Research Ideas and Outcomes 11: e174994
doi: 10.3897/rio.11.e174994

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Workshop Report

Heated settlement plates (HSPl) in global experimentation: Experiences, research questions, future applications and collaborations

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Received: 15 Oct 2025 | Published: 21 Oct 2025

Reviewable v 1

Citation: Moreno B, Peck LS, Clark MS, Dunlop KM, Barnes DKA, Bluhm B, Molis M, Ziegler A, Longsden J, Hatt A, Jordà Molina È, Souster T (2025) Heated settlement plates (HSPl) in global experimentation: Experiences, research questions, future applications and collaborations. Research Ideas and Outcomes 11: e174994. https://doi.org/10.3897/rio.11.e174994

Abstract

Predicting how benthic assemblages respond to ocean warming remains a central challenge in marine ecology. Artificial units of habitat such as settlement plates have long been used to study marine lithophilic assemblage dynamics under natural and experimental conditions. Recently, heated settlement plate (HSPl) experiments have been deployed in polar and temperate seas to simulate likely near-future thermal regimes in situ. We convened a one-day hybrid workshop bringing together researchers who pioneered HSPl approaches with a broader international community of benthic researchers including project managers, senior scientists and early career researchers. The workshop aimed to: i) share experiences and outcomes from existing HSPl deployments; ii) identify technical and logistical challenges; iii) prioritise emerging research questions and applications; and iv) scope pathways for future collaborations and funding. Participants outlined desirable minimum standards for imaging and metadata in HSPl photosampling, compared design choices and replication strategies; and highlighted context-specific considerations for polar vs. temperate sites (e.g. ice scouring, permitting frameworks, diver safety considerations). A preliminary research agenda was developed spanning community assembly processes, trait-mediated responses, priority effects under warming and the integration of HSPl imagery with automated pipelines for analysis and data FAIRness. The workshop represents a first step towards building a cohesive global network to coordinate cross-site experiments, promote open protocols and data sharing and enable meta-analyses that will strengthen the understanding of how marine environmental change affects lithophilic assemblages across ecosystems.

Keywords

active heating experiment, benthic monitoring, experimental ecology, lithophilic assemblages, marine heat waves, non-native species, polar benthic ecology, succession, underwater optical imagery

Date and place

11 August 2025. Teknologibygget, UiT The Arctic University of Norway, Tromsø, Norway & online.

Abbreviations

AUH: artificial units of habitat;

DARKLITH: deep-learning of arctic marine lithophiles;

DMP: data management plan;

FAIR (principles): findability, accessibility, interoperability, reusability;

HSPl: heated settlement plate;

Hsp: heat-shock proteins;

iFDO: image FAIR digital objects;

MHW: marine heat waves;

RDM: research data management;

ROI: region of interest;

SOP: standard operating procedure.

Introduction

Predicting assemblage-level responses to a changing climate in the context of a multi-stressor seascape is one of the main challenges of marine ecology. Some marine environmental pressures include ocean warming, freshening, acidification and deoxygenation, pollution, overfishing and the spread of non-native species. This situation has motivated the study of responses of assemblages to different variables — individual and in combination — through experimental manipulation.

An experimental procedure is an "activity in which a given system is observed when it is subject to a set of conditions whose values, numerical or otherwise, are selected and, ideally, controlled by the observer" (Barnes 1967). However, traditional mesocosm experiments in laboratory settings — while powerful tools for manipulating multiple stressors simultaneously and for enabling highly controlled mechanistic studies — also have limitations. They are often constrained by scale, may lack realistic environmental variability and can struggle to reproduce complex feedback loops and long-term exposures relevant to slow-growing benthic species (Ashton et al. 2017, Ashton et al. 2022). To complement such approaches, in situ methods using artificial units of habitat (AUH) — such as settlement plates — have become broadly used tools for investigating colonisation, recruitment, succession, structure and organisation of marine lithophilic assemblages. Settlement plates can be built from a variety of materials including perspex (Barnes 1996, Barnes et al. 2025), high-impact polystyrene (Kuklinski et al. 2022, Sowa et al. 2023), acrylic (Pacheco et al. 2010), PVC (Uribe et al. 2015), metal (Parker 1924) and other materials (Visscher 1928). An adequate AUH should provide a standardised sampling platform within complex seascapes, ensuring sufficient uniformity for replication across treatments, while minimising uncontrolled variability associated with natural substrata (Glasby and Connell 2001, Underwood and Chapman 2006).

In recent years, AUH approaches have been extended to include active heating experiments to examine the response of primary foundation species exposed to simulated marine heatwaves (MHW, +3°C to +5°C heating) (Montie and Thomsen 2023) and future seawater temperatures predicted for the next hundred years in polar environments (+1°C to +2°C) (Ashton et al. 2017), the latter using the innovative heated settlement plates (HSPl) experimental approach. This approach can be particularly valuable at sites where there is contextual data of mid- to long-term natural variability in settlement, recruitment and early assemblage development (e.g. Sowa et al. (2024), Sowa (2025), Barnes et al. (2025)). Research initiatives that cover broad spatial ranges are ideal for testing global patterns. The development of standardised methodological approaches and procedures is, therefore, key to enable meta-analyses for similar research questions, but, at the same time, flexible enough to cover peculiar nuances of different environmental set-ups and enable the diversion of more specific research questions.

We convened a one-day hybrid workshop that brought together researchers with direct experience of HSPl deployments and a broader international community of benthic researchers. The aims were to exchange experiences, identify technical and logistical challenges, prioritise research questions and explore pathways towards standardisation, collaboration and joint funding.

Aims of the workshop

General aim of the HSPI–workshop:

Establish a coordinated, standards-driven HSPI–network that enables comparable, scalable in situ active heating experiments across marine ecoregions to investigate assemblage-level responses to ocean warming and support evidence-based management of coastal ecosystems.

Specific aims:

- Define best practices, minimum technical and imaging standards for high-quality HSPI photosampling and metadata;
- Map research questions for HSPI experiments – from community assembly and trait/functional shifts, to biological interaction networks and invasive-species risk – linking hypotheses to experimental designs and analysis plans;
- Characterise site-dependent nuances (e.g. polar vs. temperate): deployment logistics, seasonal windows, electrical power source and delivery, ice disturbance, legal permitting, health and safety considerations;
- Build a framework for open-access methods and data-pipeline: shared protocols, versioned SOPs, image repositories and reproducible workflows for automated annotation and application into computer vision schemes;
- Identify and pursue funding, collaborations and partnerships for survey pilots and multi-site deployments including infrastructure sharing.

Workshop agenda

The one-day hybrid workshop was structured around a combination of presentations and open discussions designed to provide scientific context, share practical experiences and generate a collective research agenda.

Presentations:

- Introduction and background — Terri Souster (UiT);
- Past research using HSPI — Lloyd Peck (BAS);
- Molecular ecology applied to HSPI experiments — Melody Clark (BAS);
- Succession of lithophilic assemblages in high-Arctic sublittoral shallows (West Spitsbergen 78°N) — Bernabé Moreno (IOPAN);

- Ecological questions and hypotheses using HSPl in Tromsø (69°N) — Markus Molis (UiT).

Open discussions:

- Opportunities for student involvement, including the integration of MSc projects into ongoing HSPl studies;
- Planning future analytical steps, manuscript development and data management strategies;
- Application of HSPl results to research on climate change impacts in northern coastal ecosystems with implications for management of human impacts — led by Kathy Dunlop, Amanda Ziegler and Èric Jordà-Molina;
- Identification of future project applications and mapping of potential grant proposals to sustain and expand HSPl research.

Brief descriptions of workshop participants

The workshop brought together an interdisciplinary group of researchers from Norway, the UK and Poland, combining expertise in experimental ecology, molecular biology, benthic community dynamics, coastal management and underwater optical imaging. Their complementary perspectives ensured that the workshop discussions spanned from fundamental ecological processes to applied management and industry contexts.

Workshop lead – The Arctic University of Norway (UiT)

- **Dr. Terri Souster** – Project Manager for iC3 Centre for ice, Carbon, Climate and Cryosphere. Benthic ecologist with research interests in physiology, biodiversity and the effects of climate change on marine assemblages in relation to sea ice loss, seawater warming and blue carbon. email: terri.souster@uit.no; ORCID: 0000-0002-7585-1999

Workshop contributors:

British Antarctic Survey (UKRI, online)

- **Prof. Lloyd S. Peck** – Head of the Biodiversity, Evolution and Adaptations Team. Originator and designer of the HSPl system used in trials discussed at the workshop. Research focus on polar marine adaptations to cold and seasonal environments, linking ecology, physiology and cell biology to environmental constraints and adaptive capacities. email: lspe@bas.ac.uk; ORCID: 0000-0003-3479-6791

- **Prof. Melody S. Clark** – Project Leader in the Adaptations Team. Lead author of the only HSPl study using molecular analyses (Clark et al. 2019). Molecular biologist with expertise in marine invertebrate responses to environmental

change and adaptation to life in the cold. email: mscl@bas.ac.uk; ORCID: 0000-0002-3442-3824

- **Dr. David K.A. Barnes** – Marine benthic ecologist with long-term experience using artificial substrata to study settlement, recruitment, colonisation and spatial competition dynamics, primarily in the polar regions. Recent work includes biodiversity monitoring and rare species loss using non-heated settlement plates at Rothera Station, Antarctica (Barnes et al. 2025). email: dkab@bas.ac.uk; ORCID: 0000-0002-9076-7867

Department of Arctic and Marine Biology, The Arctic University of Norway (UiT)

- **Prof. Markus Molis** – Experimental marine ecologist focusing on mechanistic understanding of species interactions and how physical stressors and biotic cues modulate benthic assemblages on rocky intertidal and sedimentary shores. Main contact for the UiT postdoctoral position related to HSPl experiments in Tromsø. email: markus.molis@uit.no; ORCID: 0000-0002-0194-5984

- **Prof. Bodil Bluhm** – Researcher and teacher in Arctic Marine System Ecology with a focus on taxonomic and functional biodiversity, pelagic–benthic coupling, food webs and ecosystem responses to climate change. Leads long-term photographic time-series studies of hard-bottom assemblages along northern Norwegian coast and Svalbard (Al-Habahbeh et al. 2020). email: bodil.bluhm@uit.no; ORCID: 0000-0002-4584-7796

- **Prof. Raul Primicerio** – Freshwater and marine ecologist with expertise in quantitative ecology. Project manager of CLEAN (Cumulative impact of multiple stressors in High North ecosystems), integrating climate stressors into ecosystem assessments. email: raul.primicerio@uit.no; ORCID: 0000-0002-1287-0164

Marine Ecology Department, Institute of Oceanology Polish Academy of Sciences (IOPAN)

- **Bernabé Moreno** – Technical scientific diver and PhD candidate studying ecological succession of lithophilic assemblages in high-Arctic West Spitsbergen. Focused on developing tools and workflows for acquisition and curation of high-resolution and high-quality underwater optical imagery. email: bmoreno@iopan.pl; ORCID: 0000-0002-9751-6307

Institute of Marine Research (HI | IMR), Tromsø

- **Dr. Kathy Dunlop** – Researcher and Lead of Aquaculture Emissions in the Aquaculture Environmental Effects Program. Expert on human impacts on coastal benthic ecosystems, benthic mapping and coastal management, with emphasis on northern Norway. email: katherine.mary.dunlop@hi.no; ORCID: 0000-0002-2397-1841

- **Dr. Èric Jordà Molina** – Researcher leading *Artsmangfold innsamlet fauna* in the MAREANO seabed mapping program. Specialised in taxonomy and functional ecology of Arctic and subarctic soft-bottom macrofaunal assemblages, focusing on environmental drivers of community structure. email: eric.jorda.molina@hi.no; ORCID: 0000-0003-2921-4742

Akvaplan-niva

- **Dr. Amanda Ziegler** – Benthic ecologist studying how environmental conditions shape benthic communities in polar and deep-sea ecosystems. Research interests include pelagic–benthic coupling and implications for carbon cycling and ecosystem functions. email: azi@akvaplan.niva.no; ORCID: 0000-0002-9027-5766

Newcastle University (online)

- **Jack Longsden** – PhD candidate at Newcastle University and the British Antarctic Survey, researching impacts of ocean warming and marine heatwaves on biofouling communities in temperate and tropical regions. email: j.longsden1@newcastle.ac.uk; ORCID: 0009-0004-6136-8420
- **Ainsley Hatt** – PhD candidate at the British Antarctic Survey and Newcastle University, investigating the impacts of ocean warming on biofouling communities and implications for the global shipping industry. email: aintt@bas.ac.uk; ORCID: 0009-0000-3517-9651

Background — Heated settlement plates (HSPl) in polar environments

The development and application of HSPl builds on a long history of using artificial units of habitat (AUH) to investigate benthic colonisation, succession and species interactions. In polar environments, these tools have been adapted to test ecological responses to warming under highly seasonal and extreme conditions. The following subsections outline the origins of the HSPl concept and related AUH deployments, which together provide the foundation for the current research agenda.

Development of the HSPl concept

Lloyd Peck & Terri Souster

The concept of heated settlement plates (HSPl) was first developed at the British Antarctic Survey (BAS) between 2006–2008 by Lloyd Peck and engineer Mark Preston (Antarctic and Marine Engineering, AME). The aim was to design a system to heat artificial units of habitat (AUHs) in situ to simulate projected seabed warming. Initial calculations suggested that a power input of 50.75 W (watts) produced a 4.6°C increase in plate surface temperature (equivalent to 11.25 W per 1°C). These calculations provided information for subsequent prototype development, although recalibration was required to account for voltage losses across cable lengths.

The first prototypes were deployed in Ryder Bay near Rothera Research Station (67°S, Western Antarctic Peninsula). Early iterations faced significant engineering challenges such as pressure seal failures, cable malfunctions and damage by icebergs. Between 2014 and 2016, a fourth set of HSPl, incorporating improved electrical configurations and robust physical protections, was deployed and successfully recovered (Fig. 1). This configuration tested two heated treatments (+1°C and +2°C above ambient), alongside unheated controls, generating a unique dataset on benthic community responses to in situ warming (Ashton et al. 2017, Clark et al. 2019, Barnes et al. 2021). An accessible narrative of the deployment challenges has been published in *Warming up the Antarctic: Harder than you think* (Clark 2019).

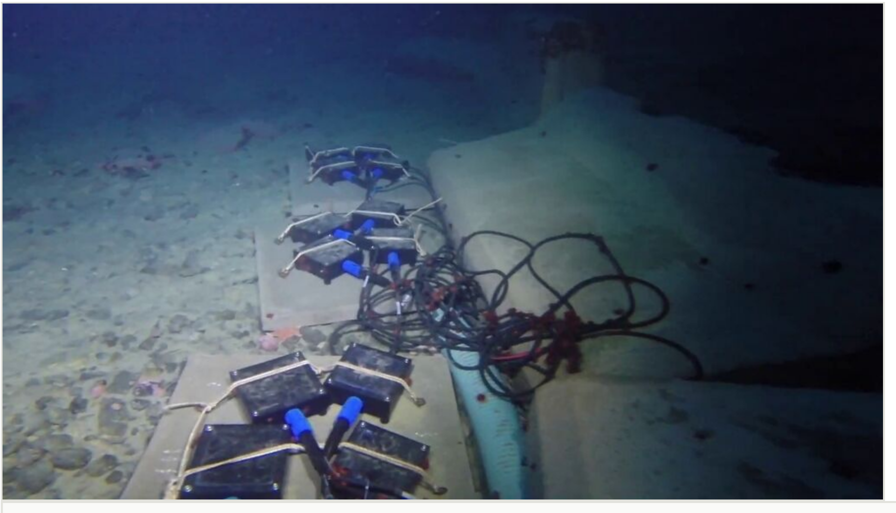

Figure 1. doi

Overview of the heated settlement plate (HSPl) experiment array at Rothera Research Station (67°S, Western Antarctic Peninsula). The installation includes heating cables and concrete blocks designed to protect the array from iceberg scouring, illustrating the logistical challenges of maintaining in situ manipulative experiments in polar environments. Photo courtesy of Gail V. Ashton. Video available in Moreno and Souster (2025) and YouTube (Standard YouTube Licence).

HSPl experiments in Tromsø, Norway

Terri Souster

The first Arctic HSPl deployment was initiated in September 2024 at Andersdalen, Tromsø Municipality, northern Norway (69°N). The array consists of three heated treatments (+1°C, +2°C, +3°C) and unheated controls, replicated four times (16 plates in total). Power is supplied via a 150 m cable from a nearby farm, with an electrical control panel housed in a protective Zarges box (Fig. 2a). The site offers several advantages: ease of access (~ 70 minutes by car and 45 minutes by RIB from Tromsø), suitable seabed topography at 10 m depth and absence of icebergs or significant winter snow or ice. However, challenges included regulatory restrictions on scuba diving (necessitating intertidal handling for photosampling), shallow-water turbulence during tidal change and freshwater input from the Andersdalelva River (Fig. 2b, Moreno and Souster (2025)).

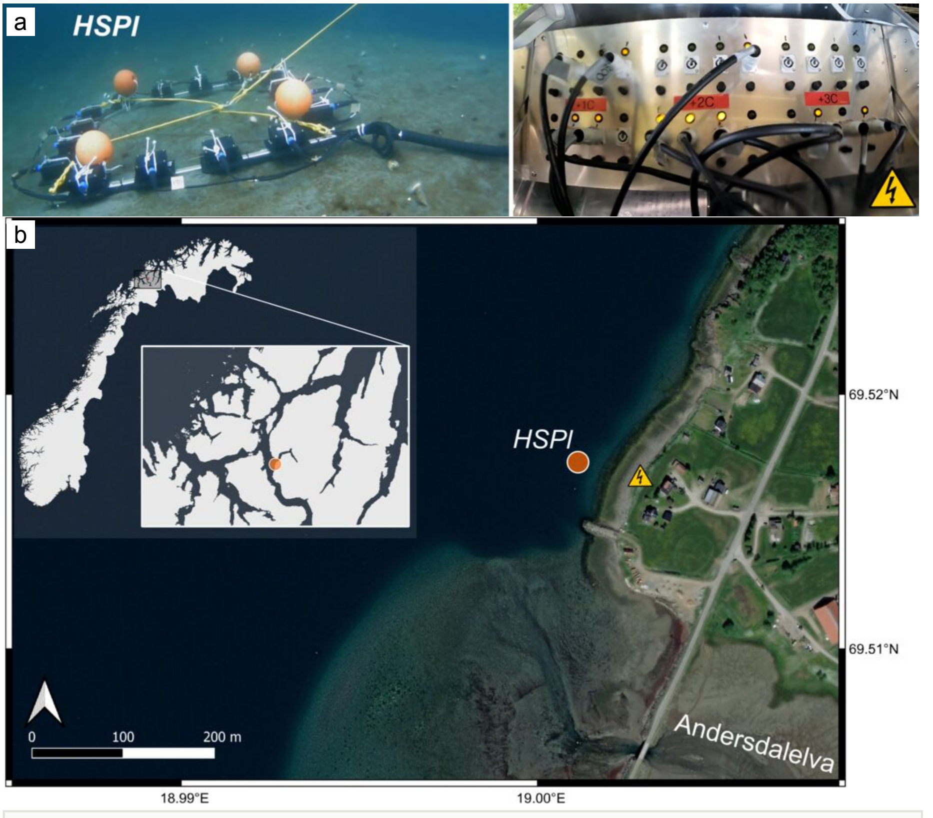

Figure 2.

Infrastructure and location of the HSPI experiment in the Arctic:

a: Underwater metal frame at 10 m depth in upper circa-littoral mixed sediments, supporting both heated treatments and controls replicated on each side (left). Onshore electric control panel secured inside a Zarges box, sheltered beneath a wooden veranda (right). Power supply was provided by a nearby farm facility, exemplifying how local infrastructure can be adapted to support advanced marine field experiments; doi

b: Location of the HSPI experiment in Andersdal (Tromsø Municipality, northern Norway). doi

Photosampling attempts in April 2025 produced poor image quality, prompting a series of trials in July and August 2025 to refine imaging protocols (Fig. 3a). These trials highlighted difficulties caused by water mixing in the shallow intertidal, but also led to practical guidelines for optimal photographic acquisition, documented in Suppl. material

1. Preliminary identifications from photomosaics included *Heteranomia squamula* and *Circeis armoricana*, with bryozoan taxa (*Cellerporella*, *Diplosolen*, *Disporella*) remaining tentative identifications pending further verification (Fig. 3b).

Figure 3.

Imaging workflows tested for HSPI experimentation in Tromsø. Operations for underwater imagery acquisition of the HSPI experiment at 69°N in Moreno and Souster (2025) or via You Tube (CCBY):

a: Freshwater trials at UiT facilities to calibrate camera parameters. Saltwater tests in Andersdal during low tide, conducted under variable mixing conditions. Photo credits: TS, AZ; doi

b: Photosampling at the field site, with image quality checks conducted inside the UiT field van serving as a mobile laboratory. Photomosaic of HSPI surfaces, where species identification was possible for the bivalve *Heteranomia squamula* and the serpulid *Circeis armoricana*. Other taxa — including the cheilostome bryozoan *Celleporella* and cyclostomes *Diplosolen* and *Disporella* — remain tentative identifications pending further verification. Photo credits: MM, BM. doi

Note: For clarity, *standardisation* in the context of HSPI refers to general workflows — such as imaging, metadata documentation and data archiving — that allow comparability across studies. It does not imply rigid uniformity in ecological timelines or deployment logistics, which necessarily vary with latitude, seasonality and site-specific constraints (e.g. intertidal vs. subtidal operations, equipment availability). This distinction is important to ensure that future cross-site syntheses remain feasible while preserving the flexibility required by local conditions.

Other AUH deployments

Workshop participants also contributed experience from a wide range of unheated AUH experiments.

David Barnes reported settlement plate deployments in Antarctica (Signy Island, 60°S; Rothera, 67°S) (Barnes 1996, Bowden et al. 2006, Barnes et al. 2025), Spitsbergen (78°N) (Sowa et al. 2023, Sowa 2025), Loch Hyne (51°N) and multiple lower-latitude sites (Barnes 2015). These experiments provide valuable baselines for interpreting HSPl results and have been central to studying settlement, recruitment, growth and competition across latitudinal and habitat gradients (Barnes and Neutel 2016).

Melody Clark described the deployment of eight Artificial Reef Monitoring Structures (ARMS) at Rothera since 2019 (Obst et al. 2020). Harsh Antarctic conditions, particularly iceberg activity, severely limited recovery: only three deployments yielded usable data, while others were damaged or lost entirely. These experiences underline both the logistical challenges of polar seawork.

Presentations, discussions and future plans

Current research using heated settlement plates

Lloyd Peck

The development of heated settlement plate (HSPl) experiments is strongly shaped by latitude and local conditions, making a rigid standard protocol for deployment undesirable. Instead, comparability across sites may be best achieved by focusing on mechanisms of assemblage development, for example, by aligning comparisons to similar successional stages or equivalent area coverage, rather than fixed deployment durations. The starting point of an experiment is also critical, as assemblage development varies depending on the season of deployment and the prevailing local thermal regime.

The growing research focus on marine heatwaves (MHWs) underscores that *warming* has context-dependent effects: its biological meaning differs not only across regions, but also across seasons within the same location. For instance, in temperate regions, such as New Zealand, warm years are associated with stronger organismal responses during summer months. Experimental configuration also matters. Vertical arrangements of HSPl in flow-through environments have shown considerable algal growth on upper sections, most likely due to shielding effects of canopy algae.

Past deployments and research collaborations

- Bangor, North Wales (53°N): shallow subtidal deployment; data unfortunately lost;
- California: initial deployment, but assemblages grew too rapidly to detect meaningful changes; not repeated;
- University of Otago (45°S):
    - Doctoral thesis: Jessica M. Moffitt, *The impact of ocean warming on marine encrusting communities: Insights from an in situ experiment* (supervisor: Miles Lamare);
    - MSc thesis: Tom Massué, investigating serpulid assemblage diversity and growth;
- Newcastle University
    - PhD candidate Ainsley Hatt (supervisor: Heather Sugden): Monitoring phytobiont biomass in early-stage biofilms on HSPl, Hartlepool Marina (54°N);
    - PhD candidate Jack Longsden (supervisor: Heather Sugden): Biofouling community development under warming compared to historical datasets, Hartlepool Marina (54°N).

Planned and potential future deployments

- *King Sejong* Korean Antarctic Station (62°S): deployment planned for 2025;
- Great Barrier Reef (16°S): planned deployment under leadership of PhD candidate Jack Longsden, in collaboration with Miles LaMare and Jessica Moffitt;
- Denmark or Greenland: proposed deployments led by Jakob Thyrring (Aarhus University);
- North East of England (54°N): planned study of HSPl assemblage resistance to invasive species, using laboratory assays after field colonisation led by PhD candidate Jack Longsden (Newcastle University).

Molecular ecology applied to HSPl

Melody Clark

Only one set of heated settlement plates (HSPl) has so far been subjected to molecular ecological analysis (Clark et al. 2019). In this Antarctic study, spirorbid worms colonising the plates were investigated using transcriptomics to assess how experimental warming affected their cellular physiology. Comparisons between controls and animals exposed to +1℃ and +2℃ revealed pronounced sensitivity: even +1℃ of warming induced significant stress responses, while individuals at +2℃ exhibited metabolic shutdown consistent with terminal senescence. These findings highlight how subtle temperature increases can critically affect early colonisers at the cellular level.

Technical challenges remain in applying molecular methods to HSPl samples. Animals inhabiting the thin warmed boundary layer above the plates (2 mm above +1℃ plates in Antarctica, Barnes et al. (2021)) are typically very small, yielding insufficient DNA or RNA for sequencing from individuals alone. Pooling multiple specimens is therefore required, which limits analyses such as population genetics. For microbial biofilms, Antarctic deployments showed no detectable changes in bacterial diversity between treatments. However, this absence of taxonomic shifts does not equate to functional stability; transcriptomic approaches are necessary to reveal how microbial metabolic pathways respond to warming.

Lessons learnt from this work:

- Transcriptomes provide a more sensitive and informative measure of organismal health than candidate-gene approaches;
- Biofilm microbial assemblages should be analysed with transcriptomics to capture functional responses, not just shifts in diversity;
- Sampling for molecular analyses is destructive and best conducted at the experimental endpoint;
- Adequate preservation (e.g. liquid nitrogen storage) is essential, but logistically demanding, particularly in remote polar sites;
- Material availability is a persistent limitation, requiring methodological innovation to enable robust population- and community-level analyses.

This pioneering study demonstrates the potential of combining HSPl deployments with molecular ecology to detect early-warning signals of stress that precede visible ecological changes. Despite current logistical and methodological challenges, molecular tools represent a powerful complement to ecological observations and hold promise for future cross-site HSPl–networks.

Succession of lithophilic assemblages in high-Arctic sublittoral shallows (West Spitsbergen 78°N)

Bernabé Moreno

Research context and objectives

High-Arctic hard-bottom subtidal habitats provide natural laboratories for studying long-term ecological succession under rapid environmental variability. To explore these dynamics, lithophilic assemblages were studied using (non-heated) artificial settlement plates (Kuklinski et al. 2022) deployed in the shallow subtidal of northern (N) and southern (S1, S2) Isfjorden proper, West Spitsbergen (78°N) (Moreno et al. 2024). Site selection was guided by ecological and logistical criteria: the presence of habitat-forming brown macroalgae, environmental drivers such as seawater circulation and glacial influence, underlying geology and accessibility by rigid inflatable boat from Longyearbyen (Moreno et al. submitted to *Polar Research*).

Experimental design and methodology

Long-term successional experiments were initiated in 2009 and 2013 at the southern sites, with 10-year submersion intervals culminating in recoveries in 2019 and 2023. Yearly in situ photosampling was performed (except during recovery years) by an IOPAN scientific diver using a high-resolution macrophotography camera-system (Nikon D810, 60 mm macro lens, dual INON Z-240 strobes, SOLA-1200 focus light) (Fig. 4).

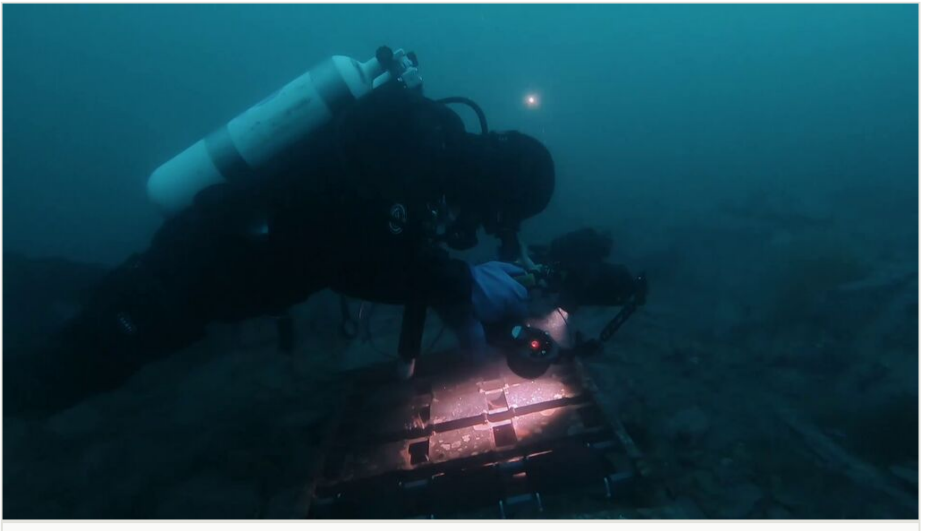

Figure 4. doi

Underwater procedures for long-term photographic monitoring of high-Arctic lithophilic assemblages in Isfjorden (Spitsbergen). IOPAN Scientific Diving Team operations, illustrating methods for in situ photography in arctic conditions, available in Moreno and Souster (2025) or via YouTube (CC BY).

Multiple overlapping images (4–9 per plate) were taken with manual *zenithal (orthogonal) control*, for both upward- and downward-facing plates (Moreno 2024). Downward-facing plates consistently supported higher abundance, richness and structural complexity, particularly during late successional stages, where assemblages reached up to 30 mm in relief. Recovered plates were preserved in ethanol, then processed under laboratory conditions using the *zenithal control* of a stereomicroscope (Leica DFC450) and LED video-lighting (40W) for detailed imaging. The Leica Application Suite X (LASX) software was used for previewing, re-labelling and saving the images. Despite improved taxonomic resolution, this set-up introduced challenges, including artefacts from the air–water interface and overheating of underwater-designed lighting. Workflow for digital archiving and analysis of lithophilic assemblage succession are illustrated in Moreno and Souster (2025) or via YouTube (CC BY).

The subsequent DARKLITH camera-system, developed during Moreno's doctoral project, resolved these issues by integrating full *xyz-axes zenithal control*, submerged optics (removing air–water interface distortions), tethered camera operation and advanced imaging protocols (e.g. exposure and HDR-bracketing). This approach significantly expanded the quality and reproducibility of benthic imagery, while also enabling broader applications in macrophotography of marine organisms.

Lessons learnt from the European high-Arctic experience:

- ***Zenithal control* is essential**: avoiding perspective distortion and error/distortion accumulation in time-series analyses;
- **Resolution ≠ quality**: high-resolution sensors alone cannot compensate for suboptimal imaging parameters;
- **Physical samples remain critical**: even the best images require voucher specimens for robust genus- or species-level identification;
- **Consistency is key**: maintaining standardised imaging systems across time increases comparability and reduces artefacts;
- **Metadata and labelling matter**: coherent, persistent labelling schemes (Moreno 2020, Moreno 2021) improve traceability and reproducibility;
- **Documentation supports continuity**: digital logbooks, SOPs (e.g. Schoening (2021)) and structured DMPs ensure workflows remain transparent and repeatable;
- **SOPs and checklists are practical tools**: they help standardise seawork (see Suppl. material 1) and laboratory protocols.

Making HSPl image data FAIR

Bernabé Moreno

Marine imagery datasets are rapidly growing in size, scope and relevance, yet they are often fragmented, inconsistently documented or poorly accessible. Following the FAIR principles (Schoening et al. 2022) is therefore critical to maximise their scientific value. In practice, this means:

- **F**indable: using persistent identifiers and standardised metadata frameworks (e.g. via iFDO – image FAIR Digital Object) to ensure datasets can be located by both humans and machines;
- **A**ccessible: archiving images in repositories with clear licensing, open file formats and minimal technical barriers to access;
- **I**nteroperable: adopting controlled vocabularies, community standards (Borremans et al. 2024) and machine-readable annotations (see *RecoMIA* Schoening et al. (2016)) to enable integration across platforms and studies;
- **R**eusable: documenting datasets with methodological detail, labelling standards, annotation protocols and quality control so that they can be confidently re-purposed.

Applying FAIR practices into HSPl experiments from the outset — through standardised imaging, consistent labelling, structured metadata, open repositories and development of frameworks like iFDO — will transform local datasets into global assets, enabling comparative analyses, machine-learning training and ecosystem-scale syntheses.

F**A**IR note: Researchers can identify appropriate repositories via the Registry of Research Data Repositories, which catalogues trusted archives across disciplines. For example, DataverseNO is a curated, FAIR-aligned Norwegian repository that ensures long-term accessibility and reusability of datasets and organises them into institutional and special collections. While primarily serving Norwegian research institutions, it offers a model for how HSPl datasets could be curated in a sustainable and interoperable manner.

Proposed research directions

Building on the high-Arctic experience, the following areas are proposed for HSPl research development:

- Standardisation of image workflows: testing and refining protocols (e.g. *zenithal control*, high dynamic range, metadata capture) across sites to ensure comparability. Standardisation here refers to reproducible imaging and metadata procedures that ensure comparability across deployments, without constraining site-specific adaptations in sampling or monitoring;
- Development of FAIR-compliant repositories: establishing HSPl image archives that support open access, machine learning and cross-project integration and integration with iFDO metadata standards;
- Adoption of segmentation and annotation standards: applying best practices from *RecoMIA* (Schoening et al. 2016) to ensure reproducible, comparable annotations across datasets;
- Comparative successional studies: linking Arctic and temperate assemblage development trajectories to assess biogeographic patterns of benthic assemblage responses;
- Integration of imagery with physical samples: combining photographic and specimen-based approaches to achieve robust species-level identification;
- Capacity building: developing shared SOPs, checklists and training materials to harmonise practices across the HSPl–network.

Ecological questions and hypotheses using HSPl in Tromsø

Markus Molis

Heated settlement plate (HSPl) deployments in northern Norway provide opportunities to test hypotheses about how temperature influences early benthic community assembly. Barnacles and their cyprid larvae can serve as a focal taxon for conceptual development, but the framework can be extended to a wide range of sessile invertebrates. Fig. 5 illustrates hypotheses concerning richness and diversity (a–d), larval settlement (e–f), performance (g), competitive interactions (h) and growth under variable food availability (i–j).

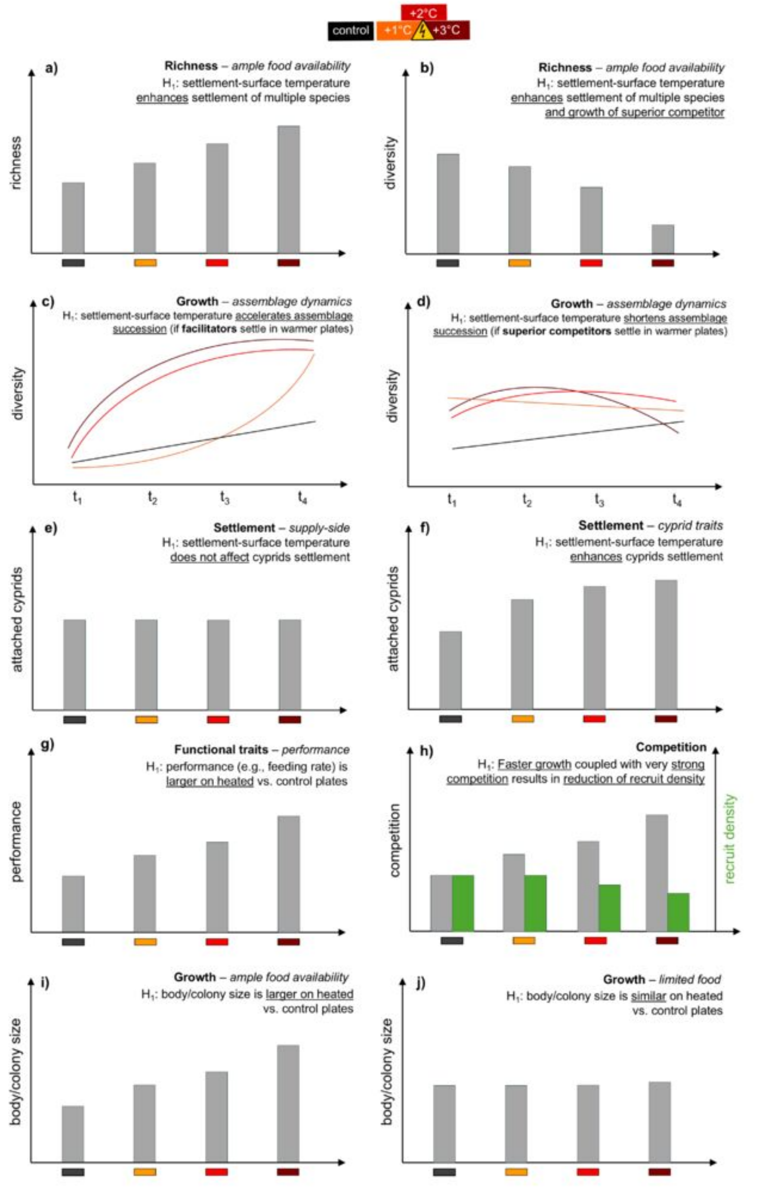

Figure 5. doi

Conceptual hypotheses to be tested with heated settlement plates (HSPl). Panels illustrate predicted processes under experimental warming: **(a–d)** changes in species richness and diversity mediated by facilitation or competitive dominance; **(e–f)** settlement responses of cyprid larvae, from temperature-independence to preference for warmer substrata; **(g)** individual performance metrics such as growth and reproduction; **(h)** recruitment outcomes shaped by competition under stress gradients; **(i–j)** body and colony growth responses under varying food availability.

Hypotheses:

- Assemblage richness and diversity
  - If food is abundant and elevated temperatures enhance settlement across multiple taxa, species richness and diversity will increase in heated treatments (Fig. 5a);
  - Conversely, if warming disproportionately benefits a dominant competitor, competitive exclusion may reduce richness and diversity (Fig. 5b).
- Successional dynamics and priority effects
  - If facilitative species preferentially settle on warmed surfaces, succession may accelerate, leading to earlier development of complex assemblages (Fig. 5c);
  - If, instead, superior competitors are advantaged by warming and settle first, succession could be slowed-down and monopolised, reducing subsequent colonisation (Fig. 5d).
- Settlement processes and larval supply
  - In short-term deployments, larvae in the plankton are not directly exposed to the altered thermal regime. If settlement is largely temperature-independent, the number of cyprids attaching will not differ between treatments (Fig. 5e);
  - If settlement-competent larvae display behavioural preference for warmer substrata, heated plates will receive more recruits (Fig. 5f). Experimental design must balance treatment contrasts and replication to separate these effects.
- Recruitment, stress gradients and competition
  - Environmental stress (e.g. thermal load, hydrodynamics) modulates both recruitment and post-settlement survival (Menge and Sutherland 1987). If recruitment increases under warming, higher densities may intensify competition, with outcomes ranging from suppressed survival to dominance by a few competitively superior individuals (Fig. 5h).
- Growth, fecundity and food availability
  - Where food is plentiful, warming may enhance reproductive output (e.g. egg production) because barnacles retain larvae until the next reproductive season (Fig. 5i).

Under food limitation, growth responses to warming may be reduced and species-specific feeding preferences (beyond bulk chlorophyll or fluorescence proxies) must be considered. A targeted model-species approach is recommended. Plates may be retrieved for controlled laboratory assays (e.g. filtration, respiration) to quantify performance.

Scales of response. Response variables should be assessed across levels of biological organisation:

- Ecological: growth, survival, fecundity, biomass (individual level); settlement and recruitment (population level);

- Physiological: respiration, metabolic rate, reproductive effort;
- Cellular: stress markers (e.g. heat-shock proteins–Hsp).

Together, these hypotheses establish a research agenda linking temperature-driven shifts in settlement and recruitment to broader community dynamics, while emphasising the interplay of facilitation, competition and resource availability.

Relevance of HSPl to coastal climate change research related to management and industry

Kathy Dunlop, Amanda Ziegler and *Èric Jordà Molina*

Coastal benthic habitats worldwide are experiencing significant impacts from both human activities and warming waters with the most rapid changes occurring in polar regions. Human impacts beyond climate change affecting the coastal zone include bottom trawling, organic enrichment from aquaculture and human settlement, contaminants, non-indigenous/invasive species and more. Sessile benthic fauna are a key element of coastal ecosystems and impacts on their settlement and establishment from rising seawater temperatures and other human activities can have far reaching impacts on benthic coastal ecosystems. Disruptions at these stages can cascade through entire assemblages, altering ecosystem functioning, resilience and services provision. Understanding the vulnerability of benthic communities and the changes that may occur to their distribution and function under climate change scenarios is a necessary step to achieve effective ecosystem-based management, a goal of many nations.

Heated settlement plate (HSPl) experiments provide a powerful targeted approach for examining how climate-driven warming modulates these processes and for addressing questions directly relevant to ecosystem-based management and industry. By coupling controlled, in situ manipulations with long-term monitoring of benthic assemblage development, HSPl studies can reveal whether rising temperatures amplify or mitigate vulnerabilities to other stressors. For example: will benthic communities be more susceptible to organic enrichment or pollution under warmer regimes and should management strategies prioritise interventions accordingly? Such insights are vital to guide adaptive policies and practices in aquaculture, offshore infrastructure and shipping, where biofouling, invasive species risks and ecosystem degradation are pressing challenges.

Priority research areas:

- Cumulative impacts in the coastal zone: disentangling the combined effects of warming, organic enrichment, sedimentation, pollutants, non-indigenous/invasive species and marine biofouling;
- Monitoring frameworks: advancing methods to track settlement of sessile organisms, early assemblage shifts and habitat resilience under warming scenarios;

- Early life stages: focusing on vulnerable taxa and habitats where settlement bottlenecks have disproportionate ecosystem or management relevance;
- Industry linkages: applying HSPI findings to predict and manage biofouling dynamics in aquaculture, offshore installations and shipping.

Illustrative proposal ideas:

- Aquaculture stressors: pilot deployments of HSPI plates beneath aquaculture facilities to test interactive effects of warming, organic enrichment, sedimentation and pollutants;
- Marine heatwaves: laboratory-based experiments examining how episodic thermal extremes influence settlement and recruitment of vulnerable, commercially important or invasive species;
- Glacial and riverine inputs: investigating how freshwater and sediment discharges affect macroalgal settlement and growth in northern Norway and Svalbard, with direct application to kelp cultivation;
- Invasive species monitoring: targeted HSPI deployments to track settlement risk of *Crassostrea gigas* (Pacific oyster) and *Didemnum vexillum* ("sea vomit") under warming;
- Restoration potential: assessing how warming shapes outcomes of benthic habitat restoration efforts, including kelp reforestation and shellfish bed recovery;
- Resource species dynamics: linking HSPI findings to the management of benthic resource species such as *Mytilus edulis* (blue mussels).

Funding pathways and collaboration mechanisms

Although success rates for large-scale international funding remain low, a cohesive HSPI–network could enhance competitiveness and efficiency by pooling expertise and infrastructure. Key funding opportunities include:

- Norwegian Seafood Research Fund (FHF): industry-financed, supporting R&D with direct application to seafood production;
- Research Council of Norway (NFR): broad national calls with environmental, industrial and international collaboration components;
- Money Follows Cooperation (MFC): a UK–Norway bilateral funding mechanism allowing shared budgets across partners;
- Municipal and regional governments: supporting locally relevant monitoring, restoration and management initiatives.

Together, these pathways highlight the translational value of HSPI research, bridging fundamental ecological insight with applied management needs in the coastal zone.

Key outcomes and workshop achievements

The workshop successfully brought together researchers with complementary expertise in polar and subpolar marine ecology, experimental design and molecular and imaging approaches. The main outcomes and achievements include:

- Establishment of a research network and dialogue forum dedicated to heated settlement plate (HSPl) experiments in polar and temperate ecosystems;
- Identification of opportunities for future collaborative proposals, including multi-site deployments, molecular ecology applications and links to management and industry;
- Shared recognition of the breadth of HSPl applications, from testing ecological hypotheses on recruitment and succession, to studying cumulative impacts of warming and human activities, to biofouling and aquaculture relevance;
- Critical discussion of timescales and limiting factors, particularly food availability in Antarctic waters, that shape how experiments should be designed and interpreted across latitudes;
- Progress towards best practices, including deployment protocols, imaging workflows, data management and guidelines for balancing replication, treatments and standardisation across sites.

Conclusions and future steps

The workshop underscored the value of HSPl experiments as a valuable in situ manipulation tool for studying benthic assemblages responses to warming in polar and temperate systems. To advance this research area, the following steps were agreed.

- Coordination of HSPl practices across sites will enhance comparability, reduce logistical costs and accelerate robust ecological inference;
- Hypothesis-driven deployments can be strategically aligned along environmental gradients, thermal anomalies (e.g. marine heatwaves, El Niño–Southern Oscillation) and shifting regimes (e.g. upwelling systems);
- Integration of multiple approaches — molecular ecology, imaging technologies and long-term ecological monitoring — will strengthen the mechanistic understanding of species- and assemblage-level responses;
- Closer links to management and industry (e.g. aquaculture, invasive species monitoring, habitat restoration) will ensure that experimental outcomes are directly relevant to applied challenges in coastal ecosystems;
- Sustained international collaboration and funding are essential to secure continuity, broaden geographical coverage and maintain the momentum initiated by this workshop.

Executive Summary

Heated settlement plates (HSPl) experiments are emerging as a unifying platform to investigate the impacts of ocean warming on benthic assemblages worldwide. This workshop brought together researchers from polar, temperate and subpolar regions to share experiences and chart a collaborative way forward.

Deployments in Rothera (Antarctica) and Tromsø (Norway) demonstrated how diverse engineering, imaging and sampling solutions can be adapted to local challenges. Advances in photography, ranging from the use of camera-systems (see HSPl camera-system in Suppl. material 2) by scientific divers and operators in the intertidal zone are enabling higher-quality imagery and more consistent monitoring. Laboratory trials complemented seawork, refining methods for sample handling and photomosaics development.

Biological insights confirm the sensitivity of polar taxa to small increments of warming. Antarctic spirorbids showed transcriptomic stress at +1°C and senescence at +2°C, while microbial communities appear more resistant, but require functional analysis. Succession experiments in Spitsbergen highlighted the importance of non-heated baselines and long-term consistency in imaging protocols.

Discussion sessions emphasised flexibility over rigid standardisation in the experimental design. Given the strong influence of latitude, seasonality and local conditions, comparability should rely on successional stage or coverage rather than fixed timeframes. Past deployments in Wales, California and New Zealand provided valuable lessons, while new collaborations are expanding to the Korean Antarctic Station, the Great Barrier Reef, Greenland and northern England.

The HSPl–network identified three priorities: (1) refining imaging and molecular protocols for greater reproducibility; (2) expanding the geographic coverage of deployments; and (3) strengthening data stewardship through coherent labelling, structured metadata and FAIR-aligned practices. Together, these efforts aim to establish HSPl as a globally relevant tool for detecting and comparing the ecological consequences of ocean warming.

Acknowledgements

BM was supported by the Polish National Agency for Academic Exchange (NAWA–BPN/PRE/2022/1/00106 & NAWA–BPI/STE/2023/1/00008), the Polish National Science Centre (NCN–Preludium22/2023/49/N/NZ8/04126–DARKLITH & NCN–PreludiumBIS-2/2020/39/O/NZ8/00376–SUKCES), Global Underwater Explorers (GUE) and the Universidad Científica del Sur (Peru). Active heating experiments in the Western Antarctic Peninsula were made possible through the Natural Environment Research Council (NERC) standard grant NE/J007501/1 (“Effects of warming on recruitment and marine benthic community development in Antarctica”) and in Tromsø through Fram Centre

Incentive Funding to TS, RP, BB and MM ("Heated settlement panels help anticipate seafloor communities in a warming Arctic"), which also supported the workshop. UiT supported the Norwegian photographic coastal hard-bottom time series, wisely established by Prof. Emeritus Bjørn Gulliksen.

BM gratefully acknowledges Gail V. Ashton for valuable discussions on HSPl deployments in Antarctica. BM and TS also thank Fabio Sarti, Data Manager for iC3: Centre for ice, Cryosphere, Carbon and Climate, for insightful discussions on the application of FAIR principles to marine image data.

Grant title

Heated settlement panels help anticipate seafloor communities in a warming Arctic

Hosting institution

UiT The Arctic University of Norway

Author contributions

Conceptualisation: BM, LSP, KMD, BB, TS. Funding acquisition: BM, BB, MM, TS. Project administration: TS. Methodology: BM, LSP, MSC, DKAB, MM, AZ, JL, AH, TS. Investigation: BM, LSP, MSC, DKAB, MM, JL, TS. Data curation: BM, DKAB. Formal analysis: MSC. Writing - original draft: BM, MSC, KMD, DKAB, BB, AZ, TS. Writing - review and editing: LSP, MM, JL, AH, EJM. Resources: LSP, KMD, BB, MM, TS. Supervision: LSP, KMD, DKAB, BB, AZ. Validation: KMD, DKAB, AZ, EJM, TS. Visualisation: BM, MM. Software: BM.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: SOP and checklist for HSPI photosampling doi

Authors: Bernabé Moreno and Terri Souster
Data type: Text and images
Brief description: This document contains a Standard Operating Procedure (SOP) and seawork-checklist for HSPI photosampling.
Download file (555.63 kb)

Suppl. material 2: HSPI camera-system doi

Authors: Bernabé Moreno and Terri Souster
Data type: image
Brief description: Different reference angles of the HSPI camera-system tested for the underwater image acquisition at Andersdal intertidal (Tromsø). Key components of the camera-system include the *zenithal control* (provided by the sliding-frame), correct focus on the macro-lens, correct position and direction of the strobelights (use built-in focus light for reference). Size of the HSPI is 150 × 150 × 50 mm.
Download file (5.40 MB)