:10: Welcome and Project Introduction, Workshop Objectives, & Logistics
10:10 – 10:50: Part 1: Presentations on Motivation and Examples for Nature-Inclusive Design
10:50 – 11:50: Part 2: Discussions on Four Topics Central to the Ongoing Project for BOEM
11:50 – 12:00: Next Steps (Results of Survey)

## Part 1: Presentations on Motivations and Examples for Nature-Inclusive Design (40 minutes)

1.1 Synthesis of Environmental Effects Research Project (NREL and PNNL)
1.2 Environmental Observations on Offshore Wind Structures including RODEO Project
    (Inspire Environmental)
1.3 Developer/Academic Initiatives in Nature-Inclusive Design (Orsted / Wageningen Univ.)
1.4 Artificial Reefs, Offshore Wind Farms as Sanctuaries, and Defining Success (Boskalis)

## Part 2: Discussions on Four Topics Central to Ongoing Project for BOEM (60 Minutes)

2.1. Impact of Perforations and Cathodic Protection on Marine Growth (Monica Maher, DOE)
2.2. Biofouling Profiles (Andrew Want, Heriot-Watt University)
2.3. Internal Chemistry in Monopiles (Bruinsma and Jansen, Deltares)
2.4. Interactions between Marine Growth and Internal Water Chemistry (Swain, Florida Tech.)