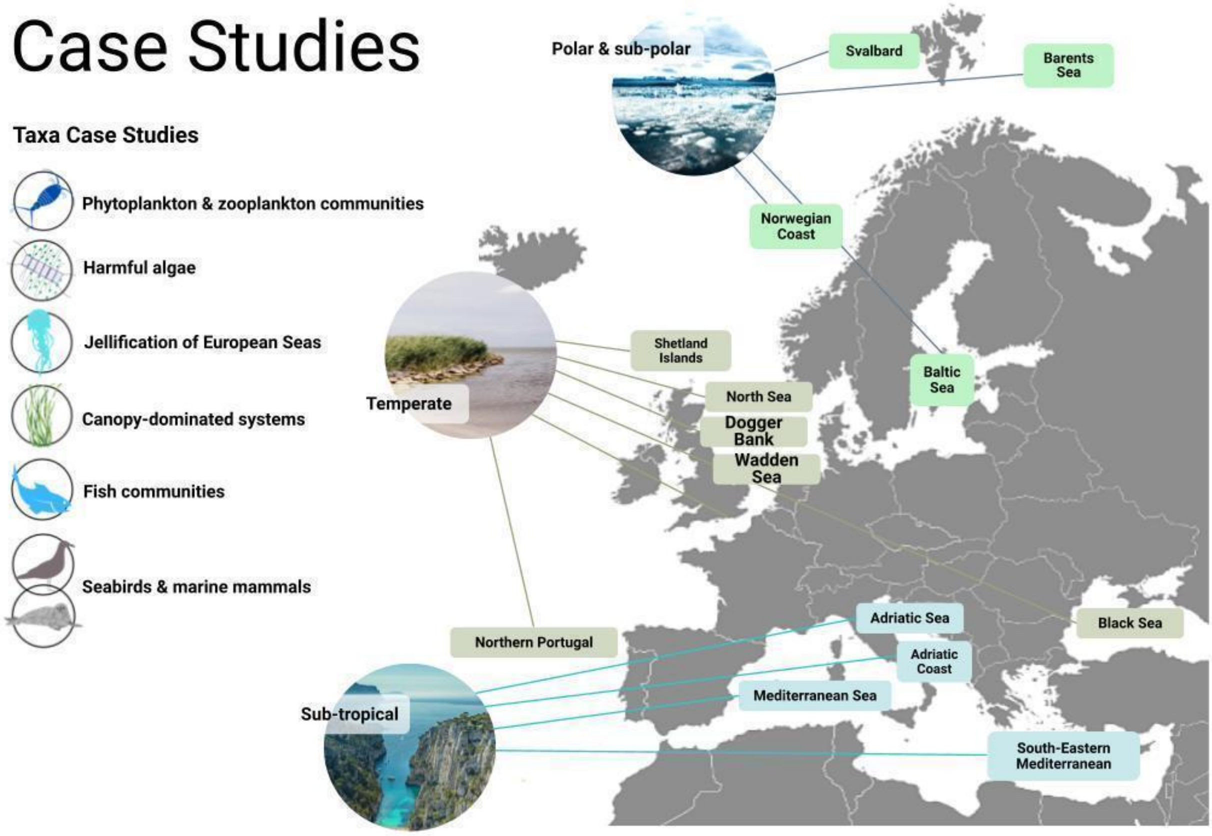
Case Study 6
Temperate

Wadden Sea UNESCO World Heritage Site



ACTNOW

ACTNOW is EU-funded research project aimed at 33^www^^ the cumulative impacts on European marine biodiversity, ecosystem functions, and services for human wellbeing. The project equips regulators and decision-makers with essential knowledge and tools to combat biodiversity loss in coastal and marine habitats threatened by climate change and other regional drivers.

Conducted across various Case Study Regions in Europe, ACTNOW focuses on delivering scientific support for adaptation and mitigation measures, sustainable blue economy expansion, and contributions to the UNFCCC.

The project is structured into six Workpackages: WP1 (Data, Indicators and Scenarios), WP2 (Marine Organisms under Multiple Drivers), WP3 (Community, Food-Web and Ecosystem), WP4 (Cumulative Risks & Biodiversity Assessments), WP5 (Synthesis, Impacts & Solutions Options), and WP6 (Communication and Dialogue).

Objectives include developing 'what if' scenarios, understanding combined impacts on ecosystems, employing advanced biologging and molecular methods, and enhancing awareness of the links between marine biodiversity and human health.

ACTNOW has 17 CSs, 11 are regional CSs while 6 are pan-European (group / taxon) CSs. All are designed to deliver a cause-and-effect understanding, build predictive capacity in models, and to develop indicators and tools for decision-makers charged with the stewardship of European marine biodiversity under threats from multiple drivers (stressors in call) (see fig below). In each case, drivers examined represent the local/regional priorities from regulators who co-create what-if scenarios of interacting drivers including envisioned management actions.

1. Case Study 6: Wadden Sea UNESCO World Heritage Site

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Description

For the Wadden Sea case study, ACTNOW specifically aims to **1. Determine mechanistic single species physiological responses:** Laboratory experiments will quantify performance curves of macrozoobenthos. Fitness-related performance measures such as survival, metabolism, growth and reproduction, are quantified under multiple drivers that are projected to largely change in a future ocean, e.g. temperature, oxygen, carbon dioxide, and food availability. This will identify physiological tipping points due to the long-term negative energy budget, mortality or infertility. **2. Describe the food web of the Dutch Wadden Sea:** The current food web of the Dutch Wadden Sea and the impacts of global changes (e.g., Temperatures, Fisheries, Sea-level rise) on this ecosystem will be described. Using Ecopath with Ecosim, this food web model, comprising 53 functional groups and based on long-term datasets available for the area (NIOZ, Wageningen Marine Research, Sovon, available literature), will be used to describe the present structure and trophic links of the Dutch Wadden Sea and create multiple projections based on different 'what-if' scenarios. **3. Analyse population trends of the German Wadden Sea:** Time series data from over 3000 populations across all ecosystem components (from microalgae to birds) in the Wadden Sea will be gathered to conduct a systematic and quantitative population trend analysis and generalise trends independent of the unit of measurement. In a meta-analysis, winners alongside losers of environmental change will be identified using different taxonomic resolutions and temporal fluctuations in the direction of trends will be analysed. These results will help to paint a more holistic picture of potential biodiversity re-organisation in the German Wadden Sea and provide new perspectives on current biodiversity assessments.

Regional Context

The Wadden Sea UNESCO World Heritage Site is located in northwestern Europe and covers an area of 14,900 km^2 along the Dutch, German and Danish coasts which makes it the largest tidal flat system in the world. It is a mesotidal barrier island system, with sediments primarily supplied from the North Sea. Unlike many intertidal systems, the tidal flats near the inlets are predominantly sandy, while those near the coast are muddy. This system provides highly dynamic transitional habitats such as intertidal mud flats, sand flats, shellfish beds, seagrass meadows, subtidal channels and barrier islands with dune and saltmarsh systems (Heron et al. 2020). The area includes the estuaries of the Ems, Weser and Elbe Rivers and thus connects freshwater with marine habitats. The diverse habitats are exposed to a high seasonality in temperature, strong tides and water exchange, as well as variations in salinity and high turbidity (Heron et al. 2020, Rönn et al. 2023). It is the unique combination of these habitats that supports the high level of biodiversity and ecological productivity.

The Wadden Sea is a biodiversity hotspot with high ecological importance. Its shallow waters form critical nursery habitats for ecologically and commercially important fishes from the North Sea and foraging and breeding habitats for marine mammals and threatened shorebirds. It serves a particularly important role as a refuelling station in the spring and autumn for migratory birds using the east Atlantic Flyway, connecting their wintering grounds in Mauritania and Guinea-Bissau to their breeding grounds in the Arctic. The birds' main prey are macrozoobenthos. Macrozoobenthos are the most abundant group in terms of numbers and biomass in the Wadden Sea. They are important prey for many taxa, regulate ecosystem services and some groups, such as bivalves and polychaetes, are ecosystem engineers that create habitat for other taxa.

The Wadden Sea is of important socio-economic value for its bordering countries as a source of food (shrimp fisheries, shellfish harvesting, and aquaculture), gas (energy), and sand (dredging), but also for providing services, such as transport of goods (shipping) and coastal as well as marine tourism (hiking, bird watching, pleasure boating) (Kloepper et al. 2017).

There is a long history of monitoring of plankton, macrozoobenthos, fish, birds, and seals in the Wadden Sea. In addition, the human impacts are well documented. Together this makes the Wadden Sea an ideal candidate for a case study in ACTNOW. To protect and sustainably manage this ecosystem, an international cooperation between The Netherlands, Germany, and Denmark was created in 1978, the Trilateral Wadden Sea Cooperation. Its actions are supported and facilitated by the Common Wadden Sea Secretariat, which also oversees the implementation of the obligations derived from the UNESCO World Heritage Convention.

Interacting drivers of biodiversity change

A multitude of interacting climate and anthropogenic drivers are precedingly impacting the Wadden Sea ecosystem. Climate-driven warming has caused a mean seawater temperature increase of 2°C between 1970 and 2020 (Beukema and Dekker, 2020; van Aken, 2008). In June and July 2023, sea water temperatures were the highest ever recorded since the beginning of the measurements in 1861 (van Leeuwen, unpublished data from the NIOZ jetty). The increase in sea water temperature coupled with heat waves has led to shifts in species distributions and phenology, mass-mortalities, and increased risk of harmful algal blooms. In addition, changes in atmospheric conditions such as increased air temperatures and more frequent storms also impact the intertidal ecosystem by influencing macrozoobenthos reproduction and mortality.

Also sea-level rise is threatening the Wadden Sea biodiversity. The Wadden Sea is composed of shallow waters and an equally flat coast, the reason why dikes border much of the coastline. The impact that this phenomenon might have in the intertidal areas is unclear, as it also depends on changes in the currents and sediment dynamic. Thus, a shift in the distribution and/or size of intertidal flats is possible, which may lead to the destruction/modification of this habitat and the species that live in and depend on it.

Direct anthropogenic interventions such as shipping, fisheries and energy production are accompanied by pollution, eutrophication and increasing tourism (Rönn et al. 2023). The most direct pressure on the Wadden Sea comes from fishing for brown shrimp (*Crangon crangon*) and mussel farming (*Mytilus edulis*). These two commercially targeted species are also important prey for different taxa (Poiesz et al. 2020). Their excessive harvesting has impacts that may cascade through the food web (Widdows et al. 1995, Herlyn et al. 2000, Temming & Hufnagl 2015), while the process of harvesting can disturb benthic habitats.

The Wadden Sea is experiencing eutrophication. In the eastern Wadden Sea, eutrophication started in the late 1950s and peaked in the late 1980s (van Beusekom 2005, Cloern et al. 2016, van Beusekom et al. 2019), culminating in severe oxygen depletion in the back-barrier reefs (Neira et al. 1996, Freitag et al. 2003). In the western Wadden Sea, the increase of riverine nutrient loads resulted in a doubling of phytoplankton biomass and primary production (Cadée and Hegeman, 2002), especially *Phaeocystis*-blooms (Lancelot et al. 1987) and an increased macroalgae cover (Reise and Siebert 1994). Starting in the late 1980s, watershed management regulations led to a 50% reduction of nutrients in rivers and coastal waters and increase in the ratio of total nitrogen to phosphorus (van Beusekom et al., 2019, Rönn et al. 2023), indicative of an increasing phosphorus limitation (Burson et al. 2016, Rönn et al. 2023). In consequence, chlorophyll concentrations were either reduced or increased in some areas of the Wadden Sea after 1990 (Capuzzo et al. 2015, Xu et al. 2020), while phytoplankton biomass did not show a decreasing trend (Di Cavalho et al. 2024).

Scenarios describing future society and economy

ACTNOW developed four what-if scenarios based on commonly used IPCC frameworks. These scenarios are currently being regionalised based on stakeholder perspectives to guide activities such as model simulations and risk assessments. The stakeholder event will happen in November 2024.

Research Needs

Significant changes in the phenology, distribution and interactions of species have been observed in the last decades in the Wadden Sea. These changes have been linked

to climate-driven warming but a series of direct (thus manageable) anthropogenic drivers also originated from multiple sources (e.g., land subsidence, fishing, and eutrophication). Attributing shifts in the status of the Wadden Sea ecosystem to changes in drivers is challenging due to the complex interaction between abiotic and biotic processes. Drivers can interact in various ways and cause different responses in different components of the system. One way to get closer to this understanding is by studying the structure and dynamic of its food web, the important links and the key species that constitute it, but also the factors that influence and impact each species/functional group. This ecosystemic view of the Wadden Sea will then allow us to comprehend direct and indirect processes and to make predictions based on observed data.
For example, driver responses can be synergistic and amplified sensitivities have been observed for specific functional groups such as plankton exposed to both elevated temperature and altered dissolved nutrient concentrations or commercially important bivalves exposed to elevated temperature and heavy metals. The question of how such specific responses scale up to cumulative effects for the whole ecosystem is especially pivotal for the conservation and management planning that safeguards ecosystem services.
The evaluation and use of the data, as well as the understanding of drivers, is highly univariate and sectorial. ACTNOW can and should work towards i) implementing multiple driver assessments, and ii) understanding cross-organism responses including changes in composition and functional diversity.

Research Planned in ACTNOW

T2.3 Laboratory experiments are being conducted on macrozoobenthic species to explore the impacts of multiple driver gradients such as temperature, carbon dioxide, and food availability.
T3.3 Development of a spatio-temporal food web model of the Wadden Sea using Ecopath with Ecosim (and Ecospace) to create projections based on different "what-if" scenarios (SSP1, SSP4, SSP5)
T4.1 A systematic and quantitative analysis of population trends (>3000 trends) across a wide range of organism groups (from phytoplankton to birds) for the Wadden Sea
T5.1 Projections are being made of the effects of climate change and other interacting stressors on the dynamics of the Wadden Sea food web.

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