Surveying the seabed. Photo by Laura Govers.

16th International Scientific Wadden Sea Symposium

Synthesis Report

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Content

Reading guide

This report summarises the new research insight and key recommendations of the 16th ISWSS. The executive summary highlights the main policy recommendations for the upcoming Trilateral Governmental Conference, which will take place in May 2026 in Esbjerg, Denmark.

The actual report begins with an introduction to the symposium (chapter 1), followed by a chapter presenting the main thematic conclusions and recommendations (chapter 2). It then provides an overview of the keynotes (chapter 3) and specific sessions. Each sessions includes a summary of key insights, discussion points, recommendations for further research, and policy recommendations (chapter 4).

The accompanying abstract book contains the selected abstracts for the keynotes, thematic sessions, and posters.

Executive summary

The Wadden Sea in Transition: Cumulative Pressures and Conservation
Groningen, The Netherlands | 28-30 October 2025

The Wadden Sea is undergoing rapid ecological and environmental change. At the 16th International Scientific Wadden Sea Symposium, trilateral experts explored how natural and human-induced forces interact and impact the Outstanding Universal Value (OUV) of the Wadden Sea World Heritage Site. This executive summary highlights the most relevant and urgent policy recommendations from the 16th ISWSS to safeguard the natural values of the Wadden Sea World Heritage Site.

1. **Foster and stimulate engagement within the scientific community**
   Continuous efforts to inform and interconnect the Wadden Sea scientists are needed to sustain their broad interest and strong involvement in Wadden Sea research. Underlying barriers restricting participation in events by relevant scientists should be identified and addressed to further strengthen the multidisciplinary and trilateral approach of the scientific community in the Wadden Sea.

2. **Build scenarios for sustainable management of the Wadden Sea**
   Climate change and human countermeasures to deal with unwanted effects will put additional pressures on the Wadden Sea ecosystem. Developing science-based scenarios, considering multi-functional use of the Wadden Sea, is key to explore consequences of adaptation strategies towards sustainable management of a resilient Wadden Sea ecosystem.

3. **Combine scientific methodologies to assess and forecast cumulative effects**
   Present and future pressures, including human activities and climate change, can have compounding effects that could trigger irreversible and undesirable ecosystem shifts. There is an urgent need to assess present and forecast future cumulative impacts. Hereto, various multiple learning algorithms can be combined to obtain better predictive performance (ensemble learning). Fostering cross-disciplinary collaboration on cumulation is critical here.

4. **Coordinate implementation of nature protection and restoration laws**
   The Wadden Sea is subject to a suite of international, European, trilateral, national and regional conventions and directives which are differently implemented throughout the area. The upcoming EU Nature Restoration Plan should be taken as a starting point to develop an overarching trilateral view on and approach for nature protection and restoration activities, doing justice to the spirit of all conventions and directives.

5. **Actualise monitoring and assessment of the status of the Wadden Sea**
   Present monitoring (Trilateral Monitoring and Assessment Programme; TMAP) and assessment (Quality Status Report; QSR) efforts do not fully comply to outlined needs from

science and society. In addition to demands from scenario building and cumulative impact assessments, TMAP and QSR should be more explicitly targeting needs raised by UNESCO and the EU.

6. **Implement an integrated, ecosystem-based approach**
   To assess the Status of the Wadden Sea, we need to consider bottom-up and top-down effects. In order to detect ecosystem shifts and receive early warnings, research and monitoring should include multi-species, ecosystem-based frameworks. These should take the interconnection of different components of the Wadden Sea ecosystem into account, also beyond the boundaries of the World Heritage Site.

7. **Improve science-policy information exchange**
   Scientific outcomes are still not fully heard and taken up by relevant Wadden Sea stakeholders and challenges of these stakeholders not fully acknowledged by the scientific community. Science-policy exchange could benefit from stronger scientific outreach and from more explicit scientific requests by stakeholders.

8. **Streamline integration of scientific knowledge for trilateral policies**
   Schedule the next International Scientific Wadden Sea Symposium in the spring of 2029. This allows sufficient time for integration of the symposium's outcomes into the preparation of the next Trilateral Ministerial Declaration.

Preface

The Wadden Sea is in transition. Human activities such as coastal protection, energy, tourism, shipping, and fisheries, combined with the accelerating impacts of climate change, biodiversity loss, and pollution, are placing growing pressure on this unique ecosystem. These influences interact in complex and interconnected ways, creating cumulative effects that are challenging to understand and even harder to manage. As a trilateral cooperation, recognition and response to these combined pressures is one of our most urgent tasks. The theme of the 16th International Wadden Sea Symposium "**The Wadden Sea in Transition: Cumulative Pressures and Conservation**," was developed to address this challenge and to emphasise the need for coordinated, evidence-based management across the three Wadden Sea countries.

More than 200 scientists and stakeholders from Denmark, Germany, and the Netherlands answered our invitation to Groningen. From 28 to 30 October 2025, we exchanged the latest knowledge on the Wadden Sea World Heritage Site, deepened our shared understanding of the cumulative pressures acting on this unique ecosystem, and discussed emerging issues and knowledge gaps relevant for trilateral decision making. The exceptionally high interest—all 200 seats filled within days after opening up the registration and another 200 followed the conference online —reflects the urgency and policy relevance of the issues addressed.

Anne Marie Rasmussen, Chair of the Wadden Sea Board, and Arno Brok, Chair of the Wadden Region Environmental Council, set the stage with reflections on current challenges and opportunities. Throughout the following three days and across three keynote lectures, more than 60 oral presentations, 40 posters, and four excursions, the participants of the symposium explored how natural dynamics and human induced influences interact to affect the site's Outstanding Universal Value (OUV). The insights presented in Groningen offer a unique evidence base that can support harmonised policy development, strengthen cross border alignment, and bring us on the pathway towards long term ecological resilience in the Wadden Sea Region.

One of the recurring messages throughout the symposium was the importance of transboundary cooperation: the Wadden Sea is one ecosystem—dynamic, interconnected, and shared by us all. Addressing cumulative pressures, therefore, requires joint scientific understanding, joint monitoring, and joint management responses. We were encouraged by the many examples of cross border collaboration presented during the sessions and by the willingness of participants to challenge, refine, and expand one another's perspectives. This is the spirit that has driven the Trilateral Cooperation for almost half a century now and we call on all partners in the Wadden Sea to continue this path.

We thank the presenters, moderators, r and participants for their contributions, commitment, and continued engagement. We express our appreciation to the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature for supporting this symposium, and to the Netherlands

Enterprise Agency and our organisational teams at the Waddenacademie and the Common Wadden Sea Secretariat for ensuring its effective delivery.

As a central purpose of the symposium was to generate the scientific input in preparations for the Trilateral Governmental Conference in May 2026, we hope that this conference report will serve both as documentation of the knowledge shared and as a resource for policymakers, managers, and stakeholders to make informed, future oriented decisions for the protection and sustainable management of the Wadden Sea World Heritage Site.

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1. About the 16th ISWSS

The 16th International Scientific Wadden Sea Symposium (ISWSS) took place from Tuesday 28 October to Thursday 30 October 2025 in Groningen, the Netherlands. Under the theme "The Wadden Sea in Transition: Cumulative Pressures and Conservation," the symposium explored how natural and human-induced forces interact and affect the Outstanding Universal Value (OUV) of the Wadden Sea World Heritage Site. The aim of the symposium was to gain a better understanding of these combined influences and their implications for management and policy.

Over the course of three days, participants exchanged the latest knowledge on the pillars of the OUV and on transition pathways towards sustainability in the Wadden Sea region through presentations, posters and excursions:

- Three keynote lectures addressed the EU Nature Restoration Law, the method of Strategic Environmental Assessment, and the historical human footprint in the Wadden Sea region.
- The excursions provided an opportunity to view key projects in the Groningen region. Participants could choose between visiting the 'Werelderfgoedcentrum' (WEC) in Lauwersoog, the Lauwersmeer National Park, the Ems estuary or the Wadden Sea coastline.
- In the poster session there was specific attention to the progress of the NWO projects, a German-Dutch research programme on understanding complex pressures on the Wadden Sea.
- Main focus of the symposium were the 55 presentations divided into thematic sessions throughout the symposium.

Before the symposium, a call for abstracts was issued to identify and select the most recent research to be presented during the event. This call focused on cumulative impacts of natural (e.g., tides and seasons) and human-induced forces (e.g., climate change, pollution, fisheries, energy, ports & shipping, coastal defence, tourism) on the OUV of the Wadden Sea World Heritage Site.

Figure 1. Themes call for abstracts. The Wadden Sea in Transition: Cumulative Pressures and Conservation

The call for abstracts received an overwhelming number of submissions (more than 120) for both oral and poster presentations, a clear indication of the continuing importance of Wadden Sea research. Contributions were mainly submitted by Germany and Dutch scientists (see table 1).

Table 1. Country of origin of applicants of abstracts

Country	Number of applicants
Denmark	3
Germany	58
Netherlands	63
Other	3
Total	**127**

Table 2: Number of abstracts per theme (poster and/or presentation) submitted for the call

Theme	Number of abstracts
1.Geological Processes	36
2. Ecological processes	61
3. Biodiversity	51
4. Integrity	6
5. Protection and Management	55
6. Climate Action	24
7. Green Shipping	2
8. Tourism	11
9. Water Resilience	3
10. Broad Prosperity	3
11. Sustainable Fisheries	14
12. Renewable Energy	5

The submitted abstracts revealed a strong focus on geological and ecological processes, as well as biodiversity and protection and management as the main research areas currently being studied in the Wadden Sea. In contrast, only a limited number of contributions were received on topics such as renewable energy, green shipping, broad prosperity, integrity and water resilience (Note: abstracts could be submitted under multiple themes).

2. Conclusions and Recommendations

2.1. CONCLUSIONS AND RECOMMENDATIONS: GEOLOGICAL PROCESSES

Recent research titled "**Footprints of Sunken Settlements – Geophysical and Geoarchaeological Investigations in the Wadden Sea of North Frisia**" has revealed the remains of two drowned medieval villages using magnetic gradiometry and seismic reflection. The study identified traces of terps, dykes, buildings, and peat extraction areas, illustrating how historical land use and peat removal increased vulnerability to flooding. It shows how human activities have long shaped the Wadden Sea landscape and how erosion and tourism now threaten its buried cultural heritage. These findings highlight the need for continued archaeological and interdisciplinary research on landscape evolution and environmental impacts in the region.

Morphodynamics in the Wadden Sea are driven by the interplay of natural forces and long-term human interventions. Dredging, land reclamation, and channel deepening have altered sediment pathways and reduced the system's natural capacity to retain fine sediments, increasing sediment mobility and reducing cross-border exchange. More specifically, all existing and planned actions related to fine sediment dynamics in the Dutch part of the Wadden Sea reduce the cross-border transport towards the East. Sustainable coastal management requires an adaptive and collaborative approach that integrates historical impacts, cross-border sediment dynamics, and tidal flat resilience under rising sea levels. By combining existing tools, such as field data analysis, remote sensing, and numerical modelling, with emerging technologies like machine learning and AI, we can deepen our understanding of morphodynamic processes in the Trilateral Wadden Sea. Effective management depends on linking scientific insights with socioeconomic realities and fostering cooperation across disciplines and national borders.

Nature-based approaches in the Wadden Sea for **coastal protection** demonstrate that dredged sediment can be repurposed to support salt marsh restoration, dike reinforcement, and ecological enhancement. Pilot projects such as Mud Motor, Marconi, and Kleirijperij show how engineered interventions can work with natural sedimentation processes, while advanced sediment tracing techniques improve understanding of sediment transport and nourishment impacts. Effective, socially supported and durable coastal protection strategies require context-specific, place-based solutions that acknowledge historical development and community identity. A one-size-fits-all coastal engineering is not viable in the Wadden Sea and tailoring nature-based coastal protection as standard practice by integrating multidisciplinary strategies is the key to a successful outcome.

Sediment sinks, areas where transported sediment accumulates, play a central role in shaping the Wadden Sea's intertidal habitats, where hydrodynamics, vegetation, and human activities strongly interact. Shellfish beds function as dynamic sediment sinks influenced by dredging and sea-level rise. In salt marshes with brushwood groynes, changes in water flow boost sediment buildup and influence how vegetation zones form through biogeomorphic feedbacks. Drone-based

monitoring identifies site-specific elevation thresholds for vegetation, showing that sheltered sites support plant growth at lower levels. Shellfish beds and brushwood groyne fields are nature-based solutions that promote sedimentation and show that sedimentation rates are spatially variable. Natural and managed processes can jointly control sediment dynamics and habitat evolution, guiding sustainable coastal and ecological management in the Wadden Sea.

2.1.1. Recommendations Geological Processes

Scientific

- Conduct integrated, cross-border studies across the Dutch, German and Danish Wadden Sea, that compare long-term morphological developments under sea-level rise, human interventions, and improved insights into sediment connectivity and transport pathways. This should result in the extension and refinement of the trilateral mud balance as the basis for the development of regional sediment management strategies.
- Undertake integrated research that combines field data, remote sensing, and process-based numerical models with emerging machine-learning and AI techniques to improve predictions for the morphological dynamics of the Trilateral Wadden Sea under climate change.
- Focus on a multidisciplinary approach in geological science in the Wadden Sea. 1) Develop coupled physical-biological models to integrate the influence of biological processes on sediment dynamics and habitat formation. 2) Combine geomorphology, ecology and social sciences to refine integrated coastal zone management strategies.
- Execute long term monitoring of pilot projects on coastal protection. Assess the durability of dredged material for dike reinforcement or the results of sand nourishment to determine the long-term effectiveness of nature-based engineering for coastal protection, erosion resistance and ecosystem responses. At the same time, assess the impact of these measures on the regional and trilateral sediment budgets.
- Use participatory research to engage local communities and stakeholders in co-designing flood safety and landscape management plans. Explore how locally tailored strategies can improve social acceptance and ecological effectiveness.
- Foster international collaboration and data sharing across the trilateral Wadden Sea region to address sediment dynamics and morphological changes holistically.
- Promote integrated monitoring programs combining bathymetry, hydrodynamics, and ecological indicators to support evidence-based decision-making.

Policy and Management

- Incorporate knowledge of historic human interventions and delayed system responses into coastal management planning and impact assessments.
- Prioritise adaptive sediment management strategies that consider cross-border sediment budgets, especially in light of anticipated sea-level rise and increasing sediment extraction pressures.

- Promote nature-based coastal protection as standard practice in policies and actively involve local stakeholders to create resilient, multifunctional coastal systems.
- Use and regularly maintain brushwood groyne fields and shellfish beds as nature-based solutions to trap sediments, thereby strengthening shoreline protection.
- Embed cultural, social, and stakeholder perspectives in coastal protection strategies. Locally tailored solutions must consider the cultural landscape, heritage values, and community involvement.

2.2. CONCLUSIONS AND RECOMMENDATIONS: BIODIVERSITY AND ECOLOGICAL PROCESSES

Habitat complexity and ecosystem structure are key drivers of **biodiversity recovery** and resilience. Structural elements in habitats (e.g. wood, sediment composition, microhabitats) directly influence the ecosystem functioning. Restoring or maintaining these structures supports juvenile development, energy transfer and overall ecosystem productivity. System-wide, multi-taxa monitoring is essential to understand and manage biodiversity changes. Long-term trends in the Wadden Sea and other coastal systems reveal synchronous declines in foundational species, shifts favouring non-native species, and hidden impacts of diffuse anthropogenic taxonomic groups, including often-overlooked sensitive organisms like meiofauna, to detect ecosystem-wide shifts, tipping points and drivers of change.

Different factors influence the waterbirds along the **East Atlantic Flyway**. Key species are influenced by food availability, climate change and mercury pollution, with a cumulative effect of multiple anthropogenic stressors and unpredictable events such as outbreaks of avian influenza. General waterbird abundance and composition in the Wadden Sea correlate with climate indices, nutrient discharge via river systems in the North Sea, benthic biomass and sediment dynamics, showing ecosystem processes directly impact bird population. For migratory species other sites along the East Atlantic Flyway are also important, highlighting the needs for flyway monitoring to understand population trends and figure out the impact of local management and conservation measures.

Different new **emerging insights** were presented during the symposium. Underwater sounds are studied, to match acoustic activity to biodiversity patterns and seasonal patterns. Above water sudden disturbances such as the avian influenza can cause a rapid impact on waterbird populations. On land carrion ecology shows how carcasses contribute to local biodiversity by supporting distinct scavenger communities.

The **primary productivity** in the Western Wadden Sea has remained relatively stable in recent years (2012-2023) but this balance may be fragile given the ongoing decline in biomass input from the North Sea and shifts in local light conditions. Integrated source to sea research shows that a healthy Wadden Sea ecosystem is dependent on land-based and riverine nutrient management:

nutrient loads need to be decreased by 30-50% to reach a healthy state. More monitoring and management is needed on Nitrogen: Phosphor ratios, to avoid destabilising shifts in the ecosystem.

Historic human interventions and salt marsh restoration influence the **blue carbon potential** of Wadden Sea salt marshes. Salt marsh restoration can recover blue carbon potential suggesting climate mitigation co-benefits. Man-made structures like dams and ditches leave an imprint on marsh carbon content, indicating that cultural landscape history affects ecological functioning. There is an urgent need for quantification of carbon sequestration rates and greenhouse gas fluxes of salt marshes and mudflats under different management regimes. Sites with high restoration potential (e.g. summer polders) can be prioritised to improve landscape-scale carbon sequestration.

2.2.1. Recommendations for Biodiversity and Ecological Processes

Scientific

- Investigate the influence of cumulative effects on thresholds and tipping points; there is limited understanding on how these might push ecosystems into irreversible shifts.
- To conserve waterbirds along the East Atlantic Flyway we need to understand changes at the population level but also gain more insight into their environment and how it is affected by different human activities.
- Passive Acoustic Monitoring of vocal activities of fish should be expanded to document more species and their interaction with anthropogenic sounds.
- Strengthen the monitoring of the Wadden Sea to include meiofauna and help capture ecological functioning and early signs of stress.
- Investigate the role of nutrients other than nitrogen, such as phosphorus and silica in controlling algae bloom composition and ecosystem responses. Also monitor nitrogen-phosphorus ratios to avoid shifts that could destabilise phytoplankton communities or degrade organic matter quality.
- Use large-scale catchment models to illustrate the impact of riverine and land systems on the Wadden Sea.
- There is an urgent need to quantify carbon sequestration rates and greenhouse gas fluxes of salt marshes and mudflats, considering hydrodynamics, sedimentation and vegetation succession, also under different climate change and management scenarios.
- Identify sites with high salt marsh restoration potential through model development.

Policy and Management

Biodiversity and Recovery

- Consider nature-based solutions such as reintroduction of tree-reefs in the marine restoration programs. They represent cost-effective, ecologically grounded tools for restoring habitat complexity and improve the coastal stability.

- Policy approaches should move towards ecosystem-wide, multi-taxa strategies, also including meiofauna and other benthic microfauna. This requires a shift from the current focus on single-species protection towards an ecosystem-based approach. Standardised long-term monitoring across all major taxonomic groups can help identify critical points of ecological change and key environmental drivers.

Emerging Insights

- Establish coordinated international surveillance and rapid response frameworks for disease outbreaks to minimise spread.
- Recognise carrion's ecological role in coastal management plans by maintaining natural processes that allow scavenger communities to thrive.

East Atlantic Flyway

- Support and expand the Wadden Sea Flyway Initiative (WSFI) via secure long-term funding to build capacity in key regions (especially Africa) and ensure coordinated international monitoring and conservation efforts.

Primary Productivity

- Foster integrated catchment-coastal management policies acknowledging the Wadden Sea as dependent on upstream actions.
- Implement more stringent nutrient reduction targets, aiming for at least 30-50% decreases in riverine nitrogen loads relative to 2010 levels to support Wadden Sea seagrass recovery and reduce eutrophication impacts.
- Manage nitrogen-phosphorus ratios to avoid shifts that could destabilise phytoplankton communities or degrade organic matter quality.

Carbon Sequestration

- Support salt marsh restoration as a climate mitigation strategy, especially in regions where restoration reconnects summerpolders to the tidal influence. Integrate blue carbon accounting into restoration project planning and reporting, as requested by EU law.
- Support salt marsh restoration to improve natural dynamics.

2.3. CONCLUSIONS AND RECOMMENDATIONS: PROTECTION AND MANAGEMENT

The **EU Nature Restoration Law** is a new and proactive law (since 2024) which can play a crucial role in the protection of the Wadden Sea. Member States are required to develop and implement National Restoration Plans to reach a 30% coverage of sea areas with active restoration measures in 2030 and a 100% coverage in 2050. The Nature Restoration Law can be successful for the improvement of the Wadden Sea region if it is applied proactively by the Member States, grounded in scientific evidence and supported by a trilateral approach.

The Wadden Sea is required to execute a **Strategic Environmental Assessment** in the coming years. The SEA is a systematic process to evaluate the significant environmental effects of policies, plans and programmes. Via the SEA for the Wadden Sea recommendations will be formulated to secure the Outstanding Universal Value (OUV) of the Wadden Sea; what can be done to improve the quality of the area? Currently, a trilateral group is studying the scope of the SEA. Assessing cumulative impact on the OUV will be one of the big challenges in this SEA.

Cumulative impacts in the Wadden Sea ecosystem are highly complex due to multiple pressures, including human activities, climate change and cross-boundary effects from the adjacent North Sea. Monitoring, and addressing cumulative impacts in the Wadden Sea requires multi-disciplinary, cross-border approaches combining advanced spatial assessment tools, ecological modelling and ecosystem-based governance to maintain ecosystem resilience amid ongoing pressures. Therefore, there is an urgent need for integrated, trilateral governance and ecosystem-based Marine Spatial Planning that links Wadden Sea conservation with broader North Sea management to effectively address cumulative impacts across boundaries.

Different methods focus on the monitoring of these **pressures and the state** of the Wadden Sea area. In the Dutch 'State of the Nature of the Wadden' different ecological indicators give a coherent overview of the status of the Wadden Sea. Benthic species data reveals a fine-scale spatial variability and connections between biodiversity patterns and anthropogenic pressures. The combined findings emphasise the complexity and multi-scale nature of pressures on the Wadden Sea, from localised habitat changes to broad-scale ecological transformations. To incorporate different facets of ecological variation it is recommended to protect different gradients within the Wadden Sea system.

There are new **frameworks** available to better incorporate ecological values within the socio-economic valuation. Biomimicry can help address cultural and narrative dimensions, enriching nature-based innovation with relational and symbolic meaning. A meta-analysis of willingness to pay for nature-based solutions reveals how economic valuation depends on different factors, which can be used to tailor policy and investment decisions. Social-ecologic visualisation through Sankey diagrams highlights interlinked ecological and social components for integrated conservation planning.

2.3.1. Recommendations for Protection and Management

Scientific

- Pressures on the Wadden Sea originate from an area beyond the Wadden Sea. To get a comprehensive image of the pressures research has to take into account a larger study area including river basins, flyways and swimways.

- Collect and/or create more spatial data on human activities and pressures. Refine and validate pressure-state relationships with empirical data and long-term monitoring to increase knowledge on additive and interactive effects and to improve predictive accuracy.
- Develop standardised, integrative methods for combining biological, physical, and socioeconomic data in cumulative impact assessments. Incorporate sensitivity mapping, climate change projections and scenario modelling to anticipate future cumulative pressures and represent alternative management pathways.
- Investigate functional traits and ecosystem processes (e.g., autotrophy vs heterotrophy balance) in benthic communities to better understand the ecological consequences of species introductions and shifts. Develop scenario modelling to predict future benthic ecosystem states under different climate and management regimes, including novel ecosystem trajectories.
- Explore cross-border data integration to expand the monitoring framework for holistic regional assessments.
- Further refinement and regional calibration of the economic meta-analysis model, incorporating Wadden Sea-specific data on ecosystem services, local stakeholder values, and long-term climate risk scenarios.

Policy and Management

- From a policy perspective, proper reference values for the Wadden Sea have to be defined. When is the status of the Wadden Sea good enough?
- Apply the EU Nature Restoration Law proactively, grounded in scientific evidence and supported by a trilateral approach.
- Adopt spatially explicit, ecosystem-based cumulative impact assessments like SCAIRM as strategic decision-support tools to identify high-risk activities and risk-sensitive areas, prioritise mitigation and restoration efforts, and for enabling integrated, ecosystem-based Wadden Sea management.
- There is an urgent need for integrated, trilateral governance and ecosystem-based Marine Spatial Planning (MSP) that links Wadden Sea conservation with broader North Sea management to effectively address cumulative impacts across boundaries. Also, enhance the social-ecological link visualisation by integrating more quantitative data from monitoring programs and expanding to include additional species, ecosystem services, and stakeholder groups for comprehensive MPA planning.
- For effective protection of the Wadden Sea it is recommended to protect gradients, so that you incorporate all facets of variation and dynamics.
- Use cross-disciplinary collaboration to explore how economic valuations, social-ecological visualisations, and biomimetic design principles can be combined into a unified decision-support framework for coastal management.

2.4. CONCLUSIONS AND RECOMMENDATIONS: CLIMATE CHANGE

Studies on **warming** examine the impacts of **rising temperatures** on key coastal species in the Wadden Sea. They investigate both direct physiological responses and broader ecological consequences. Elevated substrate temperatures affect recruitment and predator-prey interactions, potentially altering intertidal community composition, as warm summers lead to shifts in habitat use, species abundance, and phenology over multiple decades, highlighting potential implications for ecosystem function and resilience. Climate warming does not affect species equally, creating potential 'climate winners' and 'losers'. For example, active intertidal macrozoobenthos species experience increased mortality and altered physiological responses during simulated marine heatwaves, while warmer conditions favour the growth and spread of non-native algal species through enhanced primary production and photosynthesis. These findings indicate that global warming will differentially impact Wadden Sea species, causing heat-sensitive fauna to decline while promoting warm-adapted algae. Species-specific and trait-based approaches can help predict community-level changes under marine heatwave events. This dual impact emphasises the need for integrated management strategies that account for both physiological limits and broader ecosystem changes to protect the biodiversity and ecological functionality of the Wadden Sea under climate change.

The Wadden Sea's morphological and ecological development under **sea level rise** is strongly influenced by sediment dynamics and vegetation, which are key drivers of coastal resilience. Over the past decades, geomorphological changes show asymmetric patterns of accretion and erosion, with spatial variability in sedimentation. Vegetation dynamics along tidal areas are shaped by hydrodynamics, sedimentation, and climate stressors, affecting plant growth and mortality. Understanding the feedbacks between sedimentation and vegetation is essential for predicting marsh development and stabilising shorelines under rising sea levels.

Storm events in the Wadden Sea and broader North Sea region have shaped both historical and contemporary coastal responses. Sedimentary evidence, such as Klappklei layers, reveals the impact of prehistoric storm surges along the undiked Holocene coastline. Experiments in full-scale flumes demonstrate that salt marshes are resilient to strong storm surges and can act as effective natural buffers. Understanding both the long-term geological imprint of storm surges and the short-term physical responses of salt marsh systems is essential for assessing coastal resilience and guiding sustainable adaptation strategies in the Wadden Sea region.

2.4.1. Recommendations for Climate Change

<u>Scientific</u>

Warming

- Conduct field experiments to verify warming effects under realistic intertidal exposure conditions.

- Continue and expand long-term and seasonal monitoring of coastal species to capture interannual variability, temperature-driven shifts, and phenological changes, including habitat and depth influences.
- Investigate physiological and behavioural mechanisms of benthic species and algae as well as the community responses of native fauna to thermal acclimation, including thermal history effects, stress responses, microhabitat selection, and species-specific vulnerability under warming conditions.
- Spatial comparisons: Compare Wadden Sea responses to other coastal and Arctic sites to assess regional differences in vulnerability and resilience, conduct cross-regional comparative studies to understand why warming effects differ between temperate and Arctic coasts.
- Investigate ecosystem-level consequences of heat stress and algal proliferation, including effects on benthic fauna, sediment biogeochemistry, nutrient fluxes, and trophic interactions.
- Support integrated, long-term ecological monitoring programs and long-term seasonal surveys to detect changes in abundance, size, and habitat use of species. Also, monitor and manage invasive species risks. The findings indicate that continued warming may favour warm-adapted and non-native species. This suggests that future species expansions are possible under ongoing climate warming.

Sea Level Rise

- Analyse spatially explicit patterns of erosion and accretion, including gradients in tidal elevation, flow, waves, and sediment type, to better understand drivers of sediment dynamics in different parts of the Wadden Sea.
- Extend vegetation models to include other processes such as waves and multi-saltmarsh species interactions to improve predictions and understanding of the system.

Storms

- Investigate Klappklei sediments origins and multi-event erosion trajectories, including species-specific vegetation responses, to understand saltmarsh resilience and storm impacts and map inland reach of past storm surges
- Conduct field validation of flume experiments on the resilience of salt marshes to storm surges across diverse saltmarsh and soil types to ensure results are generalisable and applicable to the Wadden Sea.

<u>Policy and Management</u>

Warming

- Incorporate species-specific and trait-based heat sensitivity data into conservation planning to identify vulnerable species and prioritise protection or restoration efforts.
- Consider adaptive management strategies that reduce additional stressors (e.g., pollution, habitat loss) to increase resilience of native benthic communities to climate change and

promote habitat heterogeneity to provide thermal refuges for vulnerable species during marine heatwaves

Sea Level Rise

- Promote understanding of large spatial trends in future sediment availability for different regions of the Wadden Sea area and use this information to set up adaptive sediment management strategies that enhance natural sediment supply to vulnerable Wadden Sea regions, especially where erosion dominates.
- Foster cross-sectoral cooperation, linking sediment and vegetation management with coastal protection, shipping, agriculture, and nature conservation policies.
- Prioritise monitoring programs to track morphodynamic and vegetation changes, enabling responsive management to emerging risks.
- Integrate vegetation conservation and restoration (e.g., reedbeds, salt marshes) into coastal protection plans and use improved process-based models to strengthen shoreline resilience and support management under future climate scenarios.

Storms

- Preserve, expand, and monitor natural saltmarshes as resilient buffers against storm surges, combining ongoing stability assessments with adaptive management under climate change and sea-level rise.
- In coastal protection and land-use planning, integrate nature-based solutions as complementary to hard infrastructure and historical storm data from paleo-records to inform long-term resilience strategies.

2.5. SOCIOECONOMIC INTERACTIONS

Degrowth-inspired tourism is a tool to align ecological limits, social well-being, and sustainable development goals. Since stakeholders hold divergent understandings of 'sustainable tourism development' from growth-oriented (visitor numbers, revenues) to degrowth-oriented (capacity limits, quality, and well-being), no universal model for degrowth applies. Success depends on locally adapted, network approaches that build on existing structures, connect to related frameworks like regenerative tourism and World Heritage, and include diverse community voices. One challenge is the debate over extending tourism seasons versus allowing ecological and social "resting periods."

The development of **ports and offshore wind farms** in the Wadden Sea region involves complex trade-offs across economic growth, coastal ecosystem integrity, and biodiversity conservation. The studies show it is important to integrate broad prosperity indicators into port development policies and relate that to regional broad prosperity developments to futureproof inclusive and sustainable regional development. Also, they show the need to make integrated

choices about offshore wind development based offshore wind farm effects on coastal ecosystems. It thus requires integrated frameworks combining socio-economic metrics, advanced environmental modelling, and ecological monitoring to inform balanced policies promoting sustainable regional prosperity and ecosystem resilience.

Mussel **fisheries** in the Wadden Sea have significant ecological consequences, particularly regarding mussel aquaculture and interactions between native and non-native bivalves. Mussel culture structures can support greater biodiversity than soft sediments but introduce spatial and temporal complexity that requires integrated management. The actual biodiversity benefits, especially compared to wild mussel beds, remain unclear. So far there are no signs that former commercial mussel aquaculture areas have a higher recolonisation rate of natural shellfish species. However, the proliferation of Pacific oysters negatively affects blue mussels, indicating potential long-term shifts in species dynamics and ecosystem functioning. Long-term, large-scale monitoring is essential to understand succession in aquaculture sites and biotic interactions on wild beds.

Brown shrimp stocks in the Wadden Sea are under significant pressure, with evidence of both growth overfishing and regional recruitment overfishing. Seasonal dynamics reveal that winter-hatched shrimp grow faster than summer cohorts, highlighting the need for adaptive management that protects egg-bearing females in winter and juvenile shrimp in summer. Current voluntary, self-regulatory management has not prevented stock declines, suggesting the need for stronger governance and binding measures. Effective management should include adaptive harvest strategies, seasonal or spatial closures based on cohort growth, and ecosystem-based approaches that consider habitat and multi-species interactions. Reducing fishing effort may improve both stock recovery and catch efficiency. Enhanced monitoring, controlled fishing-effort trials, and integration of scientific advice with co-management frameworks are recommended to ensure sustainable shrimp fisheries and align with broader EU sustainability goals.

2.5.1. Recommendations for Socioeconomic Interactions

Scientific

Tourism

- Include degrowth-inspired thinking into research of (sustainable) tourism, develop measurable indicators and frameworks for tourism degrowth in protected areas and test applicability,
- Link to regenerative tourism and World Heritage interpretation connecting conservation, community resilience, and cultural understanding.

Ports and Windfarms

- Conduct interdisciplinary studies linking socio-economic data with environmental indicators to develop a comprehensive “broad prosperity” vision for Wadden Sea ports.
- Expand modelling of offshore windfarms impacts to include cumulative effects with port activities and climate change scenarios.

- Enhance monitoring programs on biodiversity across the entire Wadden Sea to incorporate lighting mitigation experiments to quantify benefits.

Mussel and Shrimp Fisheries

- Investigate the carrying capacity of mixed beds for filter feeders, focusing on nutrient limitation and food web impacts.
- Long-term ecological monitoring: extend biodiversity and habitat assessments on former mussel culture plots to better understand successional dynamics, resilience thresholds, and biotic interactions over time.
- Model the long-term ecosystem effects of species replacement, particularly Pacific oyster dominance.
- Expand monitoring to include higher trophic levels (e.g. predators, seabirds) that depend on or affect mussel beds, and compare ecosystem functioning across wild, cultured, and mixed beds under climate stressors (e.g. temperature, eutrophication).
- Comparative studies across Wadden Sea regions: assess where similar aquaculture cessations are occurring to detect regional patterns of resilience, adaptation, or ecological collapse.
- Pilot trials with reduced fishing intensity to quantify ecological responses (e.g. biomass recovery, size structure) and economic trade-offs (e.g. CPUE, cost-efficiency). It should be noted that natural variability can certainly override the effects of management measures.
- Ecosystem-based modelling: Improve existing integrated bioeconomic and ecosystem models that simulate outcomes of different management strategies and regulatory regimes, accounting for growth rates, recruitment, market dynamics, and ecosystem impacts (including climate change).
- Expand demographic monitoring: More detailed life-history data, especially related to egg-bearing females and cohort growth rates across seasons and regions, is needed to support dynamic harvest strategies.
- Evaluate governance effectiveness: Study the efficacy of the self-regulatory management, comparing it to other EU-regulated fisheries, and explore hybrid approaches blending voluntary and statutory measures.

<u>Policy and Management</u>

Tourism

- Facilitate inclusive, participatory tourism planning that integrates degrowth principles, considers residents' well-being, and balances economic, social, and ecological goals across the Wadden Sea region.
- Promote low-impact, sustainable tourism infrastructure and practices, including visitor flow management, economic diversification, and educational programs to reduce ecological pressure and enhance long-term social and environmental resilience.

- Promote cross-sectoral and transboundary cooperation to manage tourism impacts coherently across the Wadden Sea region.

Ports and Windfarms

- Integrate broad prosperity indicators into port development policies to ensure inclusive and sustainable growth, not solely economic expansion.
- Implement adaptive management strategies for offshore wind development that account for sediment transport changes and carbon cycle effects to protect coastal ecosystems.
- Develop guidelines and regulations to reduce light pollution in and around ports and offshore wind farms.

Mussel and Shrimp Fisheries

- Support adaptive mussel aquaculture management that includes transparent biodiversity monitoring and succession-based assessments and considers wild-culture interactions, invasive species control and ecosystem resilience.
- Implement targeted management of Pacific oyster spread, especially in high-value blue mussel habitats.
- Designate adaptive management zones: use areas like the List tidal basin as experimental recovery zones where natural dynamics inform restoration potential and low-impact fishing strategies can be tested.
- Align spatial closures with fishery behaviour and promote habitat restoration within MPA planning: future management should integrate vessel behaviour data encourage proactive transition strategies for vulnerable metiers like shrimp fishing while using insights from mussel recolonisation to inform restoration-enhanced MPAs.
- Support fishery transition programs focused amongst other on modernising brown shrimp fishery management:
  - Implement adaptive harvest strategies that reduce effort during key recruitment (winter) and growth periods (summer).
  - Introduce spatial or seasonal closures based on new cohort growth insights (e.g., protect winter hatchlings).
  - Align with EU sustainability targets (MSY) even if not directly governed under EU fisheries law.
- Incentivise sustainable behaviour:
  - Provide economic incentives or MSC-certification bonuses for vessels adopting lower-impact practices.
  - Link access to certain grounds or quotas to compliance with scientifically advised effort reduction schemes.
- Promote multi-species and habitat-conscious management:

- Position brown shrimp management within a broader ecosystem-based fisheries management approach, considering habitat interactions, predator-prey dynamics, and sediment impacts

3. Keynotes

3.1. DOES LAW MATTER – PROSPECTS OF THE EU NATURE RESTORATION LAW

Lecturer: Helle Tegner Anker | Moderator: Katja Philippart | Reporter: Els Wouda

The first keynote on Tuesday was given by **Helle Tegner Anker**, professor of Law at the University of Copenhagen. During her presentation she highlighted that **law plays a crucial role in the protection of the Wadden Sea**, particularly as the region is governed by a complex framework of international, EU and national legislation addressing the protection of nature, landscapes, water and the marine environment. The EU Nature Restoration Law (NRW) is a new and proactive law (since 2024) setting obligations on Member States to improve and restore e.g. coastal and marine ecosystems.

Key lessons that were shared considering the EU Nature Restoration Law were:

- Many laws considering the Wadden Sea region are primarily reactive, focusing on regulating new projects or activities through detailed assessment and permitting procedures. The NRW is a proactive rule focused on implementation of restoration measures to reach 30% coverage of sea areas with active restoration measures in 2030 and a 100% coverage in 2050;
- The NRD faces challenges, particularly in balancing existing land uses and stakeholders (such as farmers on land). The member states are currently required to develop and implement National Restoration Plans;
- For the Wadden Sea region a trilateral, science-based approach combining EU-level coordination with national action, could maximise the law's effectiveness while allowing for the consideration of socio-economic activities;
- The focus on restoration measures rather than a guarantee of result may limit the effectiveness of the NRW and the national Restoration Plans.

These lessons need to be taken into account by the Member States during the development of their National Restoration Plans. The Member States should apply the NRW proactively, grounded in scientific evidence and supported by a trilateral approach.

3.2. STRATEGIC ENVIRONMENTAL ASSESSMENT SUPPORTING GOVERNMENT DECISION-MAKING ON THE FUTURE OF THE WADDEN SEA

Lecturer: Arend Kolhoff | Moderator: Sascha Klöpper | Reporter: Rosanne Verbree

The keynote talk on Wednesday was given by **Arend Kolhoff**, from the Netherlands Commission for Environmental Assessment. During his presentation Arend explained **the importance of Strategic Environmental Assessment (SEA) for government decision-making on the future of the Wadden Sea** as a World Heritage Site. SEA is a legal decision-making governance

and evidence-based support tool that aims to contribute to sustainable development via government policies, plans and programs. Therefore, an integrated multi-sector approach is applied in SEA. SEA complements Environmental Impact Assessment (EIA) that aims to assess and mitigate environmental impacts at project level.

Besides the EU member states, the United Nations acknowledge the importance of SEA and promote the legal uptake and world-wide use. World Heritage Sites (WHS) under threat are requested to apply SEA and implement the recommendations to maintain their unique status. In 2023 the World Heritage Committee expressed concerns about different human activities within, near, or beneath the transboundary Wadden Sea World Heritage Site and requested a joint SEA.

Key lessons on SEA are:

- Pressures/threats to the WHS come from inside and outside. Therefore, the study area for the SEA has much larger boundaries than the WHS itself for example boundaries for the Wadden Sea may include the river basins, flyway and swimway);
- Responsible authorities for measures tackling pressures must have a key role in the process;
- Decision-making is dealing with risks and uncertainties and is also based on expert opinion next to science; SEA raises high levels of interest of the society and is therefore an open and accountable process.

These lessons have to be applied in the SEA for the Wadden Sea. By highlighting some interesting projects in the Netherlands, such as the container accident with the MSC Zoe, PAWOZ, Fish migration river, Vision Lauwerscoast 2050, Arend explains how broad the scope of the SEA might be and that outcomes of these projects need to be taken into account in the SEA. The joint SEA aims to integrate transboundary effects and consider all activities that may impact the Outstanding Universal Value (OUV) of the Wadden Sea. An important question according to Arend is: What can be done extra to improve the quality of the area, instead of meeting the minimum UNESCO requirements? Currently, a trilateral group has been established for the scoping of the SEA. The purpose of the scoping report is to set out the main issues, approach and methodology to be used in the SEA on the Wadden Sea.

3.3. FOOTPRINTS OF SUNKEN SETTLEMENTS – GEOPHYSICAL AND GEOARCHAEOLOGICAL INVESTIGATIONS IN THE WADDEN SEA OF NORTH FRISIA

Lecturer: Dennis Wilken | Moderator: Katja Philippart | Reporter: Bernike van Werven

The last keynote on Thursday was presented by **Dennis Wilken**, from Kiel University, institute of Geosciences. During his keynote Dennis Wilken told the story of their scientific study '**unravelling the history of two drowned villages in the German North Frisian Wadden Sea**'. Through magnetic gradiometry and seismic reflection geological underground imprints can be made visible showing locations of terps, dykes and buildings.

In the area of the old mythical 'village of Rungholt' a building structure was found of a 40-meter length church, many terps and a dyke system, with agricultural land where the peat was removed. The removal of peat subsequently made the area more vulnerable to storm floods. The nearby area of 'Hallig Hooge' in contrast shows an industry of peat extraction with channels, damns and pits.

Key lessons from the investigations are:

- Archaeological research is more complex in regions where land wasn't reclaimed after floods. Information lies hidden in the tidal flats;
- The research gives us more insight in historical human use of the Wadden Sea Region; where did people live, what economic activities were undertaken, and how did this impact the land?;
- The area of North Frisia is a protected area of natural heritage, so it is protected from the impact of fisheries. However, tourists collecting archaeological remains forms a pressure;
- Erosion of the area (e.g. movement of tidal creeks) is the main pressure endangering the cultural heritage. Imprints and remains get lost over time when they are exposed.

These lessons highlight the importance of archaeological prospection and integrative research on the cultural landscape development. With more research different areas can be studied in more detail. One of the topics that can be looked into is the emitted carbon from peat removal in the agricultural areas.

4. Thematic Sessions

4.1. PARALLEL SESSIONS ROUND 1

4.1.1. Geological Processes: Morphodynamics

Presentations:

- Understanding Morphodynamics in the Wadden Sea Using Observations and Numerical Modeling
  Mengyao Ma, Helmholtz-Zentrum Hereon
- Morphodynamic Patterns of the German Wadden Sea and Predictability
  Bo Miao, Helmholtz-Zentrum Hereon
- Fine Sediment Dynamics in the Trilateral Wadden Sea
  Bas van Maren, Deltares

Moderator: Sarah Dzimballa | **Reporter**: Piet Hoekstra

Scientific Insights and New Knowledge

- A morphological study based on field data (TrilaWatt) and numerical modelling of the North coast of the East Frisian Islands shows that tidal inlets and the (upper) shoreface of the islands are very dynamic. The absolute evolution range is largest for the tidal inlets. The (upper) shoreface is dynamic due to the presence of transverse bars that migrate in a alongshore direction, slightly oblique relative to the coast.
- Bidirectional migration of the transverse bars (~40 m/year, to both the West and the East) and consistent eastward migration of tidal channels (~10 m/year) have been quantitatively documented, highlighting dynamic sediment redistribution patterns.
- Numerical modelling confirms that morphological evolution results from complex interactions between hydrodynamic forces and sediment transport, with different dominant drivers in foreshore areas (alongshore currents, waves, tides) versus tidal channels (primarily tides).
- A second study based on field data, multivariate EOF analysis and numerical modelling shows a number of morphological trends; intertidal basins show accretion, tidal channels are continuously migrating and deepening and ebb deltas expanding until about 2016 (dataset 1998-2022). Both extreme water levels (storm surges) and tidal range show a significant positive correlation with the magnitude of morphological changes (EOF analysis).
- Historic and ongoing human interventions (e.g., land reclamation, creating polders, dredging and channel deepening) have long-lasting impacts on fine sediment (mud) dynamics, with system responses potentially spanning centuries and cross-border sediment availability affecting morphological equilibrium. A lot of the storage space for mud has disappeared (“removing a sink creates a source….”).
- Mud settles in fairways and after dredging is often disposed again in channels which keeps the sediment mobile. Mud remains mobile due to a lack of compaction and consolidation in response to wave action.

- There is increasing recognition that fine sediment supply and morphology in one region (e.g., Dutch Wadden Sea tidal basins) can significantly influence neighbouring areas (German and Danish Wadden Sea), underscoring the interconnectedness of this coastal system.

Scientific Discussion Points

- There is discussion about the terminology used in the first paper. What is described as megaripples (in the abstract) or sand ridges (during the presentation) is in reality a system of transverse bars that develops at the East side of outer or ebb tidal deltas along the North Sea coast.
- There were questions about the performance of the numerical model. Most of the existing sediment transport models have the tendency to flatten out existing bedforms. The migration of tidal inlets is primarily explained by tides although the alongshore transport by wave- and wind-driven currents is commonly much large than the transport by tides.
- The relative contributions and feedbacks between natural forces and anthropogenic activities require further elucidation, particularly regarding delayed system responses and spatial scales of impact.
- Do we have too much mud in the Wadden Sea system? This depends on the context. For example: sediment extraction and disposal practices may influence the long-term stability and resilience of tidal flats under changing sea levels since we also need muddy sediment to compensate for sea level rise.
- The role of seasonal and episodic events (e.g., storm surges, river discharge variability) in driving short-term morphological variability needs deeper investigation.
- The applicability and limits of combining statistical analyses, numerical modelling, and machine learning for predicting morphodynamics require further investigation

Suggestions for Scientific Follow-up

- Extend high-resolution observational datasets to better capture short-term variability and episodic events, enabling improved model validation.
- Carry out comparative studies to explain both similar and contrasting long-term morphological developments in the Dutch and German Wadden Sea (include the Danish part if relevant), in particular in relation to the potential effects of sea level rise.
- Develop coupled physical-biological models to integrate the influence of biological processes on sediment dynamics and habitat formation.
- Investigate sediment connectivity and transport pathways across national borders to inform regional sediment management strategies. In relation to this: improve, extend and refine the existing mud balance for the Trilateral Wadden Sea.
- Explore long-term predictive capabilities of machine learning approaches in tandem with process-based models and field data to refine forecasts of morphological evolution under climate change scenarios.

Recommendations for Policy/Management

- Foster international collaboration and data sharing across the trilateral Wadden Sea region to address sediment dynamics and morphological changes holistically. Incorporate knowledge of historic human interventions and delayed system responses into coastal management planning and impact assessments.
- Prioritise adaptive sediment management strategies that consider cross-border sediment budgets, especially in light of anticipated sea-level rise and increasing sediment extraction pressures.
- Promote integrated monitoring programs combining bathymetry, hydrodynamics, and ecological indicators to support evidence-based decision-making.

4.1.2. Biodiversity: Communities

Presentations:

- Tree-reefs restore trophic complexity and reef communities
  Jon Dickson, Royal Netherlands Institute for Sea Research
- Synthesis of population trends reveals seascape-wide reorganisation of biodiversity
  Kasper Meijer, Groningen Institute for Evolutionary Life-Sciences, University of Groningen
- Unseen Foundations: Meiofauna's Impact on Wadden Sea Food Web
  Alexandra Möller, Senckenberg am Meer, German Centre for Marine Biodiversity Research (DZMB)

Moderator: Oscar Franken | **Reporter**: Irene Rollingswier

Scientific Insights and New Knowledge

- Habitat complexity is fundamental to biodiversity recovery. The tree-reef study demonstrates that reintroducing lost structural elements, such as submerged wood, can restore critical benthic habitats, increase fish and shellfish abundance, and enhance trophic interactions.
- By adding wood to the sea, tree-reefs reconnect land–sea nutrient and structural inputs that were historically present but have since been lost. These complex, three-dimensional habitats support fauna of various sizes, providing essential nursery grounds for juvenile fish and egg development. The ecological implication is clear: restoring habitat structure directly strengthens biodiversity, productivity, and ecosystem resilience.
- System-wide biodiversity reorganisation is underway. A synthesis of long-term population trends shows consistent declines in foundational species such as fish, zooplankton, and plants partially masked by localised increases in bird populations. This pattern indicates a large-scale ecological restructuring driven by cumulative environmental stressors.
- A comprehensive synthesis that integrates data from all major organism groups is essential. Such integration would make it possible to detect whether different taxa are changing simultaneously in time and space, providing stronger evidence for ecosystem-wide shifts in the state of nature.

- Current data suggest that non-native species are performing better than native ones, while temporal synchrony in declines across multiple taxa points to a broad, system-wide transition in biodiversity dynamics.
- In fine sandy sediments, low friction and smaller pore volume result in a higher organic content. This supports a higher abundance of meiofauna, although diversity and individual biomass remain relatively low. In contrast, coarser sediments have higher friction and lower organic content, leading to lower meiofaunal abundance but higher diversity.
- Within the meiofauna, copepods generally occupy lower trophic levels, feeding mainly on pelagic food sources such as phytoplankton making them primary consumers. Nematodes, however, exhibit higher trophic levels, often functioning as secondary consumers or decomposers, feeding on other organisms. Copepods tend to be generalists, while nematodes show more specialised feeding behaviours depending on habitat conditions.
- This study confirms that meiofaunal community structure is strongly shaped by benthic habitat characteristics a well-known concept, but applied here for the first time in this specific research area. Meiofauna play a key role in transferring energy within benthic food webs, supporting higher trophic levels. Even at small spatial scales, clear differences in food sources and trophic niches are observed between nematodes and copepods.

Scientific Discussion Points

- An interesting ecological interaction emerged in the study area: crab populations declined near the tree-reef sites, likely due to increased predation by medium-sized cuttlefish that use the reefs as hunting grounds. This dynamic may actually benefit restoration goals, as excessive crab abundance can inhibit mussel and oyster recovery. Thus, the altered food web structure associated with tree-reefs may indirectly facilitate shellfish restoration and improve overall ecosystem balance.
- There is an ongoing discussion on how biodiversity should be measured within complex systems like the Wadden Sea, and what “biodiversity” truly means across the multiple ecological and policy frameworks applied there. The available data provide valuable insight into overall group-level trends, yet may still overlook functional and structural aspects of biodiversity change.
- Rethinking biodiversity indicators: Traditional monitoring often overlooks small, non-charismatic but functionally critical groups such as meiofauna.
- There is a need to emphasise functional diversity, trophic roles, and energy transfer pathways in both ecological research and conservation strategies.

Suggestions for Scientific Follow-up

- Extending the reintroduction of tree-reefs to intertidal mudflats could further aid the recovery of oyster populations. However, wood degradation and biofouling pose challenges that must be studied in detail to understand material longevity and maintenance needs. Investigating

alternative materials or designs that mimic natural wood structures could strengthen the scalability of these systems.

- While the meiofauna study focused primarily on population abundance, future work should incorporate additional biodiversity dimensions, such as species composition, genetic diversity, and functional traits. These insights are crucial to fully assess the ecological status of the trilateral Wadden Sea and to reverse the ongoing biodiversity crisis.
- Investigate habitat-specific feeding ecology: Further study gut content and stable isotopes to clarify trophic differentiation among meiofauna species across sediment types.

Recommendations for Policy/Management

- Implement nature-based solutions such as tree-reefs. Tree-reefs represent cost-effective, ecologically grounded tools for restoring habitat complexity and reviving oyster and shellfish populations in European coastal waters, particularly in areas degraded by human activity or climate impacts.
- Hydrodynamically, these structures function similarly to mangroves, reducing wave energy and improving coastal stability. Policymakers should integrate such structures into marine restoration programs and promote community involvement by linking them to sustainable fisheries and local livelihoods. Allowing limited public use—such as fishing opportunities—can help build public support and ensure long-term stewardship of restoration projects.
- Policy approaches should move toward system-wide, multi-taxa strategies, shifting the focus from single-species protection to the overall health and functioning of the ecosystem.
- This requires standardised, long-term monitoring across all major taxonomic groups to identify critical points of ecological change and key environmental drivers. Only by integrating ecological, spatial, and temporal data can management effectively support resilience and recovery within the Wadden Sea ecosystem.
- Integrate functional and micro-scale biodiversity into policy frameworks. Meiofauna and other benthic microfauna should be recognised as essential components of ecosystem resilience and food web stability.

4.1.3. Protection & Management: Cumulative Impacts

Presentations:

- An ecosystem-based cumulative impact assessment of the Dutch Wadden Sea, using the SCAIRM-method
  Lukas Golterman, Wageningen Marine Research
- Improving cumulative impact assessments in support of management with pressure-state relationships
  Jesse van der Grient, NIOZ
- Ecosystem-based Marine Governance: Relevance for Wadden Sea Cumulative Impacts Assessment
  Cormac Walsh, Carl von Ossietzky University Oldenburg

Moderator: Martin Baptist | **Reporter**: Soledad Luna

Scientific Insights and New Knowledge

- All three studies highlight the complexity of cumulative impacts on the Wadden Sea ecosystem due to multiple pressures, including human activities, climate change, and cross-boundary effects from the adjacent North Sea which impact ecosystem health and biodiversity.
- The SCAIRM method offers an advanced, spatially explicit ecosystem-based cumulative impact assessment integrating qualitative and quantitative data to evaluate the additive risks of direct multiple human pressures on the Wadden Sea ecosystem.
- Data-driven pressure-state relationship frameworks improve the understanding of how cumulative pressures (additive and interactive) affect key components of the Wadden Sea food web.
- Ecosystem-based Marine Spatial Planning (MSP) emerges as a necessary governance tool to coordinate conservation and sustainable use across sectors and national boundaries, emphasising the need for trilateral cooperation and integrated management frameworks that consider cumulative impacts beyond the Wadden Sea World Heritage Site boundaries.

Scientific Discussion Points

- Challenges remain in enhancing data reliability, harmonising data from different studies and methodologies, addressing uncertainties, effectively linking cumulative pressures to biological responses and incorporating these into predictive models and management tools, that are interpretable for policy makers and users
- Governance coordination across national borders and between sectors is complex, raising questions about MSP's current capacity to fully manage cumulative impacts.
- Balancing ecosystem conservation with socioeconomic activities involves navigating trade-offs and managing uncertainty inherent to cumulative impact assessments.

Suggestions for Scientific Follow-up

- Include indirect and cumulative ecological interactions (e.g., food-web effects), perform formal uncertainty analyses, refine species- and habitat-specific parameters, and strengthen data harmonisation across temporal and spatial scales.
- Collect and/or create more spatial data on human activities.
- Refine and validate pressure-state relationships with empirical data and long-term monitoring to increase knowledge on additive and interactive effects to improve predictive accuracy.
- Develop standardised, integrative methods for combining biological, physical, and socioeconomic data in cumulative impact assessments.
- Investigate the real-world effectiveness of ecosystem-based MSP in facilitating cross-sectoral and trilateral governance in the Wadden Sea region and at the interfaces between the Wadden Sea, its coastal hinterland, and the North Sea.
- Incorporate sensitivity mapping, climate change projections and scenario modelling to anticipate future cumulative pressures and represent alternative management pathways.

Recommendations for Policy/Management

- Adopt spatially explicit, ecosystem-based cumulative impact assessments like SCAIRM as strategic decision-support tools to identify high-risk activities and risk-sensitive areas, prioritise mitigation and restoration efforts, and for enabling integrated, ecosystem-based Wadden Sea management.
- Integrate pressure-state relationship frameworks to better connect human activities with ecological outcomes for providing a transparent basis for assessing cumulative pressures, prioritising mitigation, and guiding adaptive policy responses.
- Strengthen trilateral cooperation between Denmark, Germany, and the Netherlands to align Wadden Sea conservation and North Sea ecosystem-based MSP through joint sensitivity mapping, shared data frameworks, and integrated scenario planning.
- Enhance ecosystem-based cumulative impact assessments and MSP frameworks to align with UNESCO WHS goals.
- Promote cross-sectoral dialogue, data sharing, and adaptive governance across spatial and temporal scales.
- Recognise and manage impacts originating outside the Wadden Sea boundaries through broader marine spatial planning integration.
- Strengthen awareness of gaps and uncertainties in marine ecosystem science and promote in response, greater adherence to the precautionary in principle.

4.1.4. Socioeconomic Interactions: Tourism

Presentations:

- Degrowth-inspired tourism: reconceptualizing sustainable development in the Lower-Saxonian biosphere region?
  Gesa Witt, University of Vechta

Moderator: Elena Cavagnaro | **Reporter**: Anja Domnick

Scientific Insights and New Knowledge

- Conceptual innovation: A new framework for degrowth-inspired sustainable tourism that prioritises qualitative well-being and social equity overgrowth in numbers or revenues.
- Empirical findings: Stakeholders hold divergent understandings of "sustainable tourism development"—from growth-oriented (visitor numbers, revenues) to degrowth-oriented (capacity limits, quality, and well-being).
- Confirmatory result: A discrepancy in perceptions between those working within tourism and those outside of it, was unexpected for the researcher but is well-known from other studies. The latter group tends to emphasise ecological integrity and community quality of life more strongly. This finding could be framed as a confirmatory result, reflecting established patterns in other research.
- Socio-economic insight: Some tourism enterprises are reorienting values—thinking about offering year-round contracts, improving work-life balance, and prioritising employee well-being.
- No universal model applies: success depends on locally adapted, networked approaches that build on existing structures, connect to related frameworks like regenerative tourism and World Heritage, and include diverse community voices.

Scientific Discussion Points

- The challenge how to steer the debate over extending tourism seasons vs. allowing ecological and social "resting periods."
- Questions of how to operationalise tourism degrowth in protected areas and what indicators to apply.
- Potential trade-offs: Reducing tourism intensity could risk economic dependency shifts toward more harmful sectors à Assessing risks of replacing tourism income with potentially less sustainable industries.
- Necessity to define concrete indicators for degrowth-aligned tourism performance.

Suggestions for Scientific Follow-up

- Develop measurable indicators and frameworks for tourism degrowth in protected areas.
- Study different destination types and regional contexts to test applicability.

- Further explore justice aspects—balancing social and ecological equity within degrowth strategies.
- Conceptual expansion: Links to regenerative tourism and World Heritage interpretation suggest potential for integrated frameworks connecting conservation, community resilience, and cultural understanding.
- Conduct inclusive participatory research that systematically integrates voices outside the tourism sector.

Recommendations for Policy/Management

- Facilitate participatory platforms for stakeholders to discuss and negotiate tourism development pathways, integrating degrowth concepts where appropriate to balance economic and ecological goals.
- Enhance low-impact infrastructure and redistribute visitor flows to reduce pressure on ecologically sensitive areas.
- Promote cross-sectoral and transboundary cooperation to manage tourism impacts coherently across the Wadden Sea region.
- Start from what already exists: Build upon existing structures, initiatives, and local knowledge—do not start from scratch. Promote these initiatives more strongly.
- Use the degrowth lens as a value-based approach to identify and mitigate tourism-related conflicts.
- Include all voices, especially those not directly involved in tourism, in participatory planning and decision-making.
- Integrate capacity limits and residents' well-being into local and regional tourism strategies.
- Strengthen policy linkages between tourism, World Heritage interpretation, and regenerative tourism initiatives—fostering collaboration for shared sustainability goals.
- Encourage economic diversification and year-round, fair employment as strategies for social resilience and ecological balance.
- Support educational programs promoting ethical consumption and awareness of ecological limits among tourists and stakeholders.

4.2. PARALLEL SESSIONS ROUND 2

4.2.1. Geological Processes: Coastal Protection

Presentations:

- Nature based solutions for Wadden Sea Ports
  Marinka van Puijenbroek, Wageningen Marine Research, Ecoshape
- Tracing nourishment sand – results from the TRAILS project
  Jakob Wallinga, Wageningen University
- Incorporating cultural heritage variation in flood safety landscapes
  Arjan Conijn, Rijksuniversiteit Groningen

Moderator: Robert Lepper | **Reporter**: Monika Radominska

Scientific Insights and New Knowledge

- Nature-based engineering: Pilot projects Mud Motor, Marconi, and Kleirijperij show that dredged sediment – traditionally treated as waste, can be repurposed as a resource for salt marsh restoration and dike reinforcement. These pilots demonstrate how engineered interventions can support natural sedimentation processes and enhance ecological functions.
- Sediment tracing: Advanced model (Lagrangian SedTRAILS) simulates individual grain transport and luminescence-based tracing techniques offer new potential to distinguish recently nourished sand from natural sediment. These tools provide new understanding of sand and sediment dispersal, improving prediction and management of nourishment impacts on coastal systems.
- Cultural-ecological integration: Coastal flood protection strategies need to start from the understanding that the Wadden Sea coast is a combined natural and cultural landscape, shaped over centuries by human adaptation to dynamic environments. Flood safety measures must therefore be developed through landscape specific lens that integrates cultural heritage, ecological dynamics and community identity to ensure resilient outcomes.
- Multi-functionality: Coastal protection can and should simultaneously serve ecological, protective, cultural, and economic functions, where measures are designed not only for flood protection but also to support ecological processes and strengthen the cultural landscape.

Scientific Discussion Points

- How can dredged material be best repurposed for habitat development and coastal protection?
- What factors determine the short-term vs long term retention of mud in marshes?
- How does clay content influence vegetation establishment, as observed in Marconi pilot. (Clay needed for vegetation to grow).
- Scaling and transferability: How scalable and transferable are the sediment tracing models to other parts of the Wadden Sea or similar coastal systems?
- What are the limitations of luminescence tracing for understanding movement?

- Long-term effectiveness: What are the long-term ecological and geomorphological impacts of using dredged material and nourishments for coastal protection?
- How can sediment placement strategies be optimised to improve coastal protection?
- Which interventions can become self-sustainable, self-maintaining landscapes and which always require periodic reinforcement? How do benthic species influence sediment dispersal and habitat development?
- Stakeholder involvement: How best to integrate local and cultural values with technical flood safety needs without compromising either? How can historical and local knowledge guide the design of interventions that are accepted by communities?
- How do we assess whether a coastal community will embrace or resist landscape changes associated with NB strategies?

Suggestions for Scientific Follow-up

- Long-term monitoring of pilot projects to evaluate habitat development, sediment dynamics, and ecosystem responses over time. Assess the durability of dredged material for dike reinforcement. Determine long-term effectiveness of nature-based engineering for dike reinforcement – sediment stabilisation, vegetation establishment, and erosion resistance.
- Cross-disciplinary studies combining geomorphology, ecology, and social sciences to refine integrated coastal zone management strategies.
- Expand sediment tracing techniques to other Wadden Sea locations to validate models and assess regional variability and to understand sediment transport and accumulation. Examine how sediment type and local hydrodynamics affect dispersal and ecological impact.
- Participatory research engaging local communities and stakeholders in co-designing flood safety and landscape management plans. Explore how locally tailored strategies can improve social acceptance and ecological effectiveness.

Recommendations for Policy/Management

- Promote nature-based coastal protection as standard practice, leveraging dredged sediment for habitat restoration and dike reinforcement while reducing environmental impacts.
- Engage local communities early and consistently in coastal planning to ensure solutions are context-sensitive, culturally appropriate, and socially supported.

4.2.2. Biodiversity: Flyway

Presentations:

- Terns in trouble: lessons from a long-term, individual-based study
  Sandra Bouwhuis, Institute of Avian Research
- Climate, sediment and de-eutrophication affect abundance of benthos-feeding waterbirds
  Thomas Bregnballe, Aarhus University
- The flyway approach to the conservation of Wadden Sea waterbird populations
  Kristine Meise, Wadden Sea World Heritage

Moderator: John Frikke | **Reporter**: Josefine Bethke

Scientific Insights and New Knowledge

- Longitudinal, individual-level data allows insight how food availability, climate change and mercury pollution affect Common Terns, highlighting the cumulative effect of multiple anthropogenic stressors. Unpredictable events like the outbreak of avian influenza caused a 69% decline in the Common Terns colony Banter See in Wilhelmshaven.
- The Waterbird abundance and composition in the Wadden Sea correlate with climate indices (NAO), nutrient discharge via river systems in the North Sea, benthic biomass, and sediment dynamics, showing ecosystem processes directly impact bird populations.
- Confirmation that local waterbird conservation is insufficient alone; Monitoring along the entire East-Atlantic Flyway is needed to fully understand population trends and figure out sufficient management and conservation measures.

Scientific Discussion Points

- How do cumulative pressures interact (e.g., food availability, climate change, pollution, disease) to drive declines in species like the Common Tern, and are there evolutionary responses that mitigate some of the negative impacts?
- To what extent do the different drivers (nutrient discharge, sediment dynamics, NAO and benthic biomass) affect the population trend in the Wadden Sea and beyond
- How to best integrate and scale monitoring data across local, regional, and flyway levels to inform adaptive management?
- How effective are flyway-scale conservation initiatives given the varying capacities and priorities of countries along the migratory route?

Suggestions for Scientific Follow-up

- Expand longitudinal studies to other indicator species to test whether observed patterns in Common Terns hold more broadly.
- Species specific insight is needed to understand how much the different drivers (nutrient discharge, sediment dynamics, NAO and benthic biomass) affect the population trend in the Wadden Sea and beyond.

- Investigate how nutrients and sediment dynamic influence benthic organism trends and subsequent waterbird population and their reproductive success.
- Look how factors like e.g. tourism or disturbance affect waterbird trends in the Wadden Sea
- Evaluate the effectiveness of flyway-scale conservation programs to further improve the programs
- Incorporate climate change projections into flyway conservation planning to anticipate future shifts in migratory routes, breeding, and wintering sites.

Recommendations for Policy/Management

- Strengthen integrated ecosystem monitoring and management within the Wadden Sea, addressing pollution, food availability, sediment dynamics, habitat quality, and possible disease outbreaks to reduce cumulative pressures on waterbirds.
- Support and expand the Wadden Sea Flyway Initiative (WSFI) via secure long-term funding to build capacity in key regions (especially Africa) and ensure coordinated international monitoring and conservation efforts.
- Continue population-based research like the Common Tern colony, broaden the research up to different waterbird species and use the gained knowledge for habitat restoration projects and other conservation actions
- Keep in mind that the Wadden Sea is influenced by the large river systems having effects on sediment dynamics, nutrient discharge and pollution and consider adequately regulations, management and conservation

4.2.3. Protection & Management: Pressures & States

Presentations:

- Compilation of the "State of Nature of the Wadden Sea"
  Patrick Bogaart, Statistics Netherlands
- Benthic biodiversity and anthropogenic pressures in the Dutch Wadden Sea
  Oscar Franken, Royal Netherlands Institute for Sea Research
- Fundamental transformations in the benthic Wadden Sea
  Karsten Reise, Wadden Sea Station Sylt, Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI)

Moderator: Sara Anthony | **Reporter**: Sofia Bats

Scientific Insights and New Knowledge

- The monitoring framework integrates multiple ecological indicators and legal/statistical tools into a coherent system, enabling cross-comparison and aggregation for overall ecosystem state assessment.
- Detailed, grid-based benthic species data reveal fine-scale spatial variability and connections between biodiversity patterns and anthropogenic pressures.

- The benthic ecosystem is undergoing a novel transformation, with introduced species increasing biodiversity but altering ecosystem functioning (shift from autotrophy to heterotrophy), and traditional concepts of ecosystem integrity are being challenged.
- The combined findings emphasise the complexity and multi-scale nature of pressures on the Wadden Sea, from localised habitat changes to broad-scale ecological transformations.

Scientific Discussion Points

- How can monitoring frameworks balance simplicity (aggregated indicators) with the complexity and variability inherent in benthic ecosystems and pressures?
- To what extent can macrozoobenthic species serve as reliable early-warning indicators, given the ecosystem's novel state and the influx of non-native species?
- How should management adapt to the acceptance of novel ecosystems, especially when increased biodiversity might mask functional losses or altered ecosystem services?
- The challenge of integrating historical ecological knowledge with contemporary monitoring data to inform policy that anticipates ongoing ecological transitions.
- How do we define the proper biological reference state for the Wadden Sea? What should the Wadden Sea look like, when its status is good enough?
- Which data is used for defining the state, and how do we best determinate which data to use?
- It is hard to assign locations you want to protect. There are hot- and cold spots and it is not an easy decision where to focus on. A view on this is that it is easier to protect what is already there, than to work later on retrieving lost species. So that it would be logical to first work on the overlap between protected areas and hotspots. Advise in this is to protect gradients, so that you incorporate all facets of variation and dynamics.

Suggestions for Scientific Follow-up

- Implement longitudinal monitoring using the integrated framework combined with the spatially explicit species data to detect trends and responses to management actions over time.
- Investigate functional traits and ecosystem processes (e.g., autotrophy vs heterotrophy balance) in benthic communities to better understand the ecological consequences of species introductions and shifts.
- Develop scenario modelling to predict future benthic ecosystem states under different climate and management regimes, including novel ecosystem trajectories.
- Explore cross-border data integration to expand the monitoring framework beyond the Dutch Wadden Sea for holistic regional assessments.

Recommendations for Policy/Management

- Adopt the integrated monitoring framework as a decision-support tool to inform adaptive management, balancing ecological protection with socioeconomic use.

- Use the spatial biodiversity maps to identify priority areas for conservation, habitat restoration, or pressure mitigation (e.g., pollution control, fishing restrictions).
- Recognise and incorporate the concept of novel ecosystems into management goals, focusing on maintaining ecosystem functions and services rather than restoring historical baselines.
- Promote stakeholder engagement using transparent, comprehensible indicators to support collaborative governance and long-term commitment to ecosystem health.
- Encourage interdisciplinary and cross-border cooperation for data sharing and harmonised management to address pressures that transcend political boundaries.
- Protect gradients, so that you incorporate all facets of variation and dynamics.
- It is impossible to completely manage all external pressures, therefore focus on mitigating these external pressures. For example, lower the introduction of species. Also, refrain from gardening benthos.

4.2.4. Socioeconomic Interactions: Ports & Windfarms

Presentations:

- Applying 'Broad prosperity' in monitoring the Wadden Sea Ports
  Bart Kuipers, Erasmus centre for Urban, Port and Transport Economics
- Impact of offshore wind farms on sediment and organic carbon exchange between the Wadden Sea tidal basins and the North Sea
  Jiayue Chen, Helmholtz-Zentrum Hereon
- Study light pollution effects on bird migration using weather radar
  Jutta Leyrer, BioConsult SH

Moderator: Pieter van Beukering | **Reporter**: Marijn Asseldonk

Scientific Insights and New Knowledge

- Economic growth in Wadden Sea ports is increasingly driven by offshore wind energy, but traditional metrics may overlook broader welfare impacts and are not connected to broader regional developments.
- OWFs significantly influence sediment transport and organic carbon dynamics, altering natural coastal processes crucial for ecosystem resilience.
- Light pollution and weather conditions along the coast impact bird migration patterns, potentially exacerbated by port and windfarm infrastructure.

Scientific Discussion Points

- How can "broad prosperity" help to integrate social, environmental, and economic well-being in port regions?
- What are the long-term ecological consequences of altered sediment and carbon fluxes due to OWFs, and how can they be balanced with energy production goals?

- To what extent does artificial lighting disrupt migratory bird behaviour, and how can mitigation be practically implemented at ports and offshore installations?

Suggestions for Scientific Follow-up

- Conduct interdisciplinary studies linking socio-economic data with environmental indicators to develop a comprehensive "broad prosperity" vision for Wadden Sea ports.
- Expand modelling of OWF impacts to include cumulative effects with port activities and climate change scenarios.
- Enhance bird monitoring programs across the entire Wadden Sea flyway, incorporating lighting mitigation experiments to quantify benefits.

Recommendations for Policy/Management

- Integrate broad prosperity indicators into port development policies and relate that to regional broad prosperity developments to futureproof inclusive and sustainable regional development
- Implement adaptive management strategies for offshore wind development that account for sediment transport changes and carbon cycle effects to protect coastal ecosystems.
- Develop guidelines and regulations to reduce light pollution in and around ports and offshore wind farms, informed by scientific monitoring of bird migration.
- Make integrated choices about offshore wind development based on (radar) monitoring of bird migration and offshore wind farm effects on coastal ecosystems.

4.3. PARALLEL SESSIONS ROUND 3

4.3.1. Geological Processes: Sediment Sinks

Presentations:

- Trapping sediments in the Wadden-Sea: shellfish beds as sediment sinks
  Inga Nordhaus, Lower Saxon Wadden Sea National Park Authority
- Sediment Dynamics in Brushwood-Groyne Salt Marshes: A Wadden Sea Island Study
  Christina Bischoff, Leibniz University Hannover
- Where Salt Marshes Stop: Elevation Limits from Drone Data
  Sarah Dzimballa, University of Twente

Moderator: Lasse Sander | **Reporter**: Bas van Maren

Scientific Insights and New Knowledge

- Both shellfish beds and brushwood groyne fields trap fine-grained sediments. Sedimentation rates in the shellfish beds are almost an order of magnitude higher than present-day sea level rise. Sedimentation rates in the groyne fields are strongly depending on the state of the groyne fields – when degraded the sedimentation rates are very low to absent; after restoration siltation rates are much larger.
- High-resolution drone imagery provides a more accurate method to distinguish bare tidal flats from salt marshes compared to the traditional colour-based methodologies.

- Dredged sediments only limitedly reach existing shellfish beds in the Ems Estuary. But shellfish beds do not develop close to disposal sites.
- Groyne fields promote sedimentation through sheltering areas from hydrodynamic energy by both reducing direct erosion of the bed, but also by enlarging the window of opportunity for vegetation establishment
- The height of salt marshes is determined by the Mean High Water (MHW) level (with salt marsh height increasing with MHW) and by the absence of groyne fields (with higher marshes occurring in areas without salt marshes). The relationship with salt marshes suggests that salt marshes establish at lower bed levels in case brushwood groynes are present.

Scientific Discussion Points

- What is driving the difference in sedimentation rates between shellfish beds? Which processes are exactly enhancing enhanced siltation in groyne fields which are restored? Why are salt marshes higher in areas not protected by groyne fields, especially the one at Wierum?
- What is the role of dredging on shellfish beds? On the one hand the model suggests that little disposed sediments reach the shellfish beds, on the other hand shellfish beds do not exist close to disposal site despite suitable habitats.

Suggestions for Scientific Follow-up

- Further explore the use of high-resolution drones to differentiate between salt marsh vegetation and bare flat instead of (or in addition to) colour-based methods.
- Regularly restore groyne fields
- Monitor more frequently

Recommendations for Policy/Management

- The state of the groyne fields strongly influences its effectiveness and should therefore be maintained. The brushwood groynes need to be restored every 3-7 years.
- Use brushwood groyne fields and shellfish beds as nature-based solutions that trap sediments thereby strengthening shoreline protection.
- Shellfish beds do not occur close to dredge disposal locations in the Ems Estuary, despite suitability of locations in terms of hydrodynamic and bathymetric conditions

4.3.2. Ecological Processes: Emerging Insights

Presentations:

- Seasonal presence of biological sounds in the Wadden Sea
  Janneke de Bresser, Leiden University, University of Groningen
- Population developments in the Sandwich tern in relation to the highly pathogenic avian influenza
  Florian Packmor, Lower Saxon Wadden Sea National Park Authority
- At death's door to biodiversity
  Benedikt Wiggering, Lower Saxon Wadden Sea National Park Authority

Moderator: Thomas Bregnballe | **Reporter**: Max Burgoon

Scientific Insights and New Knowledge

- Passive Acoustic Monitoring (PAM) in the Wadden Sea shows that sound diversity matches biodiversity patterns. Most acoustic activity takes place in the summer and noise activity varies with daily and seasonal patterns.
- The highly pathogenic avian influenza (HPAI) outbreak in Sandwich terns documents the scale and rapid impact of disease on seabird populations, moving from a seasonal disease event to a year-round disease, locally up to 33% of the adult breeding birds died.
- The study on carrion ecology shows how carcasses contribute significantly to local biodiversity by supporting distinct scavenger communities, with variations influenced by habitat type and season. Carrion variety is important and is especially a central resource for vertebrates during winter.

Scientific Discussion Points

- Many sounds of fish species are as yet undocumented (96%).
- What are the long-term population and ecosystem impacts of repeated or large-scale disease outbreaks like HPAI on seabird communities and associated food webs?
- To what extent does carrion availability influence broader ecosystem functions and species interactions in salt marshes and similar habitats, especially under changing environmental conditions?

Suggestions for Scientific Follow-up

- Further development of PAM databases to better classify and link acoustic signals to species and ecological events.
- The interaction between anthropogenic sounds and fish vocal activity can be studied.
- Long-term, multi-species monitoring of seabirds to understand recovery trajectories and ecosystem impacts post-HPAI outbreaks.
- Expanded carrion ecology studies encompassing other trophic levels, habitat types, and the role of microbial and invertebrate decomposers to capture full ecosystem effects. It is currently understudied.

Recommendations for Policy/Management

- Integrate PAM into routine monitoring programs to enhance species tracking and inform adaptive management in coastal ecosystems.
- Establish coordinated international surveillance and rapid response frameworks for disease outbreaks affecting key species, supporting conservation and minimising spread.
- Recognise carrion's ecological role in coastal management plans by maintaining natural processes that allow scavenger communities to thrive and support biodiversity.

4.3.3. Protection & Management: Frameworks

Presentations:

- Biomimicry: Interpreting Wadden Sea Recommendations Through Functional and Symbolic Perspectives
  Catharina van den Driesche, University of Amsterdam/KADEN DESIGN
- The economic benefits of Nature-based Solutions for climate risk: A meta-analysis
  Guillermo García Alvarez, Institute for Environmental Studies, Vrije Universiteit Amsterdam
- Visualizing Social-Ecological Links for Marine Protected Area Decision-Making
  Maja Skovgaard Jessen, University of Southern Denmark

Moderator: Amelie Bernzen | **Reporter**: Sander Holthuijsen

Scientific Insights and New Knowledge

- Recognition that biomimicry can address cultural and narrative dimensions in addition to functional ones, enriching nature-based innovation with relational and symbolic meaning, thus promoting regenerative and adaptive transformations in vulnerable coastal landscapes. Try to incorporate nature as a participant.
- Quantitative evidence from a meta-analysis of willingness-to-pay for Nature Based Solutions co-benefits, revealing how economic valuation depends on factors such as GDP, size of NBS, and urban context, which can be applied to tailor policy and investment decisions. Not all NBS co-benefits are valued equally in the WTP meta-analysis. Day-to-day benefits are scored higher than long-term benefits.
- Development and application of a social-ecological visualisation tool (Sankey diagrams) adapted to local species and pressures in the Danish Wadden Sea, highlighting interlinked ecological and social components, and exposing knowledge gaps for more integrated conservation planning.

Scientific Discussion Points

- How can symbolic and cultural aspects be effectively integrated into biomimetic design without losing rigor or, importantly, becoming too abstract for practical application in ecosystem management?
- To what extent do economic valuations of NBS reflect actual willingness to invest in coastal nature-based adaptation, especially given the variation by region and scale?

- How to improve the quantitative robustness of social-ecological link models to enhance confidence and usability for local decision-makers, while managing the complexity inherent in socio-ecological systems?

Suggestions for Scientific Follow-up

- Empirical case studies applying the expanded biomimicry framework in Wadden Sea restoration or urban coastal planning projects to validate its impact on ecological and cultural resilience outcomes.
- Further refinement and regional calibration of the economic meta-analysis model, incorporating Wadden Sea-specific data on ecosystem services, local stakeholder values, and long-term climate risk scenarios.
- Enhancing the social-ecological link visualisation by integrating more quantitative data from monitoring programs, and expanding to include additional species, ecosystem services, and stakeholder groups for comprehensive MPA planning.
- Cross-disciplinary collaboration to explore how economic valuations, social-ecological visualisations, and biomimetic design principles can be combined into a unified decision-support framework for coastal management.

Recommendations for Policy/Management

- Promote adoption of biomimicry-informed regenerative design principles in policy frameworks and planning guidelines for the Wadden Sea, encouraging solutions that integrate ecological function with cultural narratives and community values. Engagement with stakeholders will be vital in the process.
- Use economic valuation insights to prioritise nature-based solutions investments that maximise societal co-benefits, particularly emphasising urban and peri-urban areas where public willingness-to-pay is highest. Use local data, when possible, fall back on the meta-analysis when needed.
- Implement and promote the social-ecological visualisation tool within MPA governance to facilitate transparent stakeholder communication, identify management priorities, and track socio-ecological feedbacks.
- Encourage cross-sectoral and transdisciplinary collaboration among ecologists, economists, designers, and local communities to ensure protection and management frameworks are holistic, adaptive, and socially inclusive.

4.3.4. Climate Change: Warming

Presentations:

- Does warming affect barnacle recruitment at temperate and Arctic sites?
  Anna Sophie Lange, Universität Rostock
- Warming-Induced Changes in Common Goby Physiology and Behavior
  Christian Aakjær Olesen, Forschungs und Technologiezentrum Westküste
- The effect of warm summers on fish
  Ingrid Tulp, Wageningen Marine Research

Moderator: Christian Buschbaum | **Reporter**: Monika Radominska

Scientific Insights and New Knowledge

- Species and community shifts: Warming can increase recruitment of warm-adapted and non-native species in temperate regions, potentially influencing local intertidal community composition.
- Barnacle recruitment responses to warming varied across sites: temperate sites (Sylt, northern Wadden Sea) showed higher recruitment under warm substrate conditions, whereas Arctic sites (Tromsoe, Helgoland) showed little or no recruitment response. This highlights regional differences in vulnerability of intertidal species to warming.
- Physiological and behavioural plasticity: The goby study demonstrates that prior thermal exposure (thermal history) affects growth and behaviour, reflecting both acclimation and potential stress responses under elevated temperatures. Additionally, gobies exposed to higher temperatures matured earlier and grew faster initially, suggesting temperature may accelerate life-history traits in ectothermic coastal fish.
- Phenological changes in fish: Warm summers lead to shifts in the timing and spatial patterns of fish habitat use in the Wadden Sea, with potential implications for ecosystem function. Some species (e.g. warm preferring juveniles) now use shallower or previously less-used habitats during warmer periods. Fish abundance and size patterns differ between the coastal North Sea and the Wadden Sea, reflecting local temperature, habitat, and species-specific preferences.
- General message -warming influences growth, recruitment, sexual maturity, behaviour, and phenology in barnacles, gobies and other fish species. Warm adapted and non-native species may gain competitive advantages, whereas cold-adapted species may experience range contradictions or reduced performance.
- Species responses seem to be mediated by thermal history and ecological interactions, as observed effects of warming are not solely direct thermal stress but are modulated by prior thermal exposure (physiological and behavioural plasticity), predator-prey dynamics, and habitat-specific conditions, underscoring the importance of considering both organismal acclimation and ecosystem-level processes when predicting climate change impacts.

Scientific Discussion Points

- How do species differ in their responses to warming?

- What environmental or biological factors explain why some species show strong warming responses while others show little to none?
- How does prior exposure to temperature influence the capacity of species to tolerate further warming?
- How does changing seasonal timing affect when and where species are present in the Wadden Sea? What might this mean for interactions among species that depend on seasonal synchrony?
- Role of invasive or range-expanding species: How might continued warming influence the distribution and abundance of warm-adapted and non-native species in the Wadden Sea region?
- Climate warming does not affect species equally, creating potential 'climate winners' and 'losers'.

Suggestions for Scientific Follow-up

- Continue and expand long-term and seasonal monitoring to better capture interannual variability and temperature driven shifts in coastal species.
- Investigate physiological mechanisms of thermal acclimation, particularly how thermal history influences behaviour and performance, as observed in goby study.
- Conduct field experiments using settlement substrates that better replicate natural microhabitats, measure temperature more precisely, or measure temperature across tidal cycles, to verify warming effects under realistic intertidal exposure conditions.
- Mechanistic studies on acclimation: Investigate underlying thermal history effects, stress responses,
- Spatial comparisons: Compare Wadden Sea responses to other coastal and Arctic sites to assess regional differences in vulnerability and resilience. – conduct cross-regional comparative studies to understand why warming effects differ between temperate and Arctic coasts.
- Repeat predation experiments with clear differentiation between barnacle species to determine whether warming differentially affects vulnerability of native vs. non-native barnacles.
- A study to measure physiological stress indicators to verify whether increased activity under warming reflects adaptive performance or stress.
- Conduct parallel field studies to determine whether gobies avoid warmer microhabitats under natural conditions, helping distinguish adaptive vs. constrained responses.
- Include habitat and depth changes in analyses of fish phenology, to separate temperature impacts from broader environmental changes.

Recommendations for Policy/Management

- Monitoring frameworks: Support integrated, long-term ecological monitoring programs and long-term seasonal surveys to detect changes in abundance, size, and habitat use.

- Manage invasive species risks: The findings indicate that continued warming may favour warm-adapted and non-native barnacle species, particularly in temperate intertidal areas. This suggests that future species expansions are possible under ongoing climate warming.

4.4. PARALLEL SESSIONS ROUND 4

4.4.1. Ecological Processes: Primary Productivity

Presentations:
- Long-term phytoplankton dynamics in western Wadden Sea: Trends and drivers
  Qing Zhan, Royal Netherlands Institute for Sea Research
- Safe ecological limits for Wadden Sea eutrophication
  Justus Beusekom, Helmholtz-Zentrum Hereon

Moderator: Justus van Beusekom | **Reporter**: Bernike van Werven

Scientific Insights and New Knowledge

- Long-term (over three decades) measurements in the Netherlands in the Marsdiep show that primary productivity has remained relatively stable in recent years (2012-2023), but this balance may be fragile given the ongoing decline in nutrient input (de-eutrophication) and increases in light conditions (locally more sand is trapped and more clear water from the North Sea enters the system).
- There is a temporal variability in primary production within the Wadden Sea, with a spring bloom (nutrient limited) and an autumn bloom (light limited). The spring bloom has shifted due to de-eutrophication.
- The primary productivity of the Wadden Sea region is influenced by the whole of Europe. Nutrients from the Rhine enter the system via the North Sea. Thus, eutrophication of the Rhine has had a large impact on the Wadden Sea ecosystem; it is amongst others corelated with the seagrass decline.
- Since the 1990's the nutrient load of the Rhine is decreasing. Summer chlorophyl and Autumn nitrogen reveal that the nitrogen loads in the Wadden Sea also decreased between 1990-2020, but with a high local variability.
- Quantitative modelling reveals that current nutrient reduction measures are insufficient to meet ecological restoration goals; for seagrass restoration another 30-40% reduction in nutrient loads is necessary.
- Nutrient stoichiometry (N:P ratios) plays a central role in controlling organic matter quality and ecosystem functioning.

Scientific Discussion Points

- The complexity of linking nutrient inputs to ecosystem responses given temporal and spatial variability in bloom phenology and productivity.

- The interplay of light availability and nutrient supply in limiting primary production, especially under changing turbidity and climate conditions.
- How climate change may alter nutrient cycling, phytoplankton composition, and thus the applicability of current nutrient thresholds.
- Potential trade-offs in nutrient management between reducing eutrophication and maintaining sufficient productivity to support higher trophic levels and ecosystem services.
- The challenge of integrating fine-scale mechanistic insights with large-scale catchment models for management.

Suggestions for Scientific Follow-up

- Expand spatial monitoring to include additional Wadden Sea subregions, integrating in-situ data with satellite remote sensing to capture system-wide productivity dynamics.
- Investigate the role of other limiting nutrients than nitrogen, such as phosphorus and silica, and their ratios with nitrogen in controlling bloom composition and ecosystem responses.
- Conduct experiments or modelling on how climate-induced changes (e.g., temperature, stratification, precipitation patterns) interact with nutrient dynamics and light availability.
- Study food web responses to shifts in phytoplankton productivity and composition, linking primary production to higher trophic levels and ecosystem services.
- Develop coupled physical-biogeochemical models incorporating nutrient inputs, light regimes, and climate variables to forecast productivity under future scenarios.

Recommendations for Policy/Management

- Implement more stringent nutrient reduction targets, aiming for at least 30-50% decreases in riverine nitrogen loads relative to 2010 levels to support seagrass recovery and reduce eutrophication impacts.
- Monitor and manage nutrient ratios (N:P) to avoid shifts that could destabilise phytoplankton communities or degrade organic matter quality.
- Promote adaptive management frameworks that continuously incorporate updated monitoring data and modelling results to refine nutrient load targets and ecosystem health indicators.
- Enhance efforts to reduce turbidity in key areas (e.g., Ems estuary) to improve light availability, thereby supporting primary productivity and habitat quality.
- Foster integrated catchment-coastal management policies acknowledging the Wadden Sea as a recipient ecosystem dependent on upstream actions, linking river basin management plans with marine ecosystem goals.

4.4.2. Climate Change: Warming

Presentations:

- Marine heatwaves and benthic life: Is mobility key to survival?
  Jasmin S. Mueller, Institute for Chemistry and Biology of the Marine Environment (ICBM) University of Oldenburg & Senckenberg am Meer, Department for Marine Research
- Primary production in non-native Vaucheria-turfs (Xanthophyceae) on a tidal sedimentary coast
  Ronny Steinberg, Universität of Bremen

Moderator: Tjitske Kooistra | **Reporter**: Guillermo Garcia Alvarez

Scientific Insights and New Knowledge

- Both studies emphasise temperature as a critical driver of ecological change.
- Species-specific physiological response to heat stress varies among benthic fauna, with certain species highly vulnerable (mass mortalities) to marine heatwaves regardless of their mobility.
- Non-native Vaucheria algae show enhanced photosynthetic performance and primary production under warmer conditions (up to ~32 °C), suggesting warming promotes their proliferation.
- Elevated temperatures may thus facilitate invasions and community restructuring through both direct stress on native fauna and indirect changes via primary producer shifts.
- The interaction between heat stress impacts on fauna and warming-driven productivity changes in algae highlights complex ecosystem responses to climate warming.
- These responses suggest potential shifts in community structure, where vulnerable native species may decline, and opportunistic or non-native species may expand.
- Together, they indicate that marine heatwave events and warming will not only directly affect individual species physiology and survival but can also indirectly reshape community composition, ecosystem productivity and function.
- The algal productivity increase may alter sediment stability, nutrient cycling, and habitat conditions, potentially impacting benthic fauna, including those vulnerable to heat stress.

Scientific Discussion Points

- How will altered species mortality patterns combined with increased productivity of non-native algae affect trophic interactions and food web stability?
- What are the longer-term ecological consequences of increased dominance of non-native primary producers in intertidal sedimentary habitats?
- To what extent do marine heatwaves act as episodic disturbances vs. sustained warming trends in driving ecosystem shifts?
- Can physiological and photosynthetic thresholds identified in experiments predict field-scale community changes under future climate scenarios?

Suggestions for Scientific Follow-up or Deepening

- Conduct in situ monitoring of marine heatwave events and seasonal temperature trends to validate experimental findings on species mortality and algal productivity.
- Document mass mortality events in the Wadden Sea area and investigate in their causes
- Investigate indirect effects of algal proliferation on benthic fauna habitat, sediment biogeochemistry, and nutrient fluxes.
- Explore multi-species interaction experiments combining vulnerable benthic species with competitive non-native algae under warming scenarios.
- Include trait-based approaches to find possible community responses to marine heatwaves.
- Model ecosystem-level consequences of combined heat stress on fauna and enhanced algal productivity, incorporating trophic and biogeochemical feedbacks.
- Assess adaptation potential or acclimation capacity of native fauna to recurrent marine heatwaves.

Recommendations for Policy/Management

- Incorporate species-specific and trait-based heat sensitivity data into conservation planning to identify vulnerable species and prioritise protection or restoration efforts.
- Monitor the spread and ecological impact of non-native Vaucheria species to anticipate and mitigate potential habitat alteration.
- Consider adaptive management strategies that reduce additional stressors (e.g., pollution, habitat loss) to increase resilience of native benthic communities to warming.
- Promote habitat heterogeneity to provide thermal refuges for vulnerable species during marine heatwaves.
- Integrate early warning systems for marine heatwaves in coastal management to facilitate rapid response and mitigation measures.

4.4.3. Climate Change: Sea Level Rise

Presentations:

- Asymmetric morphodynamics of the Wadden Sea
  Robert Lepper, Federal Waterways Engineering and Research Institute (BAW)
- Vegetation modelling at the tidal Elbe: reedbed growth as a function of hydrodynamics, morphodynamics and climate change
  Johannes Leins, Federal Institute of Hydrology

Moderator: Thomas Bregnballe | **Reporter**: Jos Muller

Scientific Insights and New Knowledge

- Spatially varying bed level elevations show asymmetric accretion/erosion patterns, with accretion generally outpacing sea level rise in many intertidal zones (3 to 4 times), but with important regional variability (e.g., erosion in the Dutch Wadden Sea).

- The morphological evolution involves expansion and steepening of the intertidal flats, driven by sedimentation at channel-flat and flat-marsh interfaces.
- For the Elbe estuary, higher bedlevel changes were measured in retreating sites than at expanding sites.
- Vegetation, particularly reedbeds, plays a crucial role in sediment retention and marsh growth along the Elbe estuary, acting as a natural buffer against erosion and wave impact under sea level rise.
- Modelling approaches that integrate sediment dynamics, flow and waves, and vegetation feedbacks
- Interdependencies:
- Sediment accretion supports marsh and reedbed expansion, while vegetation reduces flow velocities, increases local deposition rates and mitigates erosion.
- The sedimentary trends observed in the first study give an insight in sediments accumulation in the larger Wadden sea area, which is an indication of available sediments in upstream estuaries as the Elbe in the second study.
- Conversely, the vegetation models help explain how biological factors may modify sediment dynamics and thus influence future morphological trajectories outlined in the first study.

Scientific Discussion Points

- The systematic erosion and accretion patterns across regions (north of Elbe vs. Dutch Wadden Sea) implies that there is a systematic driving force causing this accumulation. The current statistical elevation distribution approach is not able to give insight in these driving patterns.
- It would be interesting to extend the geometric analysis of the Wadden sea to include the distribution of sediment type, such as sand and mud.
- Anthropomorphic influences are not yet captured by the statistical distribution method. The influence can be seen in shallowing of the channels in the Dutch Wadden Sea. This is not a natural process, which is included in the analysis.
- To what extent can sediment supply continue to compensate for accelerating sea level rise, especially under changing riverine sediment loads and human interventions?

Suggestions for Scientific Follow-up

- While the new approach in the first study gives an insight in erosion accretion based on tidal elevation, the spatial information is lost. Next step should be looking at subregions and unravel local processes that lead to accumulation and erosion
- The deployed measurement campaign will give daily characteristics such as incoming wave heights, water levels and velocities. It is important to explore what are the gradients in these driving patterns that cause the observed morphological changes.
- Extend vegetation models to include other processes such as waves and multi-saltmarsh species interactions to improve predictions and understanding of the system.

Recommendations for Policy/Management

- Promote understanding of large spatial trends in future sediment availability for different regions of the Wadden Sea area. This can lead to effectively setting up adaptive sediment management strategies that enhance natural sediment supply to vulnerable Wadden Sea regions, especially where erosion dominates.
- Use improved process-based models to inform waterway management, river sediment regulation, and coastal engineering under future climate scenarios.
- Integrate vegetation conservation and restoration (e.g., reedbeds, salt marshes) into coastal protection plans to strengthen natural shoreline resilience.
- Foster cross-sectoral cooperation, linking sediment and vegetation management with shipping, agriculture, and nature conservation policies.
- Prioritise monitoring programs to track morphodynamic and vegetation changes, enabling responsive management to emerging risks.

4.4.4. Socioeconomic Interactions: Mussel & Shrimp Fisheries

Presentations:

- Mussel culture impacts on marine biodiversity in the Wadden Sea
  Lotte Julia Bouwman, Wageningen University & Research
- Development of blue mussels and Pacific oysters on mussel beds
  Hanna Schade, BioConsult SH GmbH & CO. KG

Moderator: Katja Heubel | **Reporter**: Kasper Meijer

Scientific Insights and New Knowledge

- Mussel culture plots support benthic communities with generally higher biodiversity than soft-sediments.
- Large spatial and temporal variability in the benthic community on mussel culture plots and soft-sediment systems complicates impact assessment.
- Mussel culture structures create ecological opportunities for biodiversity enhancement but also introduce complex spatial and temporal variability that require integrated management and monitoring frameworks. Concrete biodiversity enhancement remains unknown, especially in relation to wild mussel beds.
- Pacific oysters negatively influence blue mussel condition and growth, indicating long-term shifts in species dynamics and ecosystem functioning. However, the influence is different between beds.

Scientific Discussion Points

- What are the ecological trade-offs between promoting mussel aquaculture and maintaining wild mussel beds in terms of biodiversity and ecosystem services?

- How does the proliferation of invasive oysters affect trophic dynamics and energy flow in the Wadden Sea?
- Can mussel culture plots mitigate pressure on wild beds, or do they introduce novel pressures and alter benthic succession trajectories?

Suggestions for Scientific Follow-up

- Investigate the carrying capacity of mixed beds for filter feeders, focusing on nutrient limitation and food web impacts.
- Expand monitoring to include higher trophic levels (e.g. predators, seabirds) that depend on mussel beds.
- Model the long-term ecosystem effects of species replacement, particularly Pacific oyster dominance.
- Examine how physical disturbances (ice winters, storms) reset or reinforce community trajectories.
- Compare ecosystem functioning across wild, cultured, and mixed beds under climate stressors (e.g. temperature, eutrophication).

Recommendations for Policy/Management

- Support adaptive mussel aquaculture regulation that includes biodiversity monitoring and succession-based assessments.
- Implement targeted management of Pacific oyster spread, especially in high-value blue mussel habitats.
- Develop integrated shellfish management frameworks that consider wild-culture interactions, invasive species control, and ecosystem resilience.
- Promote cooperative monitoring programs between aquaculture operators and conservation agencies to ensure sustainable use of Wadden Sea resources.

4.5. PARALLEL SESSIONS ROUND 5

4.5.1. Ecological Processes: Carbon Sequestration

Presentations:

- Does salt marsh restoration enhance blue carbon sequestration?
  Stefanie Nolte, Lower Saxon Wadden Sea National Park Administration
- Is blue carbon in salt marshes affected by man-made interventions?
  Pim Willemsen, Deltares / Wageningen University & Research

Moderator: Kai Jensen | **Reporter**: Kristine Meise

Scientific Insights and New Knowledge

- Restored summer polders can recover blue carbon potential, suggesting restoration has climate mitigation co-benefits beyond biodiversity.

- Topographic and hydrological position within the tidal frame, especially in pioneer vs. higher marsh zones, influence TOC values and their vertical distribution.
- Man-made structures like brushwood dams and drainage ditches leave an imprint on marsh carbon content, indicating that cultural landscape history affects ecological functioning.
- Sedimentation rates, silt content, and bulk density are found as key predictors of soil TOC levels in salt marshes at the mainland coast of the Wadden Sea.

Scientific Discussion Points

- Uncertainty in soil organic carbon (SOC) density (g/cm2) and carbon sequestration rates: While potential is shown, quantitative measurements of density-based stocks and sequestration rates are lacking.
- Uncertainty about other GHGs such as methane and nitrous oxide.
- Effects of anthropogenic alterations: To what extent do historic modifications constrain or enhance carbon storage capacities?
- Spatial variability in TOC highlights the need for site-specific monitoring frameworks rather than generalising across salt marsh types. Also we can learn from recent interventions and NbS regarding TOC.
- Trade-offs between engineering stability and ecological function (e.g., ditching for coastal protection vs. promoting carbon burial).
- In addition to the capacity to store additional carbon through restoration, the potential to avoid further emission needs to be highlighted, as it could be much greater than the additional carbon storage.
- Investigate the origin and/or stability of carbon (is it autochthonous, i.e. assimilated at the site, or allochthonous, i.e. incoming flux)
- In case of top-soil removal, knowledge gaps on carbon loss from extracted material needs to be analysed.
- In case of livestock grazing, the animals direct effects on methane fluxes needs to be considered in addition to carbon sequestration and GHG-fluxes between soil and the atmosphere

Suggestions for Scientific Follow-up

- Long-term monitoring of carbon sequestration rates and greenhouse gas fluxes, especially CO_2 and CH_4, in restored marshes.
- Experimental comparisons between restored/managed and natural marshes, focusing on microbial processes, Soil organic matter decomposition rates, and belowground biomass dynamics.
- Model development integrating hydrodynamics, sedimentation, and vegetation succession to predict carbon sequestration under future sea-level and management scenarios.
- Further investigation into the role of sedimentation and traditional coastal engineering structures (e.g., brushwood, drainage) on carbon sequestration rates.

- Calculate carbon density, not only content which requires information on sedimentation rates to calculate the carbon sequestration rate.
- Assess the origin and/or stability of carbon (is it autochthonous, i.e. assimilated at the site, or allochthonous, i.e. incoming flux) and labile or stable. With this it becomes clear how sustainable the carbon stock is and whether the stock is driven by the site.

Recommendations for Policy/Management

- Support salt marsh restoration as a climate mitigation strategy, especially in regions where restoration reconnects summerpolders to the tidal influence.
- Integrate blue carbon accounting into restoration project planning and evaluation, using both biogeophysical data and socioeconomic co-benefits.
- By law, EU members states have to report on carbon sequestration rates by ecosystem type: Develop a systematic monitoring framework that allows quantifying carbon sequestration rates and greenhouse gas fluxes for salt marshes and the impact of management measures (grazing, coastal protection, restoration).
- Consider the coastal squeeze in future management decisions: Salt marshes are the first land to be affected by accelerated rates of sea level rise and loss of biodiversity
- For salt marsh restoration consider the main aim to improve natural dynamics (e.g. Natura 2000, OUV etc.) and the link with nature restoration plans: de-embankment of summer polders; restoration of natural hydrology (filling of ditches to deactivate artificial drainage), top-soil removal to get rid of ditches. The success should primarily be measured based on morphological, hydrological and biodiversity parameters (return of birds and plant species)
- Develop regionally tailored carbon budgets to inform EU climate targets and support funding frameworks (e.g., carbon credits for restoration). At the same time an integral assessment including biodiversity and other ecosystem services is necessary, preventing an only carbon focused solution.

4.5.2. Climate Change: Storms

Presentations:

- Storm surges along the prehistoric coast of northwest Germany
  Ines Bruns, Lower Saxony Institute for Historical Coastal Research
- Stability of saltmarshes during extreme storms: a full-scale flume experiment
  Jos Muller, University of Twente

Moderator: Heike Schwermer | **Reporter**: Nicole Janinhof-Verdaat

Scientific Insights and New Knowledge

- Prehistoric storm surges can be identified by characteristic clastic “Klappklei” layers within peat deposits. These are reliable indicators of high-water events and allow for reconstructions of storm surge extents over Holocene time slices.

- The spatial distribution of prehistoric storm surges and their influence on landscape evolution are better understood through borehole archive data, revealing how storm impacts shaped undiked coastal areas.
- Saltmarshes show high resilience to extreme storm conditions. Even after prolonged and intense wave exposure (up to 4 m inundation and 4 m wave heights for 40 hours), only 5% of the saltmarsh volume eroded, mostly at the seaward edge with more sandy soil conditions and during the highest waves, whereas the vegetation cover towards the dike toe remains intact.
- Brushwood groin does not prevent the erosion of cliffs.
- The erosion mechanisms in modern saltmarshes begin with subsurface weakening (detachment of fine soil between roots), but once more consolidated layers are exposed, erosion stabilises.

Scientific Discussion Points

- To what extent can historical sediment markers (e.g., Klappklei) serve as reliable analogs for future storm events, especially under accelerating sea level rise and increased storm frequency?
- How do findings from controlled flume experiments translate to real-world settings with more complex variables such as vegetation diversity, existence of foreland mudflats, sediment supply, and storm variability?
- The difference in landscape vulnerability between pre-diked and modern engineered coasts raises questions about the trade-offs between hard and nature-based defences.
- What is the role of vegetation structure and root system strength in resisting erosion under storm conditions?
- Is there a critical velocity at which a high vegetation mortality occurs during a storm surge?
- Wave refection on the dike and on the cliff and how these stresses change or add up to the impact.

Suggestions for Scientific Follow-up

- Expand the reconstruction of Holocene storm surge events using additional proxies (e.g. luminescence) to confirm and date the Klappklei layers.
- Investigate the compaction of the peat layers and the amount of erosion on the prehistoric deposits.
- Investigate: where were the paleo-peat cliffs?
- Expand the investigation area- how far inland did storms surges reach inland?
- Investigate the amount of Klappklei sediments to determine if they result from one or several/clustered storm events, e.g. by comparison of fossil and modern examples (Sehestedter Außenmoor) and tests in wave flume.
- Conduct field validation of flume experiment results, especially in diverse saltmarsh and soil types across the Wadden Sea to assess generalisability.
- Investigate vegetation species-specific responses to storm conditions, including root cohesion and recovery capacity post-disturbance.

- Investigate the role of the foreland mudflats on combination with saltmarshes
- Explore multi-event erosion trajectories: How do saltmarshes respond to repeated or clustered storm events, not just a single extreme exposure?

Recommendations for Policy/Management

- Preserve and expand natural saltmarshes as effective buffers against storm surges, recognising their physical resilience.
- Integrate prehistorical and historical storm data from paleo-records into flood risk and land-use planning to inform long-term resilience strategies.
- In coastal protection planning, consider nature-based solutions as complementary to hard infrastructure, particularly in sediment-rich areas where marshes can regenerate.
- Prioritise ongoing monitoring of marsh stability during average conditions as well as during storm impacts to enable adaptive management under changing climate and sea level rise conditions.

4.5.3. Socioeconomic Interactions: Mussel & Shrimp Fisheries I

Presentations:

- Natural dynamics of epibenthic communities on former mussel culture plots
  Andreas Waser, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Wadden Sea Station Sylt
- German brown shrimp fishing behavior groups from vessel movement data
  Serra Örey, Carl von Ossietzky University Oldenburg, Institute for Chemistry and Biology of the Marine Environment (ICBM)

Moderator: Ingrid Tulp | **Reporter**: Geerten Hengeveld

Scientific Insights and New Knowledge

- The cessation of mussel aquaculture in the List tidal basin (northern Wadden Sea) since 2017 has offered a rare experimental setting to observe natural subtidal blue mussel bed recovery. Monitoring revealed important interactions between mussels, associated biodiversity, predators (e.g., sea stars), and substrate availability.
- The presence of Pacific oysters and shell debris affects blue mussel settlement, providing both opportunities (settlement substrate) and potential competition.
- Long-term Vessel Monitoring System (VMS) data show distinct spatial and temporal behavior patterns in the German brown shrimp fishery. Importantly, these behaviors are highly vulnerable to the anticipated Marine Protected Area (MPA) expansions under the EU 2023 Action Plan.
- Up to 70% of shrimp landings could be affected under pessimistic MPA expansion scenarios if fishers cannot adapt spatially. This signals high dependency of the fishery on specific, potentially protected grounds.

Scientific Discussion Points

- The removal of fishing pressure may promote ecosystem restoration (e.g., mussel bed recovery), but this benefit must be weighed against economic displacement and effort redistribution risks in other fisheries such as shrimp.
- There is a need to reconcile benthic habitat conservation (e.g., mussel reefs) with mobile gear fisheries (e.g., shrimp trawling), especially as both rely on overlapping habitats.
- Former mussel culture areas may act as "recovery zones" under suitable conditions. But predator abundance and competitive species can limit recolonisation, raising questions about active vs. passive restoration.

Suggestions for Scientific Follow-up

- Long-term ecological monitoring: extend biodiversity and habitat assessments on former mussel culture plots to better understand successional dynamics, resilience thresholds, and biotic interactions over time.
- Socio-ecological modelling: integrate fishery behaviour data with ecological impact models to simulate scenarios under different regulatory regimes and climate variables.
- Comparative studies across Wadden Sea regions: assess where similar aquaculture cessations or MPA policies are occurring to detect regional patterns of resilience, adaptation, or ecological collapse.
- Predator-prey dynamics: further investigate the role of predators (e.g., sea stars, crabs) in limiting mussel recovery and how these dynamics may change under warming and altered fishing pressure.

Recommendations for Policy/Management

- Designate adaptive management zones: use areas like the List tidal basin as experimental recovery zones where natural dynamics inform restoration potential and low-impact fishing strategies can be tested.
- Align spatial closures with fishery behaviour: future MPA expansions should integrate vessel behaviour data to minimise economic disruptions and encourage proactive transition strategies for vulnerable métiers like shrimp fishing.
- Promote habitat restoration within MPA planning: use insights from mussel recolonisation to inform restoration-enhanced MPAs, where habitat regeneration (e.g., biogenic reefs) complements conservation goals.
- Support fishery transition programs: given the looming impact of the EU Action Plan on shrimp fishing, targeted transition assistance and innovation incentives are needed for fishers to shift gears, adapt gear types, or diversify.

4.5.4. Socioeconomic Interactions: Mussel & Shrimp Fisheries II

Presentations:

- Outdated fisheries management for brown shrimp urgently needs an update
  Wouter van der Heij, Waddenvereniging
- Shrinking stocks, growing concerns: Five years of brown shrimp research
  Merten Saathoff, Alfred-Wegener-Institute, Helmholtz Centre for Polar and Marine Research

Moderator: Diana Giebels | **Reporter**: Philipp Oberdoerffer

Scientific Insights and New Knowledge

- Some evidence that growth overfishing and signs that at least on regional level recruitment overfishing is occurring: Both studies reinforce that brown shrimp stocks are under significant pressure. Findings from the CRANIMPACT and CRANMAN1&2 projects demonstrate that:
  - High fishing pressure has led to growth overfishing, where shrimp are harvested before reaching optimal size.
  - Recruitment overfishing on regional level is evident through a negative correlation of effort during winter in Dutch waters and LPUE in the following autumn in northern German waters.
- Winter vs. summer cohorts grow differently: CRANMAN2 reveals that winter-hatched shrimp grow faster than summer cohorts. This provides critical insight into seasonal dynamics in shrimp population structure, with implications for managing fishing effort to protect recruitment.
- Self-regulation may not be sufficient: The fishery's unique voluntary management system, which includes a Harvest Control Rule (HCR), has not prevented stock decline, raising questions about the resilience and enforceability of the current framework. Self-management always reaches its limits when voluntary participation leads to disadvantages compared to freeriders. Generally binding framework guidelines can help to remedy this situation.
- Due to the very rapid and variable stock dynamics, shrimp fishing requires management that can be adapted at short notice. Measures that protect egg-bearing females in winter and recruits that are still just below the minimum size in summer and preferably applied to the entire fleet are likely to have the greatest effect.

Scientific Discussion Points

- Can reduced fishing effort improve both yield and ecosystem health? A key hypothesis emerging is that lower fishing intensity may lead to higher catch-per-unit-effort (CPUE) while enabling stock growth, aligning both ecological and economic interests.
- Limits of self-management: Is the current reliance on a voluntary approach sustainable, or does it require stronger governance, scientific oversight, or binding regulation to succeed?
- Role of environmental variability: Are the observed declines in stock also influenced by climate variability or habitat degradation, which interact with fishing pressure?

- Spatio-temporal fishing strategies: Can knowledge of seasonal cohort dynamics be leveraged to design smarter, more targeted fishing closures or rotational harvest schemes?

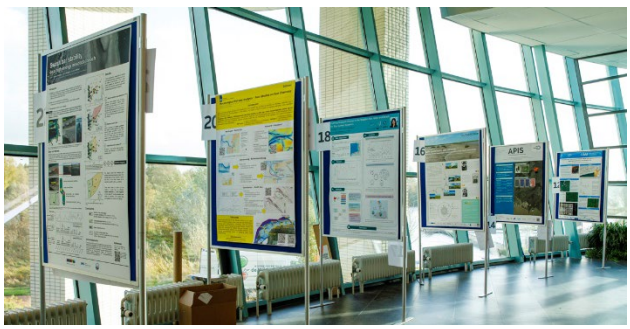
Suggestions for Scientific Follow-up or Deepening

- Controlled fishing-effort experiments: Pilot trials with reduced fishing intensity should be conducted to quantify ecological responses (e.g. biomass recovery, size structure) and economic trade-offs (e.g. CPUE, cost-efficiency). It should be noted, however, that natural variability can certainly override the effects of management measures.
- Ecosystem-based modelling: Develop and/or improve existing integrated bioeconomic and ecosystem models that simulate outcomes of different management strategies, accounting for growth rates, recruitment, market dynamics, and ecosystem impacts.
- Expand demographic monitoring: More detailed life-history data, especially related to egg-bearing females and cohort growth rates across seasons and regions, is needed to support dynamic harvest strategies.
- Evaluate governance effectiveness: Study the efficacy of the self-regulatory management, comparing it to other EU-regulated fisheries, and explore hybrid approaches blending voluntary and statutory measures.

Recommendations for Policy/Management

- Modernise brown shrimp fishery management:
- Implement adaptive harvest strategies that reduce effort during key recruitment (winter) and growth periods (summer).
- Introduce spatial or seasonal closures based on new cohort growth insights (e.g., protect winter hatchlings).
- Align with EU sustainability targets (MSY) even if not directly governed under EU fisheries law.
- Incentivise sustainable behaviour:
- Provide economic incentives or MSC-certification bonuses for vessels adopting lower-impact practices.
- Link access to certain grounds or quotas to compliance with scientifically advised effort reduction schemes.
- Ensure transparent monitoring and enforcement:
- Strengthen data collection, stock assessments and independent audits of the voluntary system.
- Explore co-management frameworks where fishers, scientists, and regulators collaboratively adjust rules in real-time.
- Promote multi-species and habitat-conscious management:
- Position brown shrimp management within a broader ecosystem-based fisheries management (EBFM) approach, considering habitat interactions, predator-prey dynamics, and sediment impacts.

5. Impressions of the Symposium



BOOK OF ABSTRACTS

16th International Scientific Wadden Sea Symposium

The Wadden Sea in Transition: Cumulative Pressures and Conservation

28-30 October 2025
Groningen, the Netherlands

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TUESDAY
28

Does law matter – prospects of the EU Nature Restoration Law?

Helle Tegner Anker, Professor of Law, University of Copenhagen, Faculty of Science

Law plays an important role in the protection of the Wadden Sea governed by numerous pieces of international, EU and national law on protection of nature, landscape, water and the marine environment. But does the law address the current challenges of the Wadden Sea in an appropriate way? Many laws are primarily reactive in the sense that they regulate new projects or activities through detailed assessment and permit requirements. Proactive rules aimed at improving or restoring the state of the environment or nature do exist, but are often suffering from implementation constraints, and possibly political unwillingness to regulate existing harmful activities and to allocate necessary resources. The 2024 EU Nature Restoration Law is in essence a proactive law setting obligations on Member States to improve and restore e.g. coastal and marine ecosystems. But what are actually the prospects of the Nature Restoration Law for the Wadden Sea area, and is it likely to achieve the objectives?

WEDNESDAY
29

Strategic Environmental Assessment supporting government decision-making on the future of the Wadden Sea

Dr Arend Kolhoff, Senior Advisor at the Netherlands Commission for Environmental Assessment

Strategic Environmental Assessment (SEA) is a legal decision-making governance and evidence based support tool that aims to contribute to sustainable development via government policies, plans and programmes. Therefore, an integrated multi-sector approach is applied in SEA. SEA complements Environmental Impact Assessment (EIA) that aims to assess and mitigate environmental impacts at project level. Besides the EU member states, the United Nations acknowledge the importance of SEA and promotes the legal uptake and world-wide use. As a result world heritage sites under threat are requested to apply SEA and implement the recommendations to maintain their unique status. In this presentation the SEA concept will be introduced and compared with EIA. Secondly, the added value of the application of SEA for world heritage sites will be presented by making use of international examples. Thirdly, I will zoom in on the SEA of the Wadden Sea a world heritage site under threat. The tailor-made SEA process of the Wadden Sea will be explained as well as the role of the Netherlands Commission for Environmental Assessment as an independent advisory body to secure the quality of the SEA process and report.

THURSDAY
30

Footprints of sunken settlements – Geophysical and geoarchaeological investigations in the Wadden sea of North Frisia (Germany)

Dennis Wilken, Institute of Geosciences, Kiel University, Kiel, Germany

The North Frisian Wadden Sea region is an area of dyked or formerly dyked salt marshes and reclaimed coastal peat bogs. This coastal wetland contains recent and past human adaptations to the environment in the form of embankments, dwelling mounds ('terps'), and canals, forming a cultural landscape of unique historical importance and maritime character. Human impact on this environment resulted in a series of unfavorable processes like land subsidence, leaving the landscape highly vulnerable to natural hazards. As a result, storm floods like the historical 1362 AD event caused major losses of embanked land. In the presented study area, namely the Wadden Sea of North Frisia, the human influence is especially visible by numerous traces of medieval to early modern settlement remains belonging to a historical cultural landscape which was ultimately lost to the sea. Imaging of the central sedimentary (waterways, paleo-surfaces, coastlines) and anthropogenic features (dykes, terps, canals) is crucial to understand this highly dynamic past environment shaped by interactions between human and natural forces. We present the results of an interdisciplinary prospection concept adapted for the tidal flat area, comprising both marine and land based methodologies.

Understanding morphodynamics in the Wadden Sea using observations and numerical modeling

Mengyao Ma, Helmholtz-Zentrum Hereon

The Wadden Sea is a complex of barrier islands, tidal flats, channels, mega-ripples and ebb deltas. Their morphological change is jointly influenced by coastal currents, tides, waves, and atmospheric conditions. This study combines long-term observational data from the TrilaWatt project with numerical simulations based on a hydro-morphodynamic model to investigate the key drivers of morphological change of the Wadden Sea, with particular focus on the tidal inlets and sand mega-ripples around the East Frisian islands. Analysis of the observational dataset reveals a bidirectional (eastward and westward) migration of mega-ripples in the foreshore area of the barrier islands, with an average rate of approximately 40 m/year. Additionally, tidal channels between the barrier islands exhibit a continuous eastward migration at around 10 m/year over the past 25 years. The numerical model was employed to further explore the underlying processes driving these morphological change patterns. Results indicate that in the foreshore areas of the barrier islands, morphology is primarily controlled by a combined influence of alongshore coastal currents, wave action, and tides. By contrast, channel migration between the islands is mainly driven by tides. On the tidal flats, tidal influence remains predominant, though seasonal river discharge introduces additional variability, particularly in estuaries.

Morphodynamic patterns of the German Wadden Sea and predictability

Bo Miao, Helmholtz-Zentrum Hereon

Based on statistical analysis combined with numerical modeling and machine learning, We investigated annual- to decadal-scale morphodynamic patterns of the German Wadden Sea and their predictability at the relevant scales. Results from the multivariate EOF (Empirical Orthogonal Function) analysis of the annual bathymetry data spanning from 1998 till 2022 and potential related drivers and environmental factors (tidal range, storm surge level and frequency, sediment properties and longshore currents) provide insights into morphodynamic patterns of the study area. Both extreme water levels (storm surges) and tidal range show a significant positive correlation with the magnitude of morphological changes, indicating their important role in controlling sediment transport and morphological evolution. Coastal longshore currents exhibit a correlation with the movement of tidal channels which are continuously migrating and deepening in the East and North Frisian regions and oscillating in the estuarine areas (Ems, Wesser and Elbe). Numerical modeling was then applied to derive a process-based understanding of the feedback mechanisms between the physical drivers and the morphology of the Wadden Sea. Finally, state-of-the-art machine learning approaches were used to explore the predictability of morphological change of the Wadden Sea and compared with numerical predictions to identify the strengths and weakness of both methods.

Fine sediment dynamics in the trilateral Wadden Sea

Bas van Maren, Deltares

The ecological value of the Wadden Sea is strongly influenced by its morphology, with the bed levels and substrate determining habitat suitability. This morphology is largely shaped by natural processes (tides, river flow, waves as well as biological processes), but is also strongly controlled by human interventions (channel deepening, hard structures, dredging and disposal). But although there is a strong focus on present-day interventions (deepening, dredging and disposal), the Wadden Sea has a much longer history of human interventions impacting its sediment dynamics. We are increasingly realizing that response time of systems such as the Wadden Sea to historic interventions may be up to centuries and cover spatial scales as large as the trilateral Wadden Sea. The availability of fine sediments in the German and Danish Wadden Sea was likely influenced by the loss of intertidal and supratidal areas covering the Dutch mainland over the past centuries, which may partly explain the apparent disequilibrium of some of the tidal flats in the German stretches of the Wadden Sea. This cross-border availability of sediments will also be influenced by sediment extraction strategies or adaptation to sea level rise in the near future, motivating cooperation through joint international research and tool development.

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Nature based solutions for Wadden Sea ports

Marinka van Puijenbroek, Wageningen Marine Research, Ecoshape

The ports along the Wadden Sea are located at the edge of the UNESCO World Heritage Site and require regular dredging to maintain safe navigational depth. However, dredging and dredge disposal impacts the region's sensitive morphology, hydrodynamics, and suspended sediment levels. Due to the area's protected status, developing new economic activities is challenging. At the same time, maintaining and improving port functions is essential to support the socio-economic viability of the region. To reconcile economic and ecological interests, a nature-based approach to port development is essential. This approach integrates ecosystem services into engineering solutions. Three key concepts support this: (1) optimizing dredging and disposal strategies, (2) promoting saltmarsh development, and (3) improving flow patterns. Three pilot projects demonstrate the potential of the nature-based approach. At the Port of Harlingen, the Slibmotor project combined strategic dredging with saltmarsh expansion. At the Port of Delfzijl, the Marconi pilot used dredged sediment to create an estuarine gradient and develop saltmarshes, while the Kleirijperij project repurposed dredged material for dike reinforcement. These pilots illustrate that dredged material can become a valuable resource for nature development and coastal protection. The presentation concludes with recommendations for embedding nature-based solutions into future port management.

Tracing nourishment sand – Results from the TRAILS project

Jakob Wallinga, Wageningen University

Sand nourishments are routinely applied to strengthen the north-sea coast of the Netherlands, also in the Wadden Sea region. Within the NWO-funded TRAILS project we developed methods to monitor and predict how sand grains from a nourishment location disperse through the system, and how this affects the ecosystem. These methods support the development of effective nourishment strategies. Three research lines were developed building on the mega-nourishment in the Ameland Inlet in 2018-19: 1) Newly developed Lagrangian SedTRAILS models allow simulating transport trajectories of individual sand grains (Van Westen et al., 2025). This allows predicting where nourished sand goes. 2) Newly developed luminescence approaches provide insight in subaqueous bleaching of natural luminescence signals and possibilities to use these signals for tracing nourishment sand. 3) Insight in the sensitivity of benthic species to nourishment sand (Kooistra et al., 2025) as well as the influence of benthic species on sediment dispersal. van Westen, et al. 2025. Lagrangian modelling reveals sediment pathways at evolving coasts. Sci Rep 15, 8793. https://doi.org/10.1038/s41598-025-92910-z Kooistra et al., 2025. Coarsening coasts: quantifying sensitivity of benthic communities to sandification. Estuarine, Coastal and Shelf Science 320, https://doi.org/10.1016/j.ecss.2025.109303.

Incorporating cultural heritage variation in flood safety landscapes

Arjan Conijn, Rijksuniversiteit Groningen

The current dikes along the Wadden Sea form a sharp physical and administrative boundary between the UNESCO world heritage area and the cultural inland landscape. However, from a geophysical, natural and cultural historical point of view, both sides of the dikes are part of the same ecosystem. In the light of rising sea levels a new integrated approach on flood protection is needed, that includes landscape values on both sides of the dike. This study investigates the cultural and physical-geographical variability of coastal salt-marsh landscapes. By integrating historical landscape processes, we aim to enhance modern flood prevention strategies beyond traditional dike systems. Our methodology follows a transect approach, emphasizing the importance of location-based strategies in coastal management. The research reveals significant variation from historical impacts, driven by regional human responses to nature. The results demonstrate that understanding local systems provides nuanced insights into tuning new coastal strategies that align with regional identity and garner local support. Ultimately, this variety can facilitate the transition from a single dike line approach to a broader coastal zone strategy that accommodates multiple functions and stakeholders. Our findings contribute to the systematic understanding of regional diversity, integrating engineering and historical geography perspectives.

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Trapping sediments in the Wadden Sea: Shellfish beds as sediment sinks

Inga Nordhaus, Lower Saxon Wadden Sea National Park Authority

Intertidal shellfish beds in the Wadden Sea World Heritage Site are an important habitat with a variety of sedimentological and ecological functions. Their extent and biomass are highly variable and are influenced by environmental factors and human interventions. The latter include maintenance dredging and waterway development, which contribute to a change in natural sediment dynamics and are suspected to influence the occurrence and condition of shellfish beds in the Outer Ems estuary. Within an interdisciplinary project, sedimentation and erosion rates, sediment composition and biomass of selected shellfish beds were determined between 2019 and 2024. The nutritional status of Mytilus edulis was compared to other beds in the Wadden Sea. A numerical model approach was developed to investigate changes in the morphodynamics and sediment transport and to quantify the long-term fate of dredged sediments in the estuary. The combined results from in-situ measurements and modelling were used to determine the influence of shellfish beds on sedimentation, erosion and sediment transport. Fluctuating depositional effects were demonstrated over the five-year period. The outcomes are presented against the background of sea level rise in the Wadden Sea and serve as a basis for the development of ecological sediment management for the Outer Ems.

Sediment dynamics in brushwood-groyne salt marshes: A Wadden Sea island study

Christina Bischoff, Leibniz University Hannover

In the Wadden Sea area, brushwood groynes are used in the dike foreshore to reduce hydrodynamic energy, enhance sediment deposition, and support salt marsh development. Despite centuries of use, the biogeomorphological effects of these interventions are still not fully understood. Salt marsh plants have species-specific growth niches within the hydrodynamic domain. Different species interact with hydrodynamic conditions in distinct ways, which results in varying plant-induced sediment accumulation patterns. The complex interactions between hydrodynamics, vegetation, and sediment dynamics, particularly in brushwood-groyne marshes, still require further investigation. This study examines vegetation and sediment dynamics on the island of Pellworm in the German Wadden Sea, where salt marshes have been shaped by anthropogenic activities, including groyne construction and dredging, over the past 70 years. Over three years, data on surface elevation changes, plant species and sediment characteristics have been collected seasonally. Key findings confirm that sediment dynamics are influenced by brushwood groynes. Furthermore, salt marsh zonation within the groyne field followed not only a landward, but also a sheltered-to-exposed dike parallel gradient in sediment and vegetation patterns, likely resulting from groyne-induced hydrodynamic conditions. This research deepens our understanding of biogeomorphic feedbacks in managed salt marshes and provides valuable insights for ecosystem-based coastal protection.

Where salt marshes stop: Elevation limits from drone data

Sarah Dzimballa, University of Twente

Salt marshes in the Wadden Sea play a key role in biodiversity and coastal protection. To secure these benefits, we need a better understanding of marsh dynamics. High-resolution drone imagery can provide spatial and temporal information on salt marshes if repeated regularly. Combining drone-derived orthomosaics with digital elevation models (DEMs) yields detailed insights into marsh development and spatial variation. Drone data was collected from four marshes in the Dutch Wadden Sea over the past three years. Using the orthomosaics, the seaward salt marsh vegetation edge, affected by inundation stress and wave exposure, can be identified through image processing. DEMs reveal the lowest elevation at which vegetation can establish. Our results show these thresholds differ between locations. Notably, sites sheltered by brushwood dams support vegetation establishment at lower elevations. By linking high-resolution drone imagery with local hydrodynamic conditions, we aim to better understand how site-specific conditions influence the seaward vegetation edge. This approach offers a method to investigate marsh dynamics and evaluate restoration measures. These insights are crucial for understanding how natural forces and human impacts shape salt marsh development, contributing to the protection and management of the Wadden Sea's unique ecological and cultural heritage.

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Seasonal presence of biological sounds in the Wadden Sea

Annebelle Kok, Leiden University, University of Groningen

Coastal ecosystems are under threat by human disturbance. To conserve these ecosystems, long-term monitoring is needed, but this is often time-intensive and logistically challenging. An increasingly popular method to monitor marine ecosystems is Passive Acoustic Monitoring (PAM). The non-invasiveness, relatively low-cost and independence of weather conditions make PAM attractive compared to traditional methods. We investigated the seasonal variation in biological sounds at a dyke ecosystem in the Dutch Wadden Sea for 10 two-week periods spread over two years. We verified our acoustic measurements with frequent fish catches to sample the marine community. Fish catches showed that many species were infrequent visitors, with a few species that were regularly present in high numbers. Similarly, many sound types occurred sporadically, while a few sound types were frequent and occurred every season. Further insights into the species-specific source of these sounds will further our understanding of the feasibility of this methodology for non-invasive monitoring of coastal marine ecosystems.

Population developments in the Sandwich tern in relation to the highly pathogenic avian influenza

Florian Packmor, Lower Saxon Wadden Sea National Park Authority

In 2022, the highly pathogenic avian influenza (HPAI) A(H5N1) virus clade 2.3.4.4b became enzootic and caused mass mortality in several colony-breeding seabird species across north-western Europe and beyond. In the Wadden Sea, the Sandwich Tern Thalasseus sandvicensis was most severely impacted species among breeding birds, with some colonies showing extremely high mortality rates of almost 100% in chicks and even >50% in adults. Within a two months period a total of 20,531 adult Sandwich Terns were found dead, which corresponds to >17% of the total north-western European breeding population. Here we provide an overview of the dynamics of the 2022 HPAI outbreak in Sandwich terns, as well as its consequences for the population developments in the following years. The case of the Sandwich tern, as an extremely mobile species which breeds at a very limited number of colony sites, stresses the need for close international collaborations to ensure comprehensive monitoring and research as the basis for effective conservation efforts.

At death's door to biodiversity

Benedikt Wiggering, Lower Saxon Wadden Sea National Park Authority

Although Carrion is a major food and energy resource of numerous animal species, both specialised and opportunistic, its impact on Biodiversity is yet rather unexplored by modern ecological research. Especially local insight in specific habitats, like salt marshes or sand dunes, is sparse at best. We here present first results of the Lower Saxon National Park contribution to the Carrion Ecology project of German National Parks. We analysed the impact of wildlife carrion on salt marsh scavenger communities by examining roe deer and harbour seal cadavers, as well as control plots without carcasses. Each plot was monitored by a wildlife camera, documenting larger vertebrate scavengers. Pictures were systematically analysed, showing that scavenger communities between mainland and island saltmarshes varied drastically, especially in regard to the frequencies and composition of mammal scavengers. Furthermore, seasonality had a big impact on the duration of carrion decomposition and, subsequently, availability of carrion for vertebrate scavengers. These first, preliminary results illustrate the importance of wildlife carrion to facilitate the undisturbed course of natural dynamics and its impact on local scavenger communities as well as species and community biodiversity.

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Long-term phytoplankton dynamics in Western Wadden Sea: Trends and drivers

Qing Zhan, Royal Netherlands Institute for Sea Research

Primary production, driven by carbon fixation using light and nutrients, underpins the Wadden Sea ecosystem. The better we understand the underlying mechanisms of phytoplankton blooms and primary production in Wadden Sea ecosystem, the better will be our means of detecting and adapting to future change in carrying capacity. Using long-term monitoring data from the Marsdiep tidal inlet (western Wadden Sea), we investigate dynamics of drivers of phytoplankton bloom and primary production. Annual sampling (40 events/year) included light measurements, nutrient analyses, chl-a, and 14C-based carbon fixation rates. Since 2012, 14C incubations under varying light conditions enabled rigorous primary production estimates (2012–2023). This dataset helps assess light vs. nutrient limitation and serves as a baseline for ecosystem carrying capacity and food web studies. We further examine shifts in bloom phenology over three decades (1990-2023). Spatial variability across the Wadden Sea is explored using remote sensing, complementing temporal Marsdiep data. Continuous updates are essential given the system's dynamic nature, particularly for management applications. Our work enhances mechanistic understanding of Wadden Sea productivity and supports adaptive management such as reducing turbidity to enhance primary production of the Ems estuary and discharging nutrient-rich freshwaters to the Wadden Sea.

Safe ecological limits for Wadden Sea eutrophication

Justus Beusekom, Helmoltz-Zentrum Hereon

The Wadden Sea is strongly impacted by major European rivers like the Rhine and Elbe. Political decisions led to improved management and decreasing eutrophication but ecological problems remain including shifts in phytoplankton composition and only a partial seagrass recovery. Within the EU project NAPSEA, we developed a more holistic approach to mitigate eutrophication by linking sources, pathways and safe ecological limits for the Wadden Sea as the ultimate receiver of nutrients and for three upstream cases studies in the Elbe, the Rhine catchment and the Hunze. Our results suggest that a further reduction of riverine N loads by about 30-40% compared to the 2010s is needed to enable seagrass recovery in the southern Wadden Sea and about 30-50% for a minimum N surplus after the Si limited spring diatom bloom. The effects of climate change as well as current and stricter policy goals were evaluated with catchment models. Currently planned measures are not sufficient to achieve the needed load reductions. Based on an analysis of N:P:C ratios in newly built Wadden Sea organic matter we argue that a further increase in riverine N:P ratios should be avoided.

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Does salt marsh restoration enhance blue carbon sequestration?

Stefanie Nolte, Lower Saxon Wadden Sea National Park Authority

The restoration of salt marshes previously had the main purposes of restoring a natural habitat for plants and animals by restoring natural dynamics to anthropogenically altered systems. This has been achieved by opening of summer dikes to reconnect summer polders to the tidal influence, or in case of artificial drainage systems by infilling of ditches and/or top-soil removal. We now wanted to know how these restoration practices affect the blue carbon potential of salt marshes. In a pilot study the carbon content of former 'borrowing pits', which can be seen as a proxy for top-soil removal, of current and previous summer polders, as well as neighboring reference marshes was assessed. We could not confirm the hypothesis that the borrowing pits contain more carbon as they were hypothesized to be wetter due to their lower position in the tidal frame and lack of drainage ditches. However, first results showed that after restoration former summer polders regain their ability to store carbon. Yet, many questions remain, as we were unable to quantify carbon sequestration rates and greenhouse gas fluxes in this study. We aim to answer these in the upcoming ANK-projects in Lower-Saxony, which will encompass 550 ha of re-opened summer polders.

Is blue carbon in salt marshes affected by man-made interventions?

Pim Willemsen, Deltares / Wageningen University & Research

Salt marshes at the border of land and sea provide climate change mitigation by sequestering carbon. However, global estimates of carbon burial potential of those marshes are very location-specific, depending on local biophysical parameters. Additionally, at the Wadden Sea mainland coast there is a rich cultural-history of man-made marshes (Dutch: kwelderwerken). These man-made marshes cover large parts of the coastline. In this study we explore what biophysical parameters affect total organic carbon (TOC) in marsh substrates. And we study whether marshes with brushwood dams and ditches show differentiating TOC values. 500+ samples were collected for TOC and soil parameters. Samples were distributed over five marsh zones and three depths, in eight marshes along the Dutch Wadden Sea mainland coast (including Ems-Dollard). Furthermore, sedimentation, vegetation cover and inundation was measured. Variability of observed TOC values decreased from the mudflat towards the high marsh. Also, larger and more distinct differences of TOC between depth layers were observed in higher marsh zones. 1) Inundation combined with plant cover, 2) silt content and 3) dry bulk density explained TOC values statistically, although a relation was also found between sedimentation and TOC. Finally, differences in TOC were observed for marshes with and without man-made interventions.

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Tree-reefs restore trophic complexity and reef communities

Jon Dickson, Royal Netherlands Institute for Sea Research

Driftwood had sailed to sea in vast amounts for hundreds of millions of years, where much of it sank and provided habitat. Fossilized seaweeds, oysters, and other animals have been found living on marine wood dating back at least 200 million years. Now, landscape domestication has replaced forests with crops and cities, while rivers have been straightened and 'cleaned' of large wood near-globally. This has deprived the marine environment of a critical source of substrate, habitat, and nutrients, alongside ecosystem services that driftwood provides such as coastal armouring, dune accretion, creation of saltmarsh habitat, reef functions for fish and invertebrates, and substrate for shellfish. In the shallow subtidal Dutch Wadden Sea, we deployed 'tree-reefs' to mimic this historic sunken driftwood. Fish populations increased sixfold versus nearby sandy-bottomed control sites after 2.5 years, while crab activity lessened by 77%. Numerous guilds of fish have been observed using reef sites for spawning, rearing, foraging, and shelter, while shellfish and other sessile organisms have established on the tree reefs. This once-bountiful source of complex woody marine structure has been functionally eliminated from developed European coasts and seas; tree-reefs offer a cost-effective, scalable, and environmentally conscious method to restore fish, shellfish, and coastal environments.

Synthesis of population trends reveals seascape-wide reorganisation of biodiversity

Kasper Meijer, Groningen Institute for Evolutionary Life-Sciences, University of Groningen

Traditional biodiversity monitoring often relies on community-wide metrics or a few key species, potentially overlooking important shifts in functionally critical but less-studied taxa. We compiled over 3,000 long-term population trends (5–91 years) across a wide range of Wadden Sea taxa to provide the first cross-taxa synthesis of biodiversity change in the region. Using a systematic vote-count method, meta-analysis, and temporally explicit trend analysis, we identified consistent declines in fish, zooplankton, and plants. Birds showed an overall increase, but this masks recent declines in specific groups since the late 1990s. Declining species tended to be phylogenetically related, while increasing species were more diverse. Several taxa exhibited synchronized shifts in population trends, suggesting shared environmental pressures. These results reveal a reorganisation of biodiversity with potential implications for ecosystem functioning and resilience. This holistic approach captures the dynamic and interconnected nature of the trilateral Wadden Sea seascape and provides a near-complete representation of the regional biodiversity status that goes beyond the assessment of key indicator species. Such an assessment may help to guide ecosystem-wide conservation and management strategies by serving as a stepping stone to understand system-wide environmental drivers of biodiversity change and highlight functionally important species groups under pressure.

Synthesis of population trends reveals seascape-wide reorganisation of biodiversity

Alexandra Möller, Senckenberg am Meer, German Centre for Marine Biodiversity Research (DZMB)

The Wadden Sea is one of the most biologically productive regions in the North Sea, hosting diverse habitats and rich biodiversity, including birds, fish, and seals. Less visible but ecologically vital are meiofauna, tiny organisms like nematodes and copepods, living between sand grains. These small creatures form a crucial part of the food chain, serving as food for larger animals and playing a key role in breaking down organic material and nutrient cycling. Meiofauna communities are highly diverse and sensitive to environmental changes, making them important indicators of ecosystem health. One focus of the FishNet project is to study meiofauna communities in different benthic habitats within the Schleswig-Holstein Wadden Sea National Park. First results show that sediment grain size is the main determinant of meiofauna composition, shaping oxygenation, food supply, and habitat structure. Consequently, community diversity and the biomass available to higher trophic levels vary spatially. Gut content and isotopic analyses of meiobenthic copepods further indicate habitat-dependent dietary preferences. These insights enhance our understanding of meiofauna contributions to food web dynamics and improve predictions of ecosystem responses to environmental disturbances.

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Terns in trouble: lessons from a long-term, individual-based study

Sandra Bouwhuis, Institute of Avian Research

The common tern (Sterna hirundo) is a colonially breeding, piscivorous and migratory seabird, used as an indicator species to monitor various aspects of the status of the Wadden Sea. At one of her breeding locations, the Banter See in Wilhelmshaven (Germany), where she is protected against impacts of mammalian predators and flooding, she has been the focus of a long-term study since 1992. Individual-based and longitudinal data on phenology, physiology, migratory behaviour, reproductive performance and survival, collected along a 7-generation deep pedigree, have allowed us to study how climate change, decreases in food availability, and environmental pollution affect fitness components and the evolutionary trajectories of these birds. In addition, they have provided us with detailed understanding of the recent impact of another anthropogenically induced stressor: the emergence of highly pathogenic avian influenza. After showing how the population has, as a result of these cumulative pressures, declined by 70%, I will show how we hope to use our research to reach the general public and inspire conservation efforts, such that further declines can hopefully be prevented.

Climate, sediment and de-eutrophication affect abundance of benthos-feeding waterbirds

Thomas Bregnballe, Aarhus University

During 1987-2019 long-term changes in the quality of the habitat of 13 benthos eating waterbird species were analysed in the Wadden Sea. The Trilateral Monitoring and Assessment Program of waterbirds revealed that several species increased or remained stable in the northern and southern sections of the Wadden Sea, while their abundance mainly decreased in more central areas. The Wadden Sea is influenced by freshwater discharge, by geomorphological dynamics, and by sea level rise and climate. We hypothesised that the abundance of waterbirds that are dependent on intertidal flats for feeding is influenced by (a) regime shifts in the southern North Sea, (b) climate affecting riverine discharge (the amount of nutrients) from rivers in the Wadden Sea area, (c) climate affecting breeding conditions at arctic and boreal breeding grounds, (d) changes in geomorphology, (e) sea level rise and (d) biomass of macrozoobenthos. The results reveal that abundance of staging waterbirds in the Wadden Sea is affected by (i) regime shifts and the North Atlantic Oscillation index (NAO), (ii) annual discharge of nutrients (Total N and Total P have both positive and negative effects) and (iii) biomass of macrozoobenthos. Accretion or erosion of intertidal flats caused local displacements of these waterbirds.

The flyway approach to the conservation of Wadden Sea waterbird populations

Kristine Meise, Common Wadden Sea Secretariat

Migratory waterbirds are a very visible and important element of the Outstanding Universal Value (OUV) of the Wadden Sea. It is essential to keep in mind that many “Wadden Sea birds” spend crucial phases of their annual cycle at sites geographically far apart. While the Wadden Sea forms a crucial link in their annual cycle, their conservation status is also influenced by pressures at other sites along the flyway. Thus, conservation efforts in the high arctic and at African coastal sites are directly linked to the aim of protecting the Wadden Sea bird populations and into the OUV of the Wadden Sea. Recognizing the close relationship between countries, the World Heritage Committee requested the Wadden Sea countries to take initiatives and share responsibility for the conservation of Wadden Sea birds along the East Atlantic Flyway. With the vision that “migratory birds find lasting refuge along the East Atlantic Flyway from northern breeding areas to their key Wadden Sea stop¬over and to the African coastline, and inspire and connect people for future generations”, the Wadden Sea Flyway Initiative (WSFI) concentrated on supporting improved monitoring and conservation management along the flyway, with a strong emphasis on building capacity, especially in coastal Africa, where capacity limitations were identified. The presentation will focus on examples of results and actions taken over the past ten years along the flyway, pointing to how they benefit Wadden Sea waterbird populations and can translate into future management and other strategic objectives.

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An ecosystem-based cumulative impact assessment of the Dutch Wadden Sea, using the SCAIRM-method

Lukas Golterman, Wageningen Marine Research

The Wadden Sea, being a system where every activity and ecosystem component is intertwined, cumulative impacts of the increasing activities need to be assessed and ecosystem-based management applied. SCAIRM stands for a Spatially explicit Cumulative Impact Assessment, specifically developed for Ecosystem-based Management. This state-of-the-art cumulative impact assessment method captures the best of previous comprehensive and quantitative CIA methods. This allows for the harmonization of qualitative and quantitative data. The SCAIRM-method is now being applied in the Dutch Wadden Sea. A unique ecosystem that is constantly changing as well being under many direct and indirect pressures, but of vital and world-wide importance for many species (as being a UNESCO world heritage site). In applying the method, we have linked the results to the recently published Staat van de Waddenzee and are now incorporating management scenarios into the assessment. The assessment will inform a new policy frame of the Dutch government expected in October 2025. In our presentation we will elaborate on the method for assessing cumulative impact in the Wadden Sea and give insights for management tools in the future. We hope for a lively discussion and hopefully new inputs and ideas.

Improving cumulative impact assessments in support of management with pressure-state relationships

Jesse van der Grient, NIOZ

The Wadden Sea is facing the cumulative impact of multiple pressures from human activities and climate change. This is well recognized but linking cumulative impacts to biological effects and using this in management remains challenging. Here we present preliminary results of a new framework developed with the aim to address this issue, using the Wadden Sea as a case study. The framework will incorporate different types of data to develop pressure-state relationships and aims to assess the effect of cumulative pressures on key groups in Wadden Sea food web. The end product will be a standardized framework to develop pressure-state relationships for cumulative pressures (additive and combined) which will enable different kinds of models and cumulative impact assessments to incorporate pressure-state relationships of interest. This work will thereby contribute to provide guidance for ecosystem-based management in the Wadden Sea.

Ecosystem-based marine governance: Relevance for Wadden Sea cumulative impacts assessment

Cormac Walsh, Carl von Ossietzky University Oldenburg

The UNESCO decision requesting a strategic environmental assessment of the Wadden Sea WHS to assess current and future cumulative impacts pays particular attention to pressures arising from human activities beyond the boundary of the Wadden Sea. Greater coordination is required between the planning and conservation of the North Sea and the conservation of the Wadden Sea to mitigate the cumulative risks posed by human activities in the southern North Sea. Maritime spatial planning (MSP) is the key policy instrument for achieving this coordination. Ecosystem-based Marine Spatial Planning (MSP) is key to ensuring the cumulative effects of human activities at sea are compatible with achieving and maintaining Good Environmental Status for the marine ecosystem. This paper assesses current practices and potentials regarding ecosystem-based Marine Spatial Planning (MSP) in Denmark, Germany, and the Netherlands. Core components of SEA are relevant for both MSP and Wadden Sea conservation and require a coordinated trilateral approach. The paper explores the potential for Marine Spatial Planning (MSP) to provide a framework for enhanced cross-sectoral and transboundary integration at the Wadden Sea/North Sea interface, outlining potential pathways for integrating Wadden Sea conservation within MSP processes.

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Compilation of the "State of nature of the Wadden Sea"

Patrick Bogaart, Statistics Netherlands

Policy development for the Wadden Sea aimed at protection and restoration of the ecosystems within this area, require a broad and consistent monitoring and evaluation framework. In the Netherlands, the Wadden Academy in collaboration with Statistics Netherlands have developed such a framework. We build upon legal frameworks as the EU Bird and Habitat Directives and the Water Framework Directive, but also on statistical frameworks such as UN Ecosystem Accounting. We pull together elements from these, and combine them with advanced statistical methodologies such as the Multi-Species Indicator and flexible trend analysis into a single combined approach. The State of Nature of the Wadden Sea includes indicators on abiotics (climate; hydrography; water quality; sediment) and biotic (habitats, phytoplankton, benthos, fish, birds and marine mammals. For each of these reference values are used to compile indicators on a common scale from 0 to 1, allowing intercomparison and aggregation of information. We present the design of the new framework, the approach taken, and the final results. We conclude that the framework as a whole not only aids in the identification of the state of the Wadden Sea, but also helps stakeholders in their discussions on the future state of this world heritage.

Benthic biodiversity and anthropogenic pressures in the Dutch Wadden Sea

Oscar Franken, Royal Netherlands Institute for Sea Research

Many shallow coastal seas, such as the Wadden Sea, are rapidly degrading due to anthropogenic pressures. To support adequate decision-making on implementing new policies and adjusting management actions for these areas, it is essential to have recent species distribution and abundance data on ecologically relevant spatial scales. Macrozoobenthic species (i.e., species living in and on the sediment) can be valuable indicators of the status of these ecosystems as they have a relatively low mobility compared to other taxonomic groups. We combine information from two large-scale sampling campaigns of macrozoobenthic species in the Dutch Wadden Sea: Waddenmozaïek for the subtidal (n 1323), and SIBES for the intertidal (n 4212). Both sampling campaigns are laid out on a grid with regular intervals (1000m for subtidal and 500m for intertidal areas), with additional random samples to improve estimates of spatial autocorrelation. This allows us to map species distributions throughout the extent of the Dutch Wadden Sea, and link distribution, biodiversity and community composition patterns to a range of anthropogenic stressors. This spatially explicit information can be used to improve our understanding of the ecological functioning of the subtidal Dutch Wadden Sea and to support informed policy and management decisions.

Fundamental transformations in the benthic Wadden Sea

Karsten Reise, Wadden Sea Station Sylt, Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI)

Human induced regional pressures, biological globalization and climate change are challenging the integrity of tidal benthos in the Wadden Sea. In Königshafen Bay (northern Wadden Sea), a fundamental transformation of the benthic ecosystem has been observed since 1925. It began with restoration attempts on an overexploited bed of European oysters and with the introduced seagrass wasting disease in 1933. It culminated with the introduction of Pacific oysters since the 1990s and an advancing flood of many more introduced species. These outnumber by far the few local extinctions, resulting in an increased benthic biodiversity. The loss of seagrass caused a decline of mud flats, while bioturbating lugworms maintained sandy flats. Finally, the spread of biogenic reefs of mixed mussels and Pacific oysters along low tide line may have caused a recent return of mud to the flats. The benthic ecosystem has shifted from prevailing autotrophy to heterotrophy by a disproportional increase of introduced suspension feeders. The emerging novel ecosystem constitutes an adaptation to ever changing conditions. Such ecological developments undermine our concept of ecosystem integrity and ask for a change in the perception of the natural values and its cultural attachments in the Wadden Sea.

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Biomimicry: Interpreting Wadden Sea recommendations through functional and symbolic Perspectives

Catharina van den Driesche, University of Amsterdam/KADEN DESIGN

The concept of biomimicry is traditionally understood as a function-driven approach emphasising biological efficiency, technological innovation and ecological performance. This paper presents a reflective synthesis for expanding the concept of biomimicry by combining three approaches; architecture, semiotics and design research. We propose a theoretical framework that bridges the functional and cultural dimensions of biomimicry by integrating symbolic and interpretive systems, reflecting on the creative tensions and insights that emerge in transdisciplinary design. By integrating cultural semiotics with nature-based innovation, we argue that biomimicry can also address relational, systemic, and narrative qualities. Grounded in Actor-Network Theory, this framework challenges the conventional divide between human and non-human actors, recognising co-agency as a foundational principle towards symbiosis. The study seeks to explore how the recommendations of the 2024 Wadden Sea Quality Status Report can be interpreted to inspire regenerative and context-sensitive transformations for the area. It illustrates how biomimicry provides a multidimensional lens beyond functionality to address the Wadden Sea's current and future challenges, enabling the translation of abstracted natural strategies into diverse design responses to climate change. This expanded perspective supports the development of regenerative and context-sensitive designs, particularly for vulnerable landscapes like the Wadden Sea, enhancing their ecological and cultural resilience.

The economic benefits of nature-based solutions for climate risk: A meta-analysis

Guillermo García Alvarez, Institute for Environmental Studies, Vrije Universiteit Amsterdam

This meta-analysis of stated preference studies among 49,500 total respondents aims to quantify the economic value of co-benefits from nature-based solutions (NBS) that address climate risks. Results show that the willingness-to-pay for co-benefits increases with GDP per capita and decreases with NBS size. Recreational and aesthetic benefits are more valued and NBS developed in urban grey areas are higher valued compared to conservation and maintenance of current nature sites. The resulting novel value transfer function can assist future research and policymakers in assessing the economic co-benefits of NBS for climate risk based on the policy site characteristics.

Visualizing social-ecological links for marine protected area decision-making

Maja Skovgaard Jessen, University of Southern Denmark

Achieving the global 30x30 conservation target requires effective implementation of Marine Protected Areas (MPAs), which is supported by the EU-funded Blue4All project. The Danish Wadden Sea serves as a study-area, where collaboration with local conservation managers revealed a need for tools to guide research and conservation investments. This study, building on insights from local conservation area managers and the framework by (Armoškaitė et al., 2020), adapts and tests a visual tool to illustrate and communicate the complex interlinkages between social and ecological systems, aiming to support informed decision-making in MPA management. Focusing on Zostera noltii and Branta bernicla bernicla in the northern Danish Wadden Sea, we modelled interlinkages among pressures, components, functions, and ecosystem services using the cascade model, and visualised them with Sankey diagrams. Link identification and quantification were expert-based, supported by scientific and grey literature. This species-focused, local approach linked human pressures to a complex social-ecological system. Preliminary results revealed a highly interconnected system emphasizing the ecological significance of both species. The process also revealed knowledge gaps when applied to this spatially confined system. While the method benefits from more quantitative data, it offers a guide for holistic decision-making in local MPA management and supports sustainable area management.

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Does warming affect barnacle recruitment at temperate and Arctic sites?

Anna Sophie Lange, Universität Rostock

Warming affects intertidal benthic species, especially sessile organisms like barnacles, which are exposed to rising air temperatures at low tide. Since some intertidal barnacle species naturally live near their thermal limit, they are suitable model organisms for studying the ecological impacts of climate change. Our study investigates barnacle recruitment on two temperate coasts and one Arctic coast by experimentally manipulating settlement substrate temperatures in the field. The results may provide deeper insights into warming effects on intertidal organisms. We predict greater shifts in barnacle abundance and changes in species composition at temperate coasts, while Arctic coasts may be less affected by warming, as they host only one intertidal barnacle species that is also adapted to temperate temperatures. In the northern Wadden Sea and on Helgoland´s rocky shore, warm-adapted barnacle species, including introduced species from warmer regions, may benefit from increased substrate temperatures. In the Wadden Sea, in addition to the direct effects, we also assess indirect effects by determining the consumption of barnacle predators at elevated temperatures. Our study aims to examine whether climate warming causes both direct and indirect effects on barnacle populations, potentially leading to intertidal community changes in the Wadden Sea and other coastal ecosystems.

Warming-induced changes in Common goby physiology and behavior

Christian Aakjær Olesen, Forschungs und Technologiezentrum Westküste

With global warming accelerating ecosystem change, understanding the species that underpin these systems is crucial. Assessing how species respond physiologically and behaviorally to rising temperatures helps predict their future resilience and guides conservation strategies. This study focused on the common goby (Pomatoschistus microps), an ecologically important coastal species. Gobies were housed in mesocosms replicating natural conditions with sediment and fauna from a blue mussel bed community. Mesocosms were maintained at three temperature regimes: ambient, ambient +1.5 °C, and ambient +3 °C. Over three months, we tracked growth and conducted behavioral assays assessing latency to first movement, swimming speed, durations of swimming and resting, and frequency of surfacing behavior. We observed clear temperature-dependent changes in both growth and behavior Notably, individuals from different temperature treatments responded differently when tested at the same temperature, suggesting lasting physiological or behavioral effects depending on their thermal history. These results indicate that while moderate warming may temporarily enhance some performance traits in P. microps, sustained exposure to higher temperatures can induce stress-related behaviors that may reduce fitness. Understanding these trade-offs is key to predicting species responses under climate change and their potential impacts on coastal ecosystems.

The effect of warm summers on fish

Ingrid Tulp, Wageningen Marine Research

The use of coastal areas, including the Wadden Sea, by fish species that were once abundant has changed significantly over the past 50 years. There is strong evidence that climate change has contributed to this shift, although other factors may also play a role. To better understand why the ecological function of the Wadden Sea has changed, it is important to study the seasonal patterns of how fish of different sizes and ages use the area. Seasonal sampling data collected in a new survey over the past six years now offer an opportunity to assess the impact of warm summers on the phenology of various fish species. As ectothermic animals, fish are particularly sensitive to temperature changes, which also affect their growth rates and physical condition. In this contribution we will summarise our findings and put them in a wider perspective in terms of area (comparison outside the Wadden Sea) and time (comparison to historic data).

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Marine heatwaves and benthic life: Is mobility key to survival?

Jasmin S. Mueller, Institute for Chemistry and Biology of the Marine Environment (ICBM) University of Oldenburg
& Senckenberg am Meer, Department for Marine Research

In an era of rapid environmental change, marine heatwaves have become increasingly frequent, are a major stressor for marine life and can cause ecosystem shifts. It is critical to understand how marine organisms are affected by marine heatwaves to predict future impacts of climate change at the ecosystem level. In an mesocosm experiment we simulated a marine heatwave with a subsequent recovery phase, focusing on marine macrozoobenthos from the Wadden Sea's intertidal flats. We investigated species with different mobility-traits: three motile species (Hediste diversicolor, Littorina littorea, Corophium spp.) and three less motile species (Cerastoderma edule, Arenicola marina, Lanice conchilega). We explored how their mobility influence their responses to heat stress and their recovery potential. To understand how these organisms can handle heat stress, we studied their physiological performance in terms of respiration, antioxidant capacity, and mortality. Our mortality rate results show species-specific responses irrespective of mobility, with high mortality observed in heat-sensitive species (Corophium spp. (motile) and L. conchilega (less motile)), while the other species survived with minimal mortality. Our findings determine the physiological resistance of marine organisms to heatwaves and provide insights into the potential ecological consequences of climate change in the Wadden Sea.

Primary production in non-native Vaucheria-turfs (Xanthophyceae) on a tidal sedimentary coast

Ronny Steinberg, Universität of Bremen

Climate change has raised seawater surface temperatures in the south-eastern North Sea by nearly 2 °C over recent decades, facilitating the spread of non-native species such as Vaucheria sp. (V. aestuarii and V. cf velutina) in the northern Wadden Sea. This study examined the photosynthetic performance of Vaucheria sp. turfs from the east coast of Sylt under six temperature conditions (16–36 °C) and increasing light intensities (100–900 µmol photons m^{-2} s^{-1}). Using a FireSting 4-channel optode system to measure oxygen production and a microscope PAM fluorometer to assess relative electron transport rate (rETR) and maximum quantum yield (Fv/Fm), the study found that primary production peaked at 32 °C, reaching 4.93 µmol O_2 L^{-1} h^{-1} mg^{-1} at 470 µmol photons m^{-2} s^{-1} and 5.82 µmol O_2 L^{-1} h^{-1} mg^{-1} at 900 µmol photons m^{-2} s^{-1}. No temperature-dependent differences were observed at the lowest light intensity (100 µmol photons m^{-2} s^{-1}), while the algae died at 36 °C. Photosynthetic parameters (rETR and Fv/Fm) differed significantly between the lowest and highest temperatures compared to intermediate ones. These results suggest that warming may increase the productivity and photosynthetic activity of Vaucheria sp., allowing it to spread further and potentially alter ecosystem dynamics in intertidal zones.

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Asymmetric morphodynamics of the Wadden Sea

Robert Lepper, Federal Waterways Engineering and Research Institute (BAW)

Sea level rise could diminish the Wadden Sea unless sediment accretion limits its submergence. Therefore, quantifying and understanding their current and projecting its future morphological evolution is of key interest. To quantify observed morphodynamics in the Wadden Sea, an ob-served, high-resolution geomorphological time-series was created and assessed with a novel sta-tistical approach over three decades. We found how (i) accretion-erosion was asymmetric from deep to shallow, (ii) topographic steepening occurred, and (iii) the morphological evolution was systematic across tidal basins. Peak accretion was observed below tidal low and above tidal high water, while the greatest erosion occurred at intermediate subtidal elevations. Most intertidal are-as accreted faster than sea level rise and accretion was prominent at the channel-flat and flat-marsh interfaces. The simultaneous deepening of tidal channels leads to topographic steepening along with intertidal expansion through the siltation of small gullies. Overall, the current net sed-iment import of the Wadden Sea is 19.7 Mm^3/yr. Most net accretion was observed North of the Elbe estuary, the North Frisian Wadden Sea, whereas the Dutch Wadden Sea had a tendency toward erosion. Our results can be applied furthermore as a Segway to extrapolate present morphodynamics robustly into the future.

Vegetation modelling at the tidal Elbe: reedbed growth as a function of hydrodynamics, morphodynamics and climate change

Johannes Leins, Federal Institute of Hydrology

The project “Parabola for Climate” uses the HaMac vegetation model to investigate marsh development in estuaries. HaMac therein estimates the effects of stressors and sea level rise (SLR) scenarios. The findings will provide the German Waterways and Shipping Administration with targeted advice for the adaptation to climate change. Riverbank protection measures are already challenging due to anthropogenic influences and estuarian dynamics. Climate change and SLR aggravates these conditions even further. In this context, reedbeds make a significant contribution to secure the shore, weaken currents and waves and accumulate sediment to allow marsh growth along the SLR. HaMac has been used before to investigate influences on growth and mortality of two reed species applying statistical models to link species occurrence with abiotic factors. The results were analyzed to determine causes of vegetation dynamics along the tidal Elbe. However, some likely significant processes for long-term forecasts have not yet been considered. The present project will include feedback processes such as sedimentation, wave impact and bed shear stress. In addition to estimating the dynamic development of marsh vegetation, robustness and validity of former calculations will be discussed using current data. Furthermore, the impact of the new processes on model results will be addressed.

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Storm surges along the prehistoric coast of northwest Germany

Ines Bruns, Lower Saxony Institute for Historical Coastal Research

Since the beginning of the Holocene, the rising sea level has resulted in a general progradational shift of the northwest German coastline. Additionally, storm surges influenced the paleo-coast and must be considered to better understand the landscape evolution in the region. Unlike to today's highly engineered coastline, the prehistoric coast was un-diked and thus, it is assumed, that prehistoric storm surges had substantial different effects on the coastal environment. While storm surge deposits have been identified along the northwest German coast, they have not yet been systematically studied. The interdisciplinary project CoastAdapt aims to investigate the inland reach of prehistoric storm surges, the geological conditions that may have favoured inundation, and if storm surges triggered transgressions. The study focuses on cm-thick clastic layers known as "Klappklei," found within Holocene peat horizons. "Klappklei" layers form only during high water levels and can therefore serve as valuable indicators of past storm surge events. We present a reconstruction of the spatial distribution of "Klappklei" across several Holocene time slices, along with estimates of associated inundation extent. The results are based on borehole archive data and updated sea-level reconstructions, complemented by a regional case study from the East Frisian coast.

Stability of saltmarshes during extreme storms: A full-scale flume experiment

Jos Muller, University of Twente

Saltmarshes offer a promising natural alternative for enhancing existing coastal defences. At the same time, they provide various ecosystem services such as habitat and carbon sequestration. However, their long term reliability remains uncertain due to limited understanding of their erosion, particularly during extreme storms. Therefore, an unique full-scale experiment was carried out in the Deltares wave flume. This included a real-life, 80 meter long saltmarsh (predominantly Elymus athericus), harvested at a field site at the Dutch Wadden Sea. Extreme storm conditions were simulated, consisting of a maximum inundation of 4 m and maximum offshore wave height of 4 m. Results show limited erosion after 40 hours of cumulative exposure, with eroded volume approximate 5% (1.5 m3) of the overall saltmarsh volume (85 m3). Most of the erosion is observed at the seaward edge of the marsh. The erosion process initiates with the detachment of fine soil particles between the roots of the vegetation, eventually leading to the uprooting of large vegetation segments. Once exposed, the bare soil erodes due to scouring until more consolidated layers are exposed after which erosion rates decrease. These findings contribute to the understanding of saltmarsh erosion and highlight their resilience under extreme storm conditions.

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Behavioural responses of seals to tourism: A basis for conservation guidelines

Emilie Stepien, Aarhus University

The Wadden Sea's designation as a World Heritage site reflects its Outstanding Universal Value (OUV), grounded in its dynamic ecological processes and rich biodiversity. Among the region's iconic species are harbour seals (Phoca vitulina) and grey seals (Halichoerus grypus), which have become focal points for an expanding nature tourism industry. However, the growing popularity of seal watching—particularly through boat-based safari tours—raises concerns about potential disturbances to seal behaviour and habitat use. Monitoring tagged and not-tagged seals, this study investigates how tourism and boat activities influence the haul-out patterns and behavioural responses of seals in the Danish part of the Wadden Sea, where the harbour seal population has shown signs of decline over the last 10 years. By identifying the conditions under which disturbances occur, the project seeks to develop practical, science-based guidelines for seal watching that allow visitors to experience wildlife without compromising animal welfare or conservation goals. Ultimately, this work supports the integration of sustainable tourism with efforts to safeguard the ecological integrity of the Wadden Sea and uphold its Outstanding Universal Value.

Degrowth-inspired tourism: reconceptualising sustainable development in the Lower-Saxonian biosphere region?

Gesa Witt, University of Vechta

In the Wadden Sea region, tourism growth expectations cause increasing pressures on natural resources and ecosystems. Sustainable tourism approaches so far do not sufficiently address conflicting interests between nature protection, tourism management, coastal protection and other sectors. Thus, this contribution aims 1) to first empirically show how different key actors in the Wadden Sea of Lower Saxony socially construct different models of sustainable tourism and notions of growth or degrowth against the backdrop of conflicts in society-environment-interactions and 2) to conceptualise degrowth-inspired sustainable tourism in UNESCO biosphere reserves. By analysing relevant documents and semi-structured interviews with tourism and nature conservation stakeholders, narratives about growth or degrowth as well as conflicts evolving through tourism growth dynamics are examined. As a result, sustainable degrowth-inspired tourism in the Wadden Sea, especially in the UNESCO biosphere region, can be conceptualised as aiming to preserve and restore healthy society-environment interactions, provide the conditions for a high quality of life and good working conditions. In conclusion, applying a degrowth-lens to conflicts emerging through different positions regarding touristic development can not only provide support through offering a value-based approach for mitigating them, but also contribute to their overall prevention through raising awareness for balancing healthy society-environment-interactions.

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Applying 'Broad prosperity' in monitoring the Wadden Sea ports

Bart Kuipers, Erasmus centre for Urban, Port and Transport Economics

Traditionally, the prosperity of seaports is measured in terms of added value, employment, investments and the formation of new businesses. This has been carried out twice by Erasmus UPT for the Dutch Wadden Sea ports, in 2017 and 2024, based on the Port Monitor, a monitoring tool for all (major) Dutch seaports, commissioned by the Wadden Academy. In general, measured with traditional measures, prosperity increased for the Wadden Sea ports as a whole, but not for all Wadden Sea ports. Investments related to offshore wind energy formed the largest source of growth for this increasing economic impact. However, it is unclear whether this growth in traditional economic indicators has translated into higher values for the broad prosperity for the Wadden Sea port cities and regions. In our contribution, the current practice of operationalizing the broad prosperity for the Dutch seaport system is presented and translated to the Wadden Sea ports in particular. This practice is based on recent research projects in Dutch ports, both for Dutch ports as a whole and for individual Dutch seaports. In addition, (first) findings are presented for a new research project to be started in which the broad welfare thinking is tailored to the Wadden Sea ports (commissioned by the Wadden Academy).

Impact of offshore wind farms on sediment and organic carbon exchange between the Wadden Sea tidal basins and the North Sea

Jiayue Chen, Helmholtz-Zentrum Hereon

The rapid expansion of offshore wind farms (OWFs) in the North Sea is altering natural sediment transport processes between the North Sea and the Wadden Sea. Using a 3D hydro-eco-morphodynamic model, this study examines how OWFs influence key transport mechanisms, including residual currents, sediment and particulate organic carbon (POC) exchange between the open sea and tidal basins. The results show that OWFs can notably alter natural sediment transport pathways by mediating the frontal systems, water level and residual sediment and POC transport flux. Understanding these impacts is crucial for managing the interconnected dynamics of coastal ecosystems, marine spatial planning, and climate-adaptive coastal protection. This research supports the development of offshore wind energy in a way that accounts for its broader environmental consequences on sediment dynamics and carbon burial.

Study light pollution effects on bird migration using weather radar

Jutta Leyrer, BioConsult SH

Within the Interreg North Sea project Darker Sky, we investigate the possibility to use weather radar data to monitor bird migration on a regional scale and to study the influence of light pollution on bird migration along coastal areas of the North Sea. We use raw data from the weather radar located on Borkum island, Germany, available on the German Meteorological Service (Deutscher Wetterdienst) data portal. We apply digital filtering methods of R package bioRad to the original data to separate bird signals from other echoes. To investigate the influence of artificial sources of light and weather conditions on the dynamic of bird migration over the southern North Sea, we compare areas with contrasting light pollution intensities. Data on light pollution are taken from satellite observations and local measurements on the ground with Sky Quality Meters (SQM). Our results will support the implementation of measures to reduce light pollution.

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Mussel culture impacts on marine biodiversity in the Wadden Sea

Lotte Julia Bouwman, Wageningen University & Research

Wild mussels are key ecosystem engineers, forming complex biogenic habitats. While mussel aquaculture provides similar structures, its impact on biodiversity, particularly at higher trophic levels, remains poorly understood. In the Netherlands, mussel culture is the largest aquaculture sector, concentrated in the Western Wadden Sea and Eastern Scheldt. These systems host both wild bivalve beds and together a total of 11.500 hectares of designated mussel bottom culture plots. A unique opportunity arose during the 2021 optimization of mussel plots, enabling before-and-after sampling (2018–2026) across six newly designated blocks in the Eastern Wadden Sea. A longitudinal sampling campaign, covering 120 locations, investigates biodiversity changes in infauna, epifauna, and pelagic fauna, offering crucial insights into the ecological effects of mussel bottom culture. Here, we present the initial findings on the quantification and development of benthic and fish communities in the Western Wadden Sea, on newly established mussel culture plots. The analysis is based on functional trait approaches and biodiversity indices, providing insights into community structure, ecological functioning and temporal dynamics. Especially the understanding of ecological succession and establishment of mobile species communities is unprecedented at this scale and will inform sustainable management practices on the effects of mussel aquaculture in the Western Wadden Sea.

Development of blue mussels and Pacific oysters on mussel beds

Hanna Schade, BioConsult SH GmbH & CO. KG

Blue mussel beds are an essential part of the Wadden Sea Ecosystem. The pacific oyster (Magallana gigas Thunberg, 1793) is one of the most prominent introduced alien species to the Wadden Sea and strongly exceeds blue mussels (Mytilus edulis) in terms of individual size and total biomass. Both species exist now in mixed communities, often dominated by oysters. Both species are filter feeder and assumed to be food limited, thus coexistence may well result in competition. For the Lister Deep we investigated on tow mussel beds whether high abundance of pacific oysters depresses growth and condition of blue mussels. We provide a long-term analysis of growth and condition of blue mussels in relation to an increasing biomass with the presence of pacific oysters Results show that length and condition of blue mussels declined with the presence of pacific oysters while length and condition of blue mussels increased for a short period after the ice winter with the decline of pacific oysters and the total biomass.

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Natural dynamics of epibenthic communities on former mussel culture plots

Andreas Waser, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Wadden Sea Station Sylt

Blue mussels (Mytilus edulis) play a vital ecological role in the Wadden Sea by forming reef structures that support a diverse community of associated organisms. However, in subtidal areas, decades of intensive mussel fishing have disrupted their natural occurrence and development, making naturally persistent subtidal mussel beds increasingly scarce. In the northern Wadden Sea of Schleswig-Holstein, a major shift in management practices took place in 2017. As part of these changes, mussel aquaculture was discontinued in the List tidal basin. Since 2020, the former culture plots in this area have been regularly monitored to assess habitat suitability for natural mussel settlement and the potential for establishing persistent subtidal mussel beds. The monitoring efforts have examined not only mussel occurrence but also associated species diversity and predator abundance (sea stars and crustaceans) as well as substrate availability for blue mussels, including the presence of Pacific oysters (Magallana gigas) and shell debris. The absence of fishery disturbance provides a valuable opportunity to study the natural recolonization potential of subtidal mussels. We examine how epibenthic species communities have developed over time on the former culture plots and discuss the key factors influencing the sustainable recovery of subtidal mussel populations.

German brown shrimp fishing behavior groups from vessel movement data

Serra Örey, Carl von Ossietzky University Oldenburg, Institute for Chemistry and Biology of the Marine Environment (ICBM)

The German brown shrimp (Crangon crangon) fleet in the North Sea is declining due to rising fuel costs and unpredictable shrimp prices. Furthermore, this fishery is adapting to new marine protection area(MPA) regulations. In February 2023, the EU Commission released an "Action Plan to protect and restore marine ecosystems for sustainable and resilient fisheries". The Commission urges Member States to gradually stop bottom fishing in both current and future MPAs by 2030. As the shrimp fishery takes place mainly in the State National Parks it will be affected by the forthcoming regulations of the Action Plan. We analyze thirteen years of Vessel Monitoring System (VMS) data spatially and temporally to investigate fisher behavior for this specific métier. We evaluated the potential effect of recently implemented and pessimistic future marine protected area (MPA) closures linked to the EU Action Plan 2023. The former have negligible overlap with areas exploited by shrimp fishers, but the latter cover grounds from which 70% of brown shrimp landings originated during 2009-2021 without effort relocation or behavioral adaptation. This work underscores the value of behavioral data in assessing the potential outcomes of future spatial regulations.

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Outdated fisheries management for brown shrimp urgently needs an update

Wouter van der Heij, Waddenvereniging

Outdated fisheries management had led to high intensity fishing for brown shrimp (Crangon crangon) in the Dutch and German Wadden Sea. Studies (recently CRANIMPACT) show that the current fishing pressure leads to growth overfishing of the species. Already ten years ago Temming and Hufnagl, 2015 (doi 10.1093) showed that the high fishing pressure is not sustainable both ecological as economical. The authors suggest to modernize fisheries management for brown shrimp by experimenting with lower fishing pressures to increase CPUE. Could reduced fishing pressure be beneficial for both shrimpers and nature restoration efforts in the Wadden Sea?

Shrinking stocks, growing concerns: Five years of brown shrimp research

Merten Saathoff, Alfred-Wegener-Institute: Helmholtz Centre for Polar and Marine Reseach

The brown shrimp (Crangon crangon) fishery in the Wadden Sea operates under a unique self-management plan aimed at Marine Stewardship Council (MSC) certification. Unlike most European fisheries, it operates outside direct EU regulation and instead relies on voluntary measures, including a Harvest Control Rule (HCR) that restricts fishing effort during periods of low catch. However, persistently low catches over the past five years and frequent HCR activation indicate that the stock may be in historically poor condition. This presentation outlines the current management framework and introduces CRANMAN2, an ongoing interdisciplinary research project aimed at improving brown shrimp management strategies. It will focus on two key findings from the project's first phase: 1. Evidence of recruitment overfishing, as shown by a consistent decline in landings-per-unit-effort (LPUE) of egg-bearing females in the first quarter. 2. New insights into seasonal growth patterns, revealing that winter-hatched cohorts may grow faster than those hatched in summer. Together, these findings raise concerns about the long-term sustainability of the fishery and the resilience of the stock under the current self-regulatory approach. The presentation will also outline the research questions guiding the second project phase, with the goal of informing future management recommendations.

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Projekt Sandküste St. Peter-Ording

Sönke Breckling, WWF Deutschland

The coastal landscape of St. Peter-Ording is an outstanding natural area within and around the Wadden Sea National Park. Its diverse coastal habitats with the high abundance of animal and plant species turn it into an exceptional biodiversity hotspot, unparalleled on the mainland of the Wadden Sea. However, some of this diversity is threatened. Climate change, accelerating rising sea levels, habitat fragmentation, and the spread of non-native species endager the local species- and habitat richness. The overarching goal of the project "Sandküste St. Peter-Ording" is to improve the conservation status of parts of the coastal landscape and to create key conditions for climate change adaption. Coastal habitats are to be ecologically enhanced, better interconnected, and brought to a favourable conservation status to preserve or restore site-specific biodiversity.The geomorphological development of the coastline and the flood protection function of the dunes in the section without a dike are being scientifically assessed. Potential adaptation measures that align with nature conservation, coastal protection, and local community development are to be developed and evaluated. Identification, acceptance for protection and experienceable of local habitats shall be increased.

Method towards determining coastal adaptation pathways for the Wadden Sea

Jelle Bulens, Utrecht University

With the current and projected climate pressures on geomorphology, ecology, and subsequently society in the Wadden Sea area, a shift towards a more natural and open system that restores the system's original flexibility can provide a perspective for adaptation. This poster presents an overview of a methodology and preliminary results on effective coastal adaptation strategies under future scenarios of sea-level rise along the trilateral Wadden sea coast. We first compile and review current and near-future adaptation strategies as well as natural analogues (e.g. Boschplaat, Terschelling; Sommerdeich realignment Langeoog; Ems estuary beneficial use of dredged sediment). After literature review and data collection focused on existing adaptation strategies, we will use numerical modelling to assess the effects of adaptation strategies on the Wadden Sea physical environment. We propose to use archetypes to help with understanding possible strategies and their potential for future upscaling in different types of Wadden Sea areas. We will use the archetypes to explore adaptive pathways for the trilateral Wadden Sea coast and provide actionable advice for future management across stakeholders.

Swash bar stability on a high-energy mesotidal beach

Jairo Cueto, Kiel University

Swash bars are intertidal bar systems characterized by a single, small, low-amplitude bar and trough, often displaying a rhythmic pattern along the shore with troughs converging into shore-normal rip channels. In this study, we assess the stability of swash bars on Spiekeroog North Beach—a high-energy mesotidal beach in the German North Sea—using high-frequency fixed-camera imagery and wave and water level records collected over >100 days. Swash bar size fluctuations and migration rates were calculated and related to water level and wave heights. Three distinct states can be defined: dynamic equilibrium (migration ≤15 m/day, associated with fair-weather conditions), active migration (migration >15 m/day, occurring under moderate to high energy levels), and no-bar states, typically following high-energy events such as storms. Additionally, bar creation and destruction patterns were analysed in relation to local hydrodynamic conditions. These findings were synthesized into a stability diagram, illustrating the likely behaviour of swash bars under specific wave and water level conditions.

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Seasonal variability of inter-tidal sand flat height

Gerald Herrling, LKN.SH, Schleswig-Holstein State Agency for Coastal Protection, National Park, and Marine Conservation

In the Wadden Sea of Schleswig-Holstein, Germany, the inter-tidal flats accumulate sediment and grow by a mid-term average of locally 4-22 mm/year (Benninghoff & Winter, 2019), and thus outgrow present rates of sea level rise. It is hypothesized, however, that the seasonal change in inter-tidal flat height could be in the order of several centimeters and up to 1-2 decimeters in the short term under the erosive effect of storms. The coastal authority (LKN.SH) started to employ terrestrial laser-scanning (LiDAR) mounted on a tower south of the island of Pellworm to measure absolute sand flat heights at an areal extent of 140x160 meters at a few surveys per year. The vertical error of the measurements was evaluated to 1-2 cm, slightly increasing with the distance from the scanner. The vertical accuracy of airborne laser-scanning, that is commonly employed to monitor the inter-tidal morphological development at large spatial reach, is of one magnitude lower (error of 10-15 cm) and only executed at an interval of 6 years. The objective is to gain a better understanding on the seasonal variability of the equilibrium height of sandy intertidal flats.

Refining the conceptual morphological models of the Vlie tidal basin for management and maintenance practices

Martijn Klein Obbink, Rijkswaterstaat WVL

A way to improve decision-making in management and maintenance is by using conceptual models (Lodder, 2022). Conceptual models are crucial in translating detailed scientific knowledge into a comprehensive overview, thereby increasing system understanding and facilitating informed decision-making. These models support the development of adaptive management strategies that reduce the anthropogenic pressures such as climate change and sea-level rise. Our case looks in more detail at the Vlie basin in the Wadden Sea and refines the existing conceptual models. Recently, several studies have been conducted for the Vlie basin within the management and maintenance research program of Rijkswaterstaat, which together contributed to an improved system understanding on a larger scale. The resulting conceptual model provides insights on three temporal and spatial scales: the western Wadden Sea (large scale), the basin, and a detailed scale zooming in on areas of interest. The larger scales provides boundary conditions for developments smaller scales, while local processes can influence large scale trends as well. The visual representation helps connect the interaction of different hydrodynamic and morphological processes. Various aspects on different spatial scales are relevant for different management questions. It is therefore essential to align the conceptual model with the questions that it should address.

Modelling the blue carbon potential of seagrass in the Wadden Sea

Veronika Mohr, Helmholtz-Zentrum Hereon

Seagrass meadows in the Wadden Sea are receiving increasing attention, not least for their role in carbon sequestration. Seagrasses not only store carbon in their biomass but also promote the accumulation of allochthonous particulate organic carbon (POC) in their sediments. However, observational studies often show that the carbon content in seagrass sediments is not significantly different from that in adjacent bare sediments. In this study, we aim to quantify the carbon storage potential of seagrass meadows through both seagrass biomass and the trapping of allochthonous POC. We use a 3D-hydrodynamical model to simulate the seagrass seasonality, hydrodynamics, sediment dynamics and POC transport in the Sylt-Romo Bight, located in the norther Wadden Sea. Our results show that, despite growing in intertidal zones and consisting of short-leaved species, Wadden Sea seagrasses can impact the processes relevant for carbon sequestration at the basin scale. In addition, seasonal growth patterns significantly impact the potential of seagrass to trap sediment and particulate organic carbon, underlining the importance of including the seasonality when assessing their carbon sequestration potential.

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Process-based modelling up and down the beach states

Amin Rahdarian, CAU (University of Kiel)

One of the most applied models for the characterization of sandy beaches is the Beach State Model (BSM) that empirically relates dissipative, intermediate and reflective beach types to wave conditions and sediment characteristics. Here we utilize the Delft3D-4 modelling system and create an idealized morphodynamics model to explain beach morphological changes under varying wave conditions. The model is capable of simulating both erosive upstate and accretive downstate sequences. Under an energetic condition the profile develops into an alongshore-uniform dissipative two-bar profile. Under low wave-energy condition, the morphology develops downstate, leading to initiation and evolution of rip currents following onshore movement of the bar. The sandbar develops as a result of sediment transport convergence of wave asymmetry and the undertow and moves offshore.

Representative residual transport pathways in a mixed-energy open tidal system

Clayton Soares, Christian-Albrechts-Universität Kiel

Set against the dynamic interface of barrier islands, tidal inlets, and intertidal flats, the North Frisian Wadden Sea (NFWS) exemplifies a mixed-energy tidal system. We applied a depth-averaged Delft3D-4 model over a representative 12-month period, chosen via a novel wind-based reduction technique, to investigate residual flow and sediment transport. Three hierarchical forcing scenarios, 1) combined waves, tides, and wind, 2) tides + wind, and 3) tides only, were used alongside residual vector analysis and flux decomposition, across offshore, flats, and channel zones to isolate each driver's impact. Results reveal an anticlockwise circulation in back-barrier channels (mean 0.04m/s, peak 0.77m/s), slower flow velocities over flats (mean 0.03m/s, peak 0.53 m/s), and stronger in channels (mean 0.05m/s, peak 0.85m/s). Sediment transport pathways are spatially variable: transport is two orders of magnitude greater in channels (~2.85×10^{-6} $m^3/s/m$) than over flats (~2.5×10^{-7} $m^3/s/m$) or offshore (~9.5×10^{-7} $m^3/s/m$), with flood-dominated back-barrier channels, ebb ward reversal seaward of channel throats, and southward bypassing longshore drift that generates migrating divergence zones along barrier islands. This study provides a first comprehensive overview of the residual flow and sediment transport in the NFWS as a prominent example of a mixed-energy open tidal system.

Morphological evolution of tidal flats in the Wadden Sea

Marthe Wassink, TU Delft

The Wadden Sea is threatened by accelerating sea level rise (SLR). Without sufficient sediment accretion, the intertidal area may shrink, impacting the ecosystem and coastal safety. Model-based predictions suggest that tidal flats in the Dutch Wadden Sea can only partially adapt to accelerated SLR, while observed present-day accretion rates in the German Wadden Sea are much higher than current SLR rates. Morphological changes on tidal flats are strongly influenced by sand-mud segregation, with muddy sediment responding different to SLR compared to sandy sediment. However, this aspect is not yet accounted for in studies analyzing long-term evolution of the tidal flats. This study aims to understand the long-term evolution of tidal flats to improve predictions of their response to SLR and to develop measures for preserving the unique ecosystem of the Wadden Sea. For this we will quantify patterns of accretion and erosion of sand and mud across the entire trilateral Wadden Sea. By developing sediment budgets, separated into sand and mud fractions, we aim to better understand transport pathways. We hypothesize trends in accretion and erosion patterns will be linked to hydrodynamic changes (tidal range, SLR, storm activity) and human interventions (dredging, reclamation, construction of closure dams). Linking these drivers and the sand-mud sediment budgets to observed trends will improve understanding of the morphological evolution of the Wadden Sea.

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Morphological Fairway Analysis – Four studies on four channels

Freek Brils, Rijkswaterstaat

Rijkswaterstaat dredges 6 million m3 of sediment to maintain the fairway channels. Due to the general trend of sedimentation in the basins this activity, including its impact on environment, is expected to grow. Together with Deltares, Rijkswaterstaat has done studies on the four most morphologically active fairway channels. These four channels provide a maintenance challenge, requiring dredging either now or in the foreseeable future. The four studies, called bottleneck analyses, provide insight into the morphological influence on the channels. This allows for proactive management and intervention. The four shipping and transport routes researched are: - Harlingen – North Sea [3]; - Holwerd – Ameland [2]; - Lauwersoog – Schiermonnikoog [1]; - Eemshaven – North Sea [4]. Main points include morphological drivers for sedimentation, suggestions for alternative channel routing, and future perspectives. [1] Carlijn Meijers (2023) – Knelpuntenanalyse Glinder en Groote Siege [2] Roy van Weerdenburg (2023) – Knelpunten-analyse Hoogwaterroute Holwerd-Ameland [3] Ellen Quataert, et al. (2024) - Knelpuntanalyse Harlingen - Noordzee [4] Reinier Schrijvershof, et. al (2025) – Knelpuntenanalyse verbinding Eemshaven Noordzee

Subtidal reefs in the northern Wadden Sea: Detection and characterization

Jasper Hoffmann, Alfred Wegener Institut, Wadden Sea Station

The trilateral Wadden Sea has its widest seaward extent offshore the island of Sylt, where an area of North Sea seafloor with a size of 1.200 km2 forms part of the national park. The area has never been fully mapped, but is known to contain several habitat types requiring detailed assessment under the EU habitats directive. These include geogenic reefs, which are highly important structures due to their complex topography, stable location, and influence on local sediment dynamics. They offer an important substrate for a variety of benthic organisms in an area dominated by mobile sands. However, the distribution of the reefs is presently poorly constrained, but crucial for sustainable management and protection. In order to provide a better assessment of the distribution of the reefs, we used archived area-wide side-scan sonar data, a local hydroacoustic time-series, and fishing vessel monitoring data. Our results show that (1) the approach provides a preliminary baseline of reef distribution in the area, that (2) further hydroacoustic surveys are necessary to evaluate the state of reefs according to the EU habitats directive, and (3) that a close communication with local fishers would be beneficial to enhance environmental values and to reduce damage of gear.

Realising erosion resistant salt marshes in the Wadden Sea

Marte Stoorvogel, University of Twente

At many locations in the Wadden Sea salt marshes occur in front of dikes, where marshes and dikes together form ‘living dikes’. Salt marshes can contribute to several ecosystem services, such as flood risk mitigation, shoreline erosion reduction, and carbon accumulation. Therefore, there is currently an interest in restoring salt marshes. However, the extent to which salt marshes can reduce flood risks depends on the width and elevation of the marsh, so newly restored marshes should be sufficiently erosion resistant to contribute to long-term flood risk mitigation. Currently we lack insight into how different marsh restoration interventions will affect the development of marsh erosion resistance. We will execute a Summer 2025 field campaign in Wadden Sea salt marshes, both in historical marshes using sedimentation fields, and in newly restored marshes using different interventions (sediment nourishment, implementation of stabilisation structures, top-soil removal, and managed realignment). Sediment erosion resistance and vegetation and sediment characteristics will be measured to improve our understanding of how restoration interventions and vegetation and sediment characteristics affect the development of marsh erosion resistance. Based on these field results we will provide design principles for the implementation of erosion resistant and sustainable salt marshes into ‘living dikes’.

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The carbon storage potential of tidal-flat habitats: Variability and controls

Seyieleno Cara Seleyi, Alfred-Wegener-Institute (AWI), Coastal Ecology, List/Sylt

Tidal flats are dynamic sedimentary environments with important ecological functions that hold the capacity to store large amounts of organic carbon from a variety of sources, an unquantified co-benefit for climate mitigation. At the beginning of the last century, seagrasses largely declined, but were able to return to parts of the northern Wadden Sea over the last decades. As a vascular plant in a dynamic sedimentary setting, seagrasses hold the potential to sequester carbon dioxide and add to the storage capacity of organic carbon in tidal flats – but the actual role of the species and the involved processes are at present unclear. Within the project sea4soCiety-2, we investigate into the spatial properties of a range of different tidal flat environments across the Wadden Sea in order to better assess differences and controls in both realized and unrealized seagrass habitats. A particular focus is the integration of detailed and site-specific investigations (e.g., grain size, carbon content, gas exchange, nutrients) with the landscape structure influencing deposition at the selected study sites. The aim is to provide a more robust understanding of the relationships between the distribution of seagrasses, habitat properties and the regional potential for increased carbon sequestration and storage.

Determining the Wadden Sea's intertidal flats using an aggregation approach

Marvin Lorenz, BAW: Bundesanstalt fur Wasserbau

Intertidal flats are parts of the coastal zone that regularly wet and dry during the tidal cycle. These unique ecosystems provide a thriving habitat for flora and fauna. In addition, they provide natural protection against waves and are an important asset for coastal protection. However, the future of these flats is under constant pressure from natural and anthropogenic morphodynamic changes in coastal zones. Therefore, quantifying the extent of intertidal flats is of great interest not only to many scientific disciplines but also to stakeholders and local authorities, who need this information for decision-making purposes. Tides, waves, storm surges, and human interventions constantly reshape the intertidal flats by moving, eroding, and depositing sediments, which makes their classification difficult. We have created a dataset of the annual intertidal flats of the Wadden Sea that accounts for the before mentioned issues by combining high-resolution topography datasets and high-resolution tidal high- and low-water information from a numerical model via an aggregation approach. Here, we detail the method how we determined the intertidal zone. Our approach allows us to provide mean tidal high and low water lines as well as their uncertainty ranges and the associated intertidal flat topographies.

Xiriton as a novel, nature-enriching building material for intertidal protection

Victoria G. Mason, Royal Netherlands Institute for Sea Research (NIOZ), Yerseke/Utrecht University

Addressing drivers of intertidal habitat loss in the Wadden Sea is a priority; in some cases it may also be necessary to place structures to protect ecosystem extent (e.g. saltmarshes) or facilitate establishment (e.g. shellfish reefs). Traditionally used materials are often limited by high costs, negative environmental impacts or limited flexibility in design. We tested the ability of a novel concrete alternative, Xiriton, to be produced with adjustable erodibility and to use locally sourced building materials (e.g. local Spartina anglica, crushed shells and sand). In doing so, we aimed to identify a material which can be tailored for different timescales e.g. marsh edge protection (decades) or shellfish reef establishment (years) while releasing only local materials into the system when degraded. We combined material testing, direct flume and field measurements of erosion and field observations of the settlement of marine organisms onto Xiriton blocks. We demonstrated that i) Xiriton degradability can be easily adjusted by altering the proportion of binding material in the mixture, ii) the use of local materials did not reduce structural integrity but did minimise potential long-term environmental impacts, and that iii) Xiriton acts as a biodiversity-enhancing building material by facilitating the rapid establishment of intertidal species.

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The Amrum-Project: Temporal variation in benthic communities of tidal creeks

Jara Bahnsen, Forschung- und Technologiezentrum Westküste (CAU)

As the largest coherent tidal flat system worldwide, the Wadden Sea is a vital habitat for a wide range of species adapted to extreme tidal conditions. It acts as a nursery for fish, a stopover for migratory birds, and a productive feeding ground. Macrozoobenthos are key secondary producers, linking to higher trophic levels while enhancing water quality and oxygenating sediments. However, the Wadden Sea and its benthic community are increasingly affected by climate change and human-induced stressors, such as shipping, fisheries, and offshore infrastructure. A major ecological concern is the rise of alien species, often introduced through hull fouling, ballast water, or aquaculture. Some become invasive and may disrupt native communities. Despite their importance, macrozoobenthic communities are typically monitored only once or twice a year, leaving seasonal dynamics largely understudied. This project addresses these gaps by repeating a study from 1983/84 and expanding it to new sites, aiming to capture seasonal variability and the spread of alien species. On Amrum alien species were present in low numbers, while benthic communities exhibited clear seasonal and geographical variation in both species composition and functional traits. Thus, our study highlights the importance of including tidal creeks and seasonal shifts in Wadden Sea surveys.

Species responses to different stressors in cultivated salt marshes of the Wadden Sea

Thaísa Fernandes Bergamo, Leibniz Universität Hannover

Salt marshes are known for regulating ecosystem services they provide and their contribution to biodiversity. In the face of the triple ecological crisis in the Wadden Sea (climate change, biodiversity loss, and pollution), salt marshes play a key role in coastal protection and in mitigating the impacts of climate change. To better understand and preserve the ecological integrity of these dynamic salt marshes, we investigate how the germination of the pioneer species Salicornia europaea is affected by increased temperature, elevated CO_2 concentration (simulating ocean acidification), and nutrient enrichment through mesocosm experiments. These experiments help us predict how early successional stages, which are critical for salt marsh establishment, may respond to future climate scenarios. Additionally, we assess the impact of these conditions on the mono-dominant, mature stage of salt marsh succession, which is mainly composed of Elymus species.Following these treatments, an assessment of soil stability will be conducted. This research is particularly important given that today's salt marsh areas along the mainland coast of the Wadden Sea are largely cultivated landscapes. Results will enhance our understanding how different stages of salt marshes will respond to future climate conditions in relation to soil stability and consequently coastal protection.

LTER-LIFE, where you build digital twins of ecosystems

Geerten Hengeveld, NIOO

Digital twins are dynamic model-data fusion tools that can help revolutionize ecological research. But what does a digital twin of an ecosystem look like, and how would you build one? The LTER-LIFE infrastructure (www.lter-life.nl) addresses these questions and – in doing so –build an infrastructure that allows ecologists to create digital twins for their own research. We illustrate the concept of digital twins, and the infrastructural needs to flexibly assemble them, using use cases that are tailored to the Waddensea and the Veluwe Long Term Ecological Research areas. With these use cases we construct workflows that have characteristics of full digital twins but are still in their developmental stages. In this presentation we will introduce the main elements of LTER-LIFE and how they solve the main challenges researchers face when bringing data together for in depth integrated analyses of ecosystems. Thus sketching the road forward for digital twinning in ecology.

Accessing the complexity of socio-ecological systems: The Wadden Sea case

Wander Jager, University College Groningen

Just as in many socio-ecological systems, the Waddensea confronts us with difficult questions regarding nature conservation of inherently dynamic systems, and the role of people as supervisors versus part of nature. Conflicts happen between e.g., windfarms, fisheries, ecosystems and protective measures against floods. Policies originating from the perspectives of mechanistic control versus organic co-existence often counteract. In our summerschool we sail the Waddensea and visit her islands. We discuss dredging through vulnerable nature to connect a windfarm to the grid. We visit eco-system restoration projects (seagrass, reefs, dunelakes, agriculture on Schiermonnikoog), and old sites (Strieper kwelder, Terschellinger polderland, Schiermonnikoog Bancks-polder) understanding how people interacted with/in nature historically. Agent-Based computer simulations of fisheries (of Actiplex project) are used to explore socio-ecological dynamics. In combination, this sailing trip provides an interdisciplinary perspective on the many dimensions of socio-ecological systems, and the interests of different – including non-human – stakeholders. In a presentation, these educational experiences will he presented along with the simulations we use. Also, ideas will be shared on how we at the Agricola school aim to build on this by developing an interactive platform to access the Waddensea from different disciplinary viewpoints.

Assessing seasonal dynamics of the Brown shrimp winter cohort

Sarah Luckau, University of Kiel

Brown shrimp (Crangon crangon) is a characteristic species of the Wadden Sea and is the target of an intensive beam trawl fishery. Despite regional differences, catch volumes under consistently high fishing effort have been dramatically declining in recent years, but the reasons remain unclear. Due to the species' continuous reproduction, short lifespan, and the absence of age-determination methods, understanding population dynamics and implementing management strategies is challenging. It is assumed that the majority of catches originate from the so-called "winter cohort", which can generate a large biomass through high growth rates. To investigate influences to which the winter cohort is exposed in the juvenile stage on the tidal flats, as well as track their occurrence (timing) and abundance, weekly sampling was conducted between April and June 2025 near Büsum. Using a push net, a defined area was sampled, species were identified, and densities and environmental variables recorded. Size structure, timing and density of brown shrimp were compared with historical data. This provided new insights into the variability of brown shrimp recruitment and helped to understand the stock decline.

Carbon sequestration in the Wadden Sea: Past and future

Wenxi Zhou, Max Planck Institute for Biogeochemistry

The Wadden Sea, the world's largest intertidal wetland system, plays a critical role in both ecological functioning and carbon sequestration. While extensive research efforts have been carried out under the Common Wadden Sea Secretariat (CWSS) and related international projects to support ecosystem conservation and restoration, carbon-related studies remain limited in scope and methodological integration. This review analyzed 1,042 Wadden Sea publications from 2010 to 2024 using keyword frequency statistics and co-occurrence network analysis. The findings show that species ecology has remained the dominant research focus, whereas carbon-related topics only emerged in recent years and remain peripheral, with weak connections to other research themes. Although management-related keywords appear frequently, they are scattered and loosely integrated with ecological or carbon-related processes. In response to these observed gaps, this review also synthesized most common carbon sequestration assessment methods. Their applicability and limitations are discussed, with particular emphasis on the importance of flux-based approaches for capturing complex carbon exchange dynamics. This review aims to provide methodological support and practical recommendations for future CWSS projects in indicator selection, methodological integration, and process-level understanding of carbon dynamics.

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APIS - Aerial Photogrammetric Integrative Surveys using drone technology

Georg Nehls, BioConsult SH

The project APIS (Aerial Photogrammetric Integrative Surveys) investigated the use of drones for species and habitat monitoring in the German Wadden Sea as a pilot project within the UAM Inno Region SH initiative. The primary objective was to establish a robust methodological foundation for innovative ecological monitoring approaches, focusing on efficiency, accuracy, and minimal disturbance to wildlife. Automatic image analysis using artificial intelligence (AI) was applied to detect and classify key ecological parameters. Thereby, the interpretation of drone images was made reproducible, transparent, and time-efficient, enabling consistent monitoring. To assess potential disturbance effects on wildlife, each drone survey was accompanied by a standardized behavioural monitoring of the present animals. We developed an integrated workflow comprising data acquisition, photogrammetric processing, AI-based analysis, and ecological interpretation to assess the area and coverage of mussel beds and seagrass meadows and to count and identify breeding birds and monitor seals. The results of APIS proved that the use of drones can provide a low-invasive and efficient method enabling a comprehensive ecological monitoring of large and difficult-to-access areas in the Wadden Sea and comparable coastal ecosystems.

Long-term decline in Grey plover numbers and its relation to food abundance in the Wadden Sea

Josefine Bethke, Institute of Biology and Environmental Sciences, Carl von Ossietzky University Oldenburg

While the trend of roosting Grey Plovers in the total Wadden Sea is stable, the numbers in Lower Saxony have been declining since the 1980s. Recently a decline in abundance and biomass of benthic organisms has been found in the East-Friesian Wadden Sea between the 1980s and 2018 which was related to decreasing nutrient input and climate change. We hypothesized that decreasing food availability for Grey Plovers was leading to lower migratory fitness. The feeding ecology of Grey Plovers during spring migration in 2023 was compared with a study from 1994. We sampled the benthic prey stock and observed foraging behaviour of Grey Plovers. Three of the most important prey organisms for Grey Plovers declined in abundance and biomass. Numbers of pecks and successes per minute were lower in 2023 than in 1994, but success rate remained at 30%. Energy intake with 306.27 kJ/tidal cycle was much less than in 1994 with 433.37 kJ/tidal cycle. The lower energy intake could explain the lower roosting numbers in the study area. We suggest further studies on possible carry-over-effects to the breeding grounds and a monitoring of benthic organisms in the Wadden Sea.

Timing of marine heatwaves can alter goby reproductive behavior

Cindy Meyer, Research and Technology Centre West Coast (FTZ)

Marine heatwaves (MHWs), ocean temperature spikes, are becoming more frequent with climate change. Predicting species responses requires understanding their ecological impact . This study investigated the impact of MHWs on the reproductive behavior of the common goby (Pomatoschistus microps), a small, abundant intertidal fish and key prey species in the Wadden Sea. Not only increased temperature per se, but also the seasonal timing of MHWs within gobies' reproductive cycle may be relevant. In a controlled laboratory experiment, gobies were exposed to simulated MHWs at two sensitive reproductive stages: during nest building and courtship, or post-mating during paternal care. We found that when heatwaves hit early in the reproductive cycle, gobies delay courtship and spawning - likely an adaptive energy-conservation strategy. However, if courtship had already begun under normal temperatures, spawning proceeded with minimal delay, potentially producing larger clutch sizes. As MHWs often occur during peak and final spawning periods, delayed reproduction may lead to life history changes given gobies' short life span . Their shallow-water habitat limits escape. Despite their resilience, MHWs affect their reproductive behavior. Shifts in gobies' reproductive decisions and their population-level consequences may serve as indicators of community changes caused by climate change in the future Wadden Sea.

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A theoretical framework for measuring the values of biodiversity of the Wadden Sea Region

Md Monzer Hossain Sarker, University of Groningen

The Wadden Sea, one of the world's largest intertidal ecosystems, supports a wide range of species, including migratory birds, benthic invertebrates, marine mammals, and salt-tolerant vegetation. Despite its ecological significance, the region is increasingly threatened by climate change, pollution, eutrophication, and human activities such as fisheries and tourism. To support effective conservation and cross-border management, this study presents a multi-scalar theoretical framework for biodiversity assessment. It addresses ecological patterns and processes across spatial, temporal, and organizational levels and is built on three main pillars: ecological complexity, ecosystem functionality, and socio-ecological integration. The framework combines remote sensing and long-term ecological data with spatial simulation tools like InVEST to map biodiversity patterns and predict responses to environmental change. By integrating ecological theory, functional metrics, and socio-political dimensions, the framework offers a holistic approach to evaluating biodiversity in the Wadden Sea. It is designed to help researchers, policymakers, and conservation stakeholders monitor ecosystem health, set conservation priorities, and coordinate strategies across national boundaries. Future efforts will focus on applying this framework through pilot studies and linking it with emerging technologies such as Earth observation and AI-based biodiversity monitoring.

NCPs to local communities: plural perspectives on Wadden Sea saltmarshes

Heike Schwermer, Center for Ocean and Society (CeOS), Department of Agricultural Economics, Christian-Albrechts-University Kiel

Along the Wadden Sea area, saltmarshes differ from purely cultivated landscapes, with a strong focus on coastal protection and agriculture to being more natural. However, human-induced pressures (triple ecological crisis) are threatening the ecological and socio-economic values of the Wadden Sea saltmarshes. To examine plural knowledge types and perspectives on the social-ecological system of saltmarshes, we conducted around 60 interviews with local communities across 6 locations in the Netherlands, Germany and Denmark. Applying a qualitative interview analysis, we explore and analyze Nature's Contributions to People (NCP) of saltmarshes to local communities depending and /or are influenced by these ecosystems. The NCP concept refers to all contributions to people (individually or collectively) at multiple scales, derive or endure from nature. By intertwining the generalizing and context-specific perspective on the research object, we provide a suitable approach to create a comprehensive and epistemological basis for peoples` framing and understanding of salt marshes. Our results contribute to the pluralistic assessment of saltmarshes providing a valuable contribution to its governance and management in the Wadden Sea area and beyond.

Mussel spatfall and mapping techniques through time

Karin Troost, Wageningen Marine Research

In 2024 an exceptionally large spatfall of blue mussels was observed in the Dutch Wadden Sea. While, at the moment of writing, the annual intertidal inventory is still underway, preliminary results suggest that the surface area of mussel beds has at least doubled and likely tripled. The vast surface area calls for innovative methods to assist in the mapping, since only a fraction of the total bed area can be covered with traditional techniques (walking around the bed with a hand-held GPS). Since 2021, we use rapid cloud-based temporal compositing of Sentinel-1 radar imagery to assess new, disappeared and changed beds. Since the available budget is not sufficient to visit all beds every year, we use this method to prioritize the time-consuming field work. The vast spatfall of summer 2024 offers the opportunity to further validate the radar imagery technique and to use this technique to map the contours. This also offers scope for more detailed analyses on the fate of the newly formed mussel beds. We will present methods and results of the 2025 mapping campaign and place these results in a historical context using survey results since 1995 and older information.

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Long-term hydrodynamical Wadden-Sea modelling: extremes, connectivity and residence times

Theo Gerkema, NIOZ, EDS, Yerseke

For management and policy decisions regarding the Wadden Sea, not only long-term observations are needed to make informed choices, but also long-term modelling. Only then can we get a proper understanding of the occurrence of extremes of this event-driven system, its inter-annual variability and the long-term mean state of key parameters. Reaching this understanding was the central aim of the LOCO-EX project (financed by ENW/NWO). We used 3D high-resolution numerical model simulations of the Dutch Wadden Sea spanning 36 years of realistic forcing conditions, including, among many other parameters, the wind velocity and sluice discharges. Using passive particles and tracers, we calculated residence and flushing time as a function of space and time. Major exit routes of particles are Marsdiep and Borndiep. Especially the latter has a large 'backyard', indicating the connectivity with the more westerly basins. Salinity extremes, either high or low, were identified using scan statistics. Major events were linked to particular wind conditions. Finally, a machine-learning based surrogate model was constructed for a very efficient prediction of transport and spreading of particles depending on the forcing conditions, potentially providing a step towards operational modelling to help make informed policy decisions regarding pollution control.

Remote sensing of salt marsh dynamics in the Wadden Sea

Nina Leestemaker, NIOZ

Salt marshes are dynamic coastal ecosystems that provide vital services such as biodiversity support, carbon sequestration, and coastal protection. However, their persistence is increasingly threatened by accelerated sea-level rise (SLR) and anthropogenic pressures. This research investigates the adaptive capacity and resilience of salt marshes across multiple temporal scales along the entire Wadden Sea, utilizing remote sensing techniques. The study is structured into four chapters: (1) evaluating salt marsh adaptive capacity by analyzing long-term trends in inundation frequency, topography change and relative sea-level rise (RSLR); (2) identifying indicators of ecological resilience through disturbance-recovery dynamics and early warning signals derived from satellite imagery; (3) quantifying the biotic, abiotic, and anthropogenic drivers of resilience and adaptive capacity using machine learning and statistical modeling; and (4) predicting future salt marsh dynamics under various SLR scenarios by integrating process-based models with remote sensing for hindcasting and validation. By combining theoretical, process-based modeling with large-scale remote sensing, this study aims to advance our understanding of salt marsh resilience in the Wadden Sea and support spatially targeted conservation and restoration strategies.

An integrated approach to razor clams in the Wadden Sea

Knut Mehler, Alfred-Wegener-Institut Helmholtz-Zentrum

Razor clams are a ubiquitous species in the Wadden Sea. The American razor clam (Ensis leei), in particular, has established highly dense populations in some areas. However, its deep-burrowing behavior, especially in sublittoral zones, poses challenges for accurately estimating biomass, density, and physiological performance. To overcome these limitations, we applied an integrated approach in the Sylt-Rømø Bight, combining quantitative grab sampling, underwater videography with image analysis, species distribution modeling, and laboratory experiments. Grab samples provided ground-truth data on local density and biomass, while underwater video surveys enabled assessment over larger spatial scales. Species distribution models, based on presence data, allowed extrapolation of clam distribution across the region.Complementary laboratory assays examined physiological responses to temperature and food availability, offering insights into species performance under variable environmental conditions. This integrated framework enhances monitoring capabilities and enables more accurate evaluation of the species' ecological impact, including trophic interactions, nutrient cycling, and food web dynamics in the Wadden Sea.

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Historic occurrence and habitat preference of the reef-building polychaete Sabellaria spp.

Martin Baptist, Wageningen Marine Research

The Wadden Sea Plan 2010 has set targets for the natural values of the trilateral Wadden Sea and Sabellaria reefs are a crucial part of those. The plan aims for a "A natural size, distribution and development of natural mussel beds, Sabellaria reefs and Zostera fields". Many Sabellaria reefs occurred along the gullies of the international Wadden Sea in the 19th and 20th centuries. Reefs of Sabellaria formed ecologically very valuable structures with high biodiversity. During the course of the 20th century the reef presence in the Wadden Sea collapsed. Decades of fishing effects are the most obvious, though unproven, explanation for the decline of Sabellaria reefs. The objective of this study is to map the historic occurrence of Sabellaria spp. in the Wadden Sea and derive the habitat preferences for Sabellaria. Results of the study show that there are suitable habitats and substrates, but the limiting factor seems to be a lack of spatfall because of a lack of donor populations for larvae in the Wadden Sea. Restoration of Sabellaria in the Wadden Sea would restore natural developments, increase biodiversity and contribute to the international trilateral policy goals.

Easy access to (Dutch) Wadden data & information

Sander Holthuijsen, Rijkswaterstaat

Basismonitoring Wadden is an initiative to obtain an integrated, system-oriented view of the condition and trends in this unique natural area. We are a collaboration of various (governmental) organizations who contribute to monitoring the Wadden Area. From nutrients and benthos to comprehensive well-being of inhabitants. The Dutch Wadden Sea is an LTSER site (LTSER Dutch Wadden Sea Area - Netherlands | DEIMS-SDR). It itself consists of intertidal mudflats and subtidal areas. The southern border of the area consists of inhabited polders, many of which consist of reclaimed saltmarsh areas. The Dutch Wadden Sea is part of the international Wadden Sea, extending along the coasts of Denmark, Germany and the Netherlands. The international Wadden Sea comprises the largest tidal flats system in the world. Our aim is to provide insight into the condition and trends of the Wadden Sea area and to promote effective and efficient monitoring. We are involved in het Expert Group Data of the Trilateral Monitoring and Assenment Program to enhance data sharing between the three Wadden countries.We make Wadden data findable and accessible in a “Waddenregister” with Datahuiswadden.nl as a starting point.

Tolerance of a mud-loving clam to sediment change and heat

Tjitske Kooistra, NIOZ

With climate change, heat waves are increasing in frequency and intensity, and coastal sediments are foreseen to coarsen due to changing hydrodynamics and sand nourishments. To assess the resilience of benthic organisms, we therefore need to test their temperature sensitivity in different sedimentary habitats. Scrobicularia plana, is a mud-dwelling bivalve. We explored the sediment sensitivity of S. plana in the Wadden Sea, and show that the species reaches optimal abundance, biomass and condition index at high mud content (>50% mud). We hypothesise this preference to be driven by the higher food content in muddy sediments, so that the species would not suffer from coarsening if food-supply remains unchanged. In a mesocosm experiment we tested whether i) the clam performs equally well in sand and mud under equal food availability, and ii) whether heat-wave sensitivity is unaffected by sediment type. Contrary to our expectations, resilience was lowest in sand, despite having a higher food availability. Valve gape activity, reburial and metabolic rates give a behavioural and physiological explanation for the decreased performance. These findings indicate the risk of predicted cumulative stressors for this key species in the Wadden Sea.

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Salinization is becoming a threat but has an opportunity as well for Wadden Sea region and the fresh water resilence

Anne Hilarides, University of Twente

Salinization is becoming a growing problem because of Climate Change and sea-level rise at coastal regions like the Wadden Sea area. Salt intrusion and extreme weather like droughts and processes like soil decline influence the fresh water availibility. Enough fresh water is needed for both nature and users like agriculture. The current practise of waterboards to pump fresh water via canals into the agricultural area costs a lot of energy. Sustainable practise are required to meet the future demand of fresh water and safeguard waterquality. Both fresh water and saline water can be used to generate energy. A highly potentional technology 'blue energy' combined with the technology of Seepcat. as innovatieve approach. The later to protect the fresh water lenses which are still available but shrink at the coastal layers. The Seepcat. pumps the saline water out of the soil by making use of the capillary action into the ground and hardly uses any energy. However, instead of letting the water flow away it can be saved and reused for the making of renewable blue energy. A coastal project where water resilence, renewable energy and economic prospect serves the area and Wadden Sea conservation. The food/water/energy nexus in real practise.

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Beyond GDP: Mapping well-being divides in the Dutch Wadden Sea Region

Marijn van Asseldonk, Het PON & Telos

As the limitations of GDP as a sole measure of regional progress become increasingly evident, there is growing momentum across Europe to adopt more comprehensive indicators of well-being. This study contributes to that shift by examining the intraregional variation of well-being in the Dutch Wadden Sea area—an ecologically and culturally significant UNESCO World Heritage Site. Using the Broad Prosperity framework, aligned with the OECD Better Life Index, we assess 12 multidimensional topics of well-being—including health, education, environment, social cohesion, and cultural landscape—across all municipalities in the region. Normalized well-being scores were calculated annually from 2020 to 2024 for three distinct geographical typologies: island, coastal, and port municipalities.Our analysis indicates that disparities in well-being do not align neatly with traditional economic indicators such as per capita GDP. Instead, the concept of Broad Prosperity highlights the importance of both the social and physical environment in shaping quality of life. Notably, sharp contrasts exist between municipalities, with some areas exhibiting significantly higher or lower levels of prosperity. These findings emphasize the need for more nuanced, place-based policy approaches that leverage local strengths and address specific vulnerabilities, rather than relying solely on aggregated economic data.

Reframing tourism: Activating visitors to safeguard the Wadden Sea

Anja Szczesinski, WWF Germany

Tourism in the Wadden Sea region exerts both beneficial and detrimental effects on its Outstanding Universal Value (OUV). While intense visitor pressure—particularly in the high season—poses threats such as overcrowding and habitat disturbance, tourism also holds untapped potential for contributing to the conservation of this World Heritage Site. The Danish-German Interreg project VaBene – Visitor Activation to Benefit Nature and Environmentinvestigates how tourism can be repositioned as a positive force for sustaining the Wadden Sea's ecological and cultural integrity. Drawing on survey data and qualitative research, we examine tourists' motivations to engage in nature conservation during their leisure time. Findings reveal a strong demand (>40%) for meaningful, participatory experiences. In response, we co-develop innovative off-season offers with stakeholders from conservation and tourism sectors. These offers combine education on ecological values, cultural heritage, and behavioral codes with hands-on activities in habitat restoration and site stewardship. By activating visitors and small tourism enterprises, VaBene proposes a paradigm shift: from extractive tourism to regenerative engagement. This aligns with EU policy goals and offers a practical pathway to mitigate cumulative pressures on the Wadden Sea while strengthening its long-term protection and public support.

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SALTGARDEN - Enabling resilient salt marshes in the Wadden Sea

Erik Horstman, University of Twente

The valuable yet vulnerable Wadden Sea ecosystem is increasingly threatened by the impacts of the triple ecological crisis. In principle, the natural dynamics of the salt marshes in the Wadden Sea can contribute to the mitigation of and adaptation to the triple crisis impacts. Their ability to trap suspended sediments and stabilise soils strengthens their role as natural coastal protection and facilitates adaptation to sea level rise due to climate change. At the same time, salt marshes can serve as important pollutant and carbon sinks, whilst delivering outstanding biodiversity. However, most Wadden Sea salt marshes have undergone anthropogenic use for centuries, with a strong focus on coastal protection and agriculture, compromising their natural dynamics. The SALTGARDEN project explores new restoration concepts that aim to maintain the ecological integrity of salt marsh systems and strengthen their associated ecosystem services. Our desired societal impact is a paradigm shift in the management of salt marshes towards new ecological guiding principles that we name Nature-based Gardening (NbG). This shift requires social and political acceptance. SALTGARDEN therefore aims to co-create socially and politically accepted NbG strategies in order to improve the functioning and resilience of the vegetated coastal ecosystems in the Wadden Sea.

PaRCA - Pathways for Realising Climate Adaptation in the Wadden Sea

Christian Winter, CAU (University of Kiel)

The transdisciplinary project PaRCA is a joint initiative of Dutch, German and Danish Wadden Sea experts from universities, research institutions and competent authorities to design and analyze ways to realize sustainable climate adaptation of the Wadden Sea. This project proposal was developed together with a consortium of stakeholders from environmental NGOs, Wadden Sea National Parks and coastal and waterway management. In-depth analyses of current and future management options are needed to mitigate the impacts of the triple ecological crisis of climate change, rapid human-induced biodiversity change and pollution on the Wadden Sea ecosystems. The transdisciplinary project PaRCA analyses different measures to support tidal flat growth, spanning from direct and indirect nourishments to managed retreat. PaRCA is part of the German-Dutch research programme on the complex pressures and (cumulative) effects for the ecosystem, the options for action and their consequences for human life in this coastal region. An interdisciplinary team of Dutch, Danish, and German partners from natural and social sciences, engineering, and management forms the group of investigators and project partners in PaRCA. The project is structured into three work packages: WP1: Governance , WP2: The Physical System, WP3: The Ecosystem

TRICMA2 project introduction: Addressing biodiversity loss, climate change and pollution

Farah Kootstra, University of Groningen

Facing the triple crisis of biodiversity loss, climate change, and pollution, Wadden Sea salt marshes are under increasing pressure. It is unclear, (i) how salt marshes are affected by individual pressures of this triple crisis and their interactions, and (ii) how sustainable trilateral management scenarios can be developed given the complex governance system. TRICMA^2 will analyze effects of the triple crisis on ecological networks, ecological connectivity, and ecosystem functioning in salt marshes across the Wadden Sea. We combine field observations with experiments (field/mesocosms) where climate, biodiversity, and pollution are manipulated and the impacts on vegetation, soil fauna, and carbon cycling are analysed. Ecological connectivity will be investigated via movement patterns and habitat use of birds and their available food sources. TRICMA^2 includes a strong societal component by joint activities of scientists and stakeholders from several socio-economic sectors, including nature conservation, coastal protection, agriculture, and tourism. Youth will be involved in our research, drawing the attention of 'future generations' to ecological pressures to Wadden Sea ecosystems. Based on acquired stakeholder knowledge, novel scientific insights, and dedicated attention of 'future generations', TRICMA^2 will develop a set of guiding principles and priorities for sustainable Wadden Sea salt marsh management.

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SedWay - Safeguarding the natural sedimentary processes in the Wadden Sea for biodiversity and people

Verena Merk, Lower Saxon Wadden Sea National Park Authority

The future of the Wadden Sea region depends on whether 'natural processes' can continue to proceed 'largely undisturbed'. It is crucial to safeguard the interactions between geomorphological and biological processes as they form the foundation of the system and underpin biodiversity. People depend on the ecosystem services provided by a dynamic and resilient Wadden Sea, yet compounding effects of climate change, human impact, pollution, and biodiversity loss threaten the naturalness of key processes. In the project SedWay, researchers and practitioners work together to create new syntheses and empirical observations on how the processes associated with the three UNESCO selection criteria. SedWay looks at the effect of alternations to sediment dynamics on biodiversity, ecosystem functioning and ecosystem services of supratidal to intertidal priority habitats, namely shellfish beds, saltmarshes and seagrass beds. In addition, is socio-ecology used as an interdisciplinary framework, creating a common trilateral understanding of 'naturalness' and combine state-of-the art scientific knowledge with locally relevant management decisions. SedWay will deliver a co-designed GIS based Decision Support System (SedWay DSS) covering all 39 tidal basins of the Wadden Sea for rapid assessments of potential threats to bio-physical interactions and for improved restoration planning to implement Nature-based Solutions.

WADWAD - WAD was - WAD can we do? Action plan for ecosystem-based land-sea transition zones

Wienke Harms, University of Oldenburg, ICBM

Dike construction and rising anthropogenic pressures have degraded the Wadden Sea's natural resilience, leading to habitat loss and reduced adaptability. WADWAD is working on a trilateral, ecosystem-based action plan to restore land-sea transition zones through integrated sedimentological, ecological, and socio-economic analysis, assessment of citizen adaptation potential, citizen empowerment and transdisciplinary stakeholder engagement. This poster provides an overview of the problems the WADWAD ecosystem-based action plan is tackling and summarizes the outcomes that it aims to achieve. It also emphasizes the need for transdisciplinary process management and evaluation to reflect upon existing management and policies. Ecological change, coastal protection, and human activities are closely interlinked and cannot be tackled in isolation. Sustainable solutions must be developed collaboratively, bringing together scientific expertise, policy frameworks, and local knowledge.

WADcouple – The synthesis and transfer project of the trilateral Wadden Sea Research

Diana Giebels, University of Oldenburg, ICBM

The five awarded projects of the trilateral Wadden Sea call together generate novel and state-of-the art knowledge about the Wadden Sea morphology, salt marshes, sediment dynamics and ecology and co-produce pathways, action plans and decision-making support for future climate-robust and adaptive management. The societal relevance and impact of all generated outcomes is guaranteed through the early involvement of societal key stakeholders in each of the individual projects. Designed as an overarching synthesis and transfer project WADcouple coordinates and supports cross-project cooperation and knowledge transfer. This poster presents the three different layers of integration and dissemination that will be created by WADcouple to achieve this. First, active integration of research plans and planned research results will be facilitated through workshops, online research meet-ups and the production of a common synthesis paper. Secondly, active integration of those societal actors that are not yet represented in the individual projects will be organized. Thirdly, further integration of research output with cutting-edge scientific insights from other domains will be employed. This layer of integration includes testing the robustness of the Östrom's socio-ecological systems framework in the context of the Wadden Sea.

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