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Climate-smart fisheries management for the Western Baltic Sea

Rüdiger Voss

Western Baltic fisheries are under distress. Stock sizes of key target species (cod and herring) have decreased drastically, caused by a combination of overfishing and climate change. Temperature increase negatively impacts stock productivity of herring and cod. Therefore, the Western Baltic Sea is a key example for the need of implementing climate-smart (fisheries) management.

Here, we present outcomes of ongoing inter- and transdisciplinary research that bridges climate models and the socio-economic dynamics of local fishing fleet segments. By using an ensemble of different modeling approaches, we aim to support decision makers in a (urgently needed) sustainability transformation.

In a first step, downscaled climate model runs have been used to create 3-D, high resolution distribution projections of abiotic conditions under different RCP scenarios. These conditions have then been used to force population models that incorporate temperature-dependent stock-recruitment relationships. We combine the outcome of traditional single-species models with a bio-economic multi-species model, and an ECOSPACE food web model to estimate future resource availability for the fishery. Finally, a tool simulating sustainability transformation is applied to develop future socio-economic scenarios for different fleet segments along the German Baltic coast. This step includes major input from transdisciplinary cooperation, including fishers, administrative bodies, etc., by utilizing various knowledge types such as system and target knowledge.

Future commercial exploitation critically needs to include climate change in order to avoid a repetition of too optimistic advice, and resulting overfishing. While the herring stock might recover (only if allowed for an initial stock rebuilding moratorium), future catch opportunities for cod are less optimistic, and will most likely stay below 5,000 tons (historically >40,000 tons), even under economically optimal management. Management using Maximum Sustainable Yield principles will result in stock decrease below precautionary limits. Instead, an EBFM approach or a Multispecies Maximum Economic Yield (MMEY) management with lower fishing mortalities result not only in healthier stock size but also economically superior performance.

Fisheries stocks productivity under changing oceans

Marie Savina-Rolland

Fisheries productivity has been long known to be affected by environmental conditions. The integration of such processes in fisheries management can be achieved in different ways, from extended stock assessments, revised management reference points, to alternative scenario testing using ecosystem models. One increasingly mobilised option is to integrate changes in productivity in management strategy evaluations. The most common approach is the empirical one where the impact of environmental drivers does not need to be formalised but rather explored through a range of plausible future outcomes, while the mechanistic approach implies specifying one or several productivity process - environmental driver relationships, and build them in the MSE operating model.

The latter was the strategy adopted in the Horizon Europe SEAWise project, aimed at providing tools and knowledge to operationalise ecosystem-based fisheries management. The impact of environmental drivers on fish productivity (reproduction, growth, body condition, and maturity) has been investigated for 60 populations of 25 species across four case studies (Baltic Sea, North Sea, Western Waters and central Mediterranean Sea), using various statistical methods and existing datasets (scientific surveys and stock object data), in the final objective of enriching existing multi-stock and multi-fleet fisheries MSE dedicated models with environment-productivity relationships. Such relationships have effectively been integrated in the MSE fisheries models for a total of 22 stocks over 3 case studies, allowing us to project their productivity in the mid-term future (2050).

This presentation aims at synthesising the general findings of the project in terms of the observed impacts of environment on fish productivity, and analysing how consistent they are with the literature, using the outcomes of a systematic literature review carried out in the early stages of the project. General trends across regions, environmental drivers, processes and widely distributed species (with several stocks over our case studies) are also discussed. Projections are finally presented and discussed with regards to other projections when available.

Ecosystem-Based Harvest Rules for a Climate-Sensitive Forage Fish Species

Maartje Oostdijk

Small forage fish play a key role in ecosystems but are vulnerable to climate change, uncertainties in assessment, and the impact of fishing. Iceland employs management with ecosystem considerations for a crucial forage fish species, capelin. We set out to model capelin management in the Atlantis framework. To do this, we introduced a novel escapement Harvest Control Rule (HCR) and an ecosystem escapement HCR into the Iceland Atlantis ecosystem model, comparing these to the hockey-stick HCR and ecosystem hockey-stick HCR, both under perfect knowledge and a scenario of uncertainty. Moreover, we perform two sensitivity analyses, simulating the negative impacts of climate change on recruitment. All precautionary rules perform well in maintaining capelin biomass, while less precautionary rules lead to more frequent overharvesting, somewhat lower biomass, and slight negative impacts on predators. An escapement-based HCR that integrates ecosystem considerations, such as predation by cod, closely resembles Iceland's real-world HCR and effectively balances harvest while maintaining spawning stock biomass, also under uncertainty and scenarios of reduced recruitment.

A climate-informed Management Strategy Evaluation for the stock of common sole in the highly mixed demersal fishery context of the Bay of Biscay

Pierre-Yves Hervann

In the Bay of Biscay (BoB) as in many ecosystems in Europe, the highly mixed nature of demersal fisheries complicates single-stock management. This challenge is exacerbated by climate change, expected to unevenly affect productivity across stocks. The BoB stock of common sole (*Solea solea*) has shown a persistent decline in productivity over recent decades, and future environmental changes combined with technical interactions may further impact the recruitment and fishery sustainability. River inputs influencing nursery trophic capacity has recently been identified as a potential driver of these changes, therefore offering promising perspectives for anticipating climate-driven changes in recruitment in the future.

Management strategy evaluation (MSE) approaches allow the incorporation of ecosystem and socio-economic information into advice, without costly changes in the governance system. We designed an MSE combining climate-driven river flow projections under four contrasted hydro-climatic narratives with management procedures consistent with the official sole stock assessment model and the Western Waters Multiannual Plan. The bio-economic multi-species model ISIS-Fish, coupled to the assessment model within a closed-loop, was used as the operating model to simulate stocks' dynamics and technical interactions across 48 demersal fleets of the BoB mixed fishery. It incorporated a quantitative relationship linking sole recruitment deviations to river flow from major BoB rivers. Projections, derived from the Explore2 project, differed in seasonal precipitation and temperature.

The framework allowed to (i) explore plausible future trajectories of sole productivity, (ii) compare ways to incorporate environmental information into management, and (iii) assess their performance in the mixed fisheries context, accounting for socioeconomic considerations. We assessed alternative management procedures integrating river flow either through adaptive HCRs adjusting target fishing mortality, or as a predictor in short-term recruitment forecasts required for TAC advice. Their short- & long-term performance and robustness across climate scenarios were compared with the current procedure.

In our simulations, all environment-informed management procedures promoted medium-term stock rebuilding and mitigated long-term climate change impacts. They were especially pertinent under the most severe productivity decline scenario, where sole became a recurrent choke species significantly impacting the fleets of this mixed fishery. However, adaptive HCR led to instability in fishing revenue under increased climate variability. More broadly, the consequences of tested procedures and the sensitivity to climate differed among fleets, reflecting the dependence of the level of resilience on their species portfolio, métiers practiced, and the flexibility in their seasonal and spatial strategy.

Although exploratory, this work lays the foundations for climate-informed MSE in the BoB.

How environmental forcing in ecosystem models affects management advice under ecosystem-based fisheries management: A “temperature check”

Leander Höhne

Management strategy evaluations (MSEs) to support ecosystem-based fisheries management rely on ecosystem models that capture the trophic interactions among species together with the bioeconomics of diverse fisheries. However, scientific advice from an MSE can be misleading, if the effects of a changing environment on stock dynamics are not factored into the assessment. Environmental forcing, while necessary, has implications for model outputs and uncertainties, as the relationships between environmental factors and demographic traits

themselves are subject to uncertainty. Using an ecosystem model of Georges Bank (Western Atlantic), we explore how climate-driven changes in key demographic traits affect the robustness of (multi-)species reference points. First, we estimate stochastic relationships between bottom sea temperature and growth, recruitment, consumption, and maturation, for the ten modeled species. We then use the ecosystem model to project stock dynamics with and without climate forcing, and under three potential scenarios of future bottom temperature trajectories. We examine how climate forcing and the magnitude of ocean warming alter reference points related to biomass, yield, revenue, and species composition. Moreover, we evaluate whether resulting uncertainties are compatible with status quo risk policies in the context of climate-informed ecosystem-based management.

Climate, Fisheries, and Foodwebs in the North Sea

Robert Thorpe

Climate change is projected to reduce the productivity of the North Sea ecosystem, with implications for fisheries management and conservation goals regarding the state of the foodweb. We use the StrathE2E2 end-to-end model to investigate the joint impacts of climate change and fishing strategy on fisheries yields and foodweb status for an idealised 12 fleet fishery. StrathE2E2 is an intermediate complexity model which has been designed as a "big picture" model of the ecosystem from nutrients to top predators, with the ability to consider bottom-up as well as top down effects in a rigorous manner. Using management strategy evaluation, we compare outcomes for fixed and climate-adaptive strategies in terms of fishery yields, foodweb states, and risks of functional group depletion for the 2020's climate and for RCP8.5 around 2050. Novel aspects of the study include multi-functional group harvest control rules for the fleet segments, and application of an integrated risk metric to assess foodweb status. We find that climate change is expected to reduce the management headroom for jointly achieving viable commercial fisheries and acceptable foodweb states, and that impacts can only partially be mitigated at the ecosystem level.

Assessing Climate-Driven Changes in Black Sea Commercial Fish Stocks under IPCC Scenarios

Aleyna Çağla Çebi

Understanding how climate change will affect commercially important fish stocks is critical for ensuring the long-term sustainability of the Black Sea ecosystem and its fisheries. Within the framework of the HE ACTNOW project, this study quantifies the projected impacts of climate change on key commercial species by the end of the 21st century under alternative IPCC Shared Socioeconomic Pathways (SSPs).

We applied the bioenergetically expanded version of the individual-based OSMOSE (Object-oriented Simulator of Marine Ecosystems Exploitation) model (BIOEN-OSMOSE) to simulate the population dynamics of eight major commercial species: anchovy, sprat, horse mackerel, red mullet, whiting, turbot, bluefish, and Atlantic bonito. A hindcast simulation for 2000–2014 was conducted to reproduce recent ecosystem dynamics and establish a reference baseline. Future projections were performed for 2086–2100 under SSP1-RCP2.6 (low-emission), SSP3-RCP7.0 (intermediate-high), and SSP5-RCP8.5 (high-emission) scenarios.

Results indicate scenario-dependent and species-specific responses in biomass trajectories, fisheries yield, and mean catch length. While low-emission scenarios suggest comparatively moderate changes, higher-emission pathways lead to pronounced alterations in stock productivity and size structure, with implications for fisheries sustainability and trophic

interactions. By evaluating projected ecosystem responses in relation to Marine Strategy Framework Directive (MSFD) descriptors, this study provides a model-based assessment of ecological status under climate stress. The findings support the development of adaptive, ecosystem-based fisheries management strategies tailored to future climate conditions in the Black Sea.

The impact of reduced data quality on the management of climate vulnerable fish

Alexandra Schneider

The efficacy of fisheries management is threatened by the impacts of climate change on fish populations, particularly when climate impacts are not accounted for in our approach to assessment and decision-making. As population dynamics change with climate, increasing data uncertainty can make the challenge of sustainable fisheries management even more difficult. Reductions in the quality or consistency of sampling for fishery independent and dependent data streams has been observed in many parts of the world due to reduced funding, programmatic shifts, and logistical constraints like weather and the COVID-19 pandemic. Stock assessments are the foundation of fisheries management, providing critical information on stock status and fishing rates that inform recommended harvest levels. Both climate impacts and altered data quality can reduce the precision and accuracy of assessment results and thus reduce the efficacy of subsequent decision making. We used management strategy evaluation (MSE) to simulate and evaluate fisheries management outcomes under increased data uncertainty and climate impacts for an Atlantic cod stock in the western Gulf of Maine, USA to inform climate ready decision making and disentangle the impacts of increased observation error and process error in management. Atlantic cod is a climate vulnerable fish in the northwest Atlantic that has experienced a reduction in fishery-independent survey coverage and commercial fishery length sampling. We simulation tested the impacts of 1) reduced sampling for the commercial catch, 2) an increase in missing fishery-independent survey data, and 3) a combination of reduced commercial port sampling and increased missing survey data. All data uncertainty scenarios included climate impacts on stock productivity in the operating model. Scenarios tested the population outcomes and fisheries performance with and without data uncertainty and climate specifications in the estimation model. Estimation models used the Woods Hole Assessment Model (WHAM), a highly flexible age-structure model that allows for the inclusion of random effects and environmental covariates to account for time-varying processes, such as climate. Estimation model results have the greatest uncertainty under the compounding effects of climate impacts and data challenges, particularly when the estimation model is mis-specified. Although assessments that incorporate time-varying processes to account for climate impacts on stock dynamics improve performance. Evaluating management under the increasing pressures of climate (i.e., process error) and data collection challenges (i.e., observation error) aid decision-making and provide insight to the synergistic and interacting effects of observation and process error.

Regional downscaling of Shared-Socioeconomic-Pathways and their implications for fisheries management in the Barents Sea

Yaël Hazard

Shared socioeconomic pathways (SSPs) are representations of archetypal global futures that integrate climate, environmental, social, economic, legal, technological, and political dimensions. These global scenarios, when downscaled at regional level, provide insights into

the local implication of planetary changes in the policy, technology, social, economic, and environmental dimensions.

Using the Barents Sea as a case study, this presentation considers the regional downscaling of several SSPs across these multiple dimensions and their consequences on the regional socio-ecological system. The food-web model RCaN is used to quantify possible changes in the dynamics of the food-web and fisheries in response to the multiple drivers considered in each SSP scenario.

The results are analysed against business-as-usual to determine how much the different scenarios are expected to impact ecosystem and fisheries dynamics. The impact of the different drivers are studied individually to determine the respective role of climate vs. other anthropogenic drivers, and to identify where policy interventions are more likely to impact ecosystem state and fisheries in the future.

Dynamic ocean management: models for megafauna and fisheries

Elliott Hazen

Dynamic ocean management (DOM) integrates real-time environmental data, species distribution models, and adaptive governance to align human activities with the shifting distributions of marine species under climate variability and change. Here we synthesize applications of DOM across multiple ecologically and economically important regions: the U.S. West Coast, Gulf of Mexico, Hawaiian Islands, and the Azores. On the U.S. West Coast, near-real-time habitat models informed by satellite oceanography and fisheries-dependent data have supported bycatch reduction and climate-ready harvest strategies, currently used for exempted fishing permits. In the Gulf of Mexico, dynamic forecasting of pelagic predator distributions and hypoxic zones provides tools for balancing yellowfin tuna fisheries with bluefin tuna conservation amid intensifying thermal stress. Around the Hawaiian Islands, DOM frameworks link oceanographic variability to multiple highly migratory species movements, enabling adaptive spatial management that enhances fleet efficiency while minimizing interactions with vulnerable megafauna. In the Azores, dynamic habitat predictions for tunas, seabirds, turtles, sharks, and whales demonstrate how DOM can inform ecosystem-based management in island-associated systems influenced by mesoscale features. These case studies illustrate how DOM can advance ecosystem-based fisheries management by offering flexible, data-driven approaches that track ecological change in near real time alongside or replacing static spatial measures. As climate-driven redistribution accelerates, scaling DOM through reproducible data streams, cross-jurisdictional governance, and climate-informed reference points will be a valuable tool towards sustaining both marine biodiversity and fisheries-dependent communities.

Spatial management of fisheries under a changing climate

Liz Talbot

Climate change is already affecting the distribution and abundance of marine fish. These changes to stocks, and subsequent impacts on capture fisheries production, combined with increased “spatial squeeze” on fisheries due to increasing demand for marine space from other sectors, is likely to have significant implications for coastal communities dependent on fisheries for their livelihoods. Understanding the impacts of climate change on marine capture fisheries and how this might influence future effort distribution is therefore an important step towards developing climate-smart spatial fisheries management measures, and anticipating possible conflicts with other maritime industries. We applied an established method of spatial

meta-analysis to assess species distribution modelling datasets for species representing >90% of landings by value into the UK. We analysed datasets under two global emissions scenarios (RCP4.5 and RCP8.5) and varying degrees of fishing pressure to quantify potential climate vulnerability of the currently targeted species assemblages. We found widespread responses to climate change in demersal species in particular, with abundances projected to decline across much of the UK EEZ, highlighting the challenges of maintaining fisheries sustainability in the face of a rapidly changing climate. It is likely that maintaining productive fisheries in the face of climate change can only be achieved through management strategies that allow for the mitigation of, and adaptation to, pressures already locked into the climate system for the near term, including maintaining access to areas where species abundances are projected to remain climate resilient. The analysis presented here may support this, providing fisheries managers with the means to identify potential climate change hotspots, bright spots and refugia, thereby supporting the development of climate-smart spatial management plans.

From multi-species modelling to ecological risk and spatial prioritisation: identifying high-value conservation areas in a warming Mediterranean Sea

Walter Zupa

The Mediterranean Sea is a global marine biodiversity hotspot exposed to intense and cumulative pressures, including rapid ocean warming and high fishing pressure. In this context, the expansion of area-based conservation measures, including Marine Protected Areas (MPAs) required to meet 30×30 biodiversity targets is challenged by heterogeneous protection levels and uncertain alignment between existing MPA networks and basin-scale ecological conservation priorities.

Here we present an integrative workflow to support climate-smart, risk-informed spatial advice to identify areas of high ecological value for conservation. More specifically, we combined multi-species distribution modelling, biodiversity hotspot mapping and trait-based community sensitivity to pressures into an exposure-driven ecological risk assessment for conservation prioritisation.

First, spatio-temporal distributions of demersal species (including fish, cephalopods and crustaceans) were modelled using a Hierarchical Multi-Species Communities (HMSC) framework, producing harmonised gridded predictions across the Mediterranean domain. These outputs were used to identify persistent biodiversity hotspots and to derive trait-based estimates of community-level sensitivity to climate change and fishing pressure, which informed the development of basin-wide ecological risk layers.

The spatial congruence between ecological hotspots and management measures was quantified through a GIS analysis accounting for the current MPA network and an extended one by including GFCM Fisheries Restricted Areas. Finally, multi-feature spatial prioritisation was performed with a Zonation approach, integrating species distributions, biodiversity indices, sensitivity and risk layers. Prioritisation scenarios were compared using performance curves and agreement-based metrics to identify high-priority areas located outside the current protection footprint.

Our results provide a coherent, decision-oriented and actionable framework to identify protection gaps, highlighting risk-exposed biodiversity areas. The methodology allows to delineate candidate locations where upgrading protection levels or expanding protected areas networks could most efficiently improve biodiversity and reduce ecological risk. The approach can improve long-term fisheries management and climate-informed conservation strategies across a warming and cumulatively impacted Mediterranean basin.

Fisheries and climate shape the future of western Baltic species – a spatially explicit trophic approach

Marcela Nascimento

Understanding how climate change and fishing interact to influence species distribution and biomass is crucial to develop effective management solutions. To evaluate the impacts of fisheries and climate on the western Baltic Sea (WBS) biodiversity, we built the first spatially explicit Ecospace model of this basin. The Ecospace model was coupled with the regionalised RCO-SCOBI biogeochemical model under no climate, RCP 4.5 and RCP 8.5 scenarios, by using monthly spatial data on water temperature, salinity, oxygen concentration, and primary production. We combined these climate scenarios with four fishing strategies: no fishing (NOF), business-as-usual (BAU), maximum sustainable yield (MSY), and ecosystem-based fisheries management (EBFM). EBFM includes fisheries biology and ecological principles, where all species are extracted at fishing mortality lower than F_{MSY} , with a precautionary approach applied to forage fish ($F = 50\% F_{MSY}$), less restrictive fish extraction for cod and flatfish ($F = 80\% F_{MSY}$), and no juvenile cod mortality. We then evaluated mid-century outcomes of these combined scenarios (average 2055-2074) by comparing biomass levels relative to no fishing for the main commercial fish (western Baltic cod, western Baltic spring-spawning herring, and flatfish) and harbour porpoise. We found that fisheries management has more pervasive and stronger influence on the status of the stocks and harbour porpoise than climate change. EBFM outperforms MSY in increasing the resilience of the trophic groups to climate change thus representing an effective strategy to achieve the long-term sustainability of the WBS.

From Ocean Models to Fish Movement in Destination Earth: Foundational Infrastructure for Climate-Smart Fisheries Decision Support

Tina Odaka

Accurate fish movement modelling is critical for climate-smart fisheries policy, yet ICES has identified major information gaps on essential habitats for key species such as European sea bass. Many existing approaches still lack the spatio-temporal fidelity required for robust, policy-relevant decision-making. Here, we show how Digital Twin infrastructure can enable operational Decision Support Tools (DSTs) for policy-makers, by coupling biologging observations to the Destination Earth platform using pangeo-fish software.

[Pangeo-fish](#) is an open-source Python package further developed through the [Global Fish Tracking System \(GFTS\)](#) on [Destination Earth \(DestinE\)](#). It implements a Hidden Markov Model integrating the DestinE Digital Twin for Climate Change Adaptation (Climate DT) data, Copernicus Marine data, GEBCO bathymetry, and biologging data from tagged fish. A key innovation is the adoption of a HEALPix Discrete Global Grid System (DGGS) within the Pangeo ecosystem. HEALPix's equal-area property supports consistent analyses at all latitudes—including high-latitude regions that are critical for climate-driven habitat environmental changes. This is strengthened by HEALPix-on-the-ellipsoid, developed in the ESA-funded [GRID4EARTH project](#) under the Digital Twin Earth (DTE) Framework, which advances a common DGGS approach for DestinE and Copernicus Sentinel data. DGGS streamlines data fusion and co-location of heterogeneous observations for global-scale workflows.

Pangeo-fish is designed as foundational infrastructure, not an end-user product. Following FAIR principles, it enables developers to build specialised DSTs without re-implementing core algorithms. Within GFTS, we developed a prototype “what-if” scenario DST that allows policy advisers to explore fish habitat temperature changes due to climate changes across decadal timescales.

Our approach addresses key priorities: bridging decadal climate information to management workflows; supporting scenario-based exploration of climate impacts on habitat conditions at any latitude; and lowering co-design barriers through modular infrastructure that supports stakeholder-specific interfaces.

The GFTS/DestinE experience demonstrates that the DGGS ecosystem is scalable; however, translating probabilistic outputs into actionable management recommendations requires sustained stakeholder engagement. Future work includes expanding scenario capabilities (e.g., additional “what-if” experiments), integrating machine learning that leverages DGGS-structured data, and exploring participatory methods across governance scales.

By establishing accurate, latitude-independent, open-source infrastructure, pangeo-fish and GFTS contributes to sustainable climate-responsive fisheries decision support.

Assessing Climate Adaptation strategies for Northern Humboldt Current Fisheries using a coupled climate-ocean-foodweb-fisheries model

Giovanni Romagnoni

The Northern Humboldt Current (NHC) off Peru is a highly productive upwelling system dominated by Peruvian anchoveta (*Engraulis ringens*), a keystone species linking plankton to higher trophic levels. Small-scale fisheries (SSF) targeting anchoveta and dozens of other species are pivotal for food security and livelihoods of coastal communities. Climate fluctuations such as the El Niño–Southern Oscillation (ENSO) strongly affect the NHC, and climate change trends are anticipated to impact severely the productivity of its ecosystem and fisheries, necessitating the development of long-term adaptive strategies.

We developed an integrated, spatio-temporally coupled food-web model for the NHC in the Ecopath with Ecosim (EwE) framework, driven by a regional ocean-biogeochemical model (CROCO-PISCES) and fitted to historical time series of biomass, catch, and fishing effort. The modeling framework captures key environmental drivers such as productivity in phyto- and zooplankton groups, ocean temperature, and dissolved oxygen, allowing simulations of trophic interactions, and emerging ecosystem responses to climate variability and fisheries exploitation. Through iterative consultation with key stakeholders, model structure was refined to include further key target species, their interactions, and thirteen individual SSF fisheries with their specificities. Tailored workshops with stakeholders from different small-scale fisheries in Peru permitted to identify perceived threats and concerns, conflicts, governance challenges and adaptation strategies to global change, and develop regionally ‘downscaled’ socio-economic scenarios including environmental fluctuations and long-term changes in climate, governance, socioeconomics and markets.

We utilize regional ocean-biogeochemical projections, based on three dynamically downscaled earth system models, to evaluate ecosystem projections under two different shared socioeconomic pathways (SSPs). We assess projected shifts in trophic dynamics, ecosystem structure and productivity under climate trends, and impacts on fisheries yields through year 2100 under SSP scenarios and climate model uncertainty. Changes in the catch portfolio are expected as key target species for SSF are projected to increase (e.g. tuna, mahimahi, jack mackerel) or decline (e.g. Humboldt squid, pacific mackerel) or become more volatile (e.g. anchoveta). We evaluate the efficacy of ecosystem-based and climate-smart adaptation strategies proposed by stakeholders to those shifts in target species under different socio-economic conditions. The developed framework demonstrates the co-design of climate-smart participatory adaptation and management measures to achieve coastal and offshore climate-ready fisheries in Peru, advancing sustainable and climate-adaptive fisheries management, participatory and adaptive governance of marine ecosystems, and integration of local ecological knowledge.

Assessing the feasibility of climate adaptation options for marine ecosystems in Europe

Elena Ojea

Adaptation to climate change and other anthropogenic pressures is crucial for resilient marine ecosystems and dependent societies. Despite evidence on adaptation options continues to grow, implemented adaptation options and effective adaptive management of coastal and marine systems is still underdeveloped. One of the main drawbacks is the lack of feasibility of many adaptation options, often related to the lack of co-creation processes that involve the participation of stakeholders and combines expertise from multiple scientific disciplines. In this research, we develop a novel decision support tool that combines expert inputs to assess the feasibility of marine solutions, by gathering information on economic, social, ecological, technological and geographical feasibility indicators from the IPCC. The tool allows to combine expert inputs for a given solution in a region or across Europe, as well as showcasing regional and sectorial feasibility results that can directly be uptaken by national and regional bodies. With usage, the tool updates its feasibility results, potentially increasing accuracy and expanding its applications and uptake by marine management bodies. The process illustrates how experts and stakeholders can be involved in an iterative process that can lead to the identification of the most feasible solutions to address the impacts of climate change and other stressors in the European marine environment.

Advancing integration of climate driven changes in fisheries assessment and management advice in the Canary Current Large Marine Ecosystem

Arnault Le Bris

As climate-driven changes in marine ecosystems become increasingly recognized, a growing number of stock assessments, and subsequent management advice, now integrate environmental considerations. Progress, however, has been uneven across regional fisheries management organizations, and particularly in regions where oceanographic observations and analytical capacity are limited.

Here, we report on ongoing efforts to facilitate the integration of climate-driven changes into fisheries assessment and management advice in the Canary Current Large Marine Ecosystem, encompassing seven member countries of the Fishery Committee for the Eastern Central Atlantic (CECAF). Focusing first on qualitative integration, our approach aims to 1) identify a set of environmental indicators tailored to fisheries resources in the region and informed by documented climate impacts; 2) develop the capacity of regional scientists to measure and quantify those indicators; and 3) encourage the systematic communication of environmental indicators during CECAF assessment working groups and scientific committee meetings. In parallel, research activities continue to refine understanding of the processes by which climate change and variability affect fisheries, with the aim of enabling the quantitative integration of environmental factors at multiple levels of the stock assessment process (i.e., standardization of biomass indices, development of climate-informed reference points). We suggest that this stepwise process, combining an immediate qualitative approach with progressively advanced quantitative methods, may help address the dilemma between the need to understand the complex and evolving processes that govern climate-fisheries interactions when issuing climate-informed recommendations, and the accelerating need for adaptive fisheries advice.

Assessing the Capacities, Gaps, Barriers and Pathways Forward for Climate-Ready Fisheries Management : Lessons from UN Decade of Ocean Science Programmes

Steven Bograd

Building networks to share knowledge and capacity is essential to understand, forecast, manage, and adapt to climate-driven changes in marine ecosystems and their associated fisheries. Several Programs endorsed by the UN Decade of Ocean Science for Sustainable Development (Ocean Decade; 2021-2030) – including the ICES-sponsored SmartNet Programme - are developing these networks, with the aim of convening global partners to address challenges associated with climate impacts, marine ecosystem health and food security. Recent SmartNet-sponsored workshops have brought together scientists from the ICES, PICES and Ocean Decade communities to share examples and assess our collective capacity to integrate climate information into decision support tools to advance ecosystem-based fisheries management. Here we explore how multiple and interacting oceanographic, ecological, and social data streams are being used to facilitate effective implementation of fisheries management and adaptation strategies within a multi-dimensional, complex and changing environment. Based on experiences of ICES and PICES partners, we provide recommendations for bridging gaps, overcoming barriers and charting pathways forward for climate-informed fishery management, including enhancing close partnerships and cross-regional collaborations amongst scientists, practitioners, rightsholders and other stakeholders.

Developing a decision-support framework for governance of shifting stocks

Kathy Mills

Climate-driven species distribution shifts are creating unprecedented challenges for fisheries management and governance. Projections under future climate scenarios indicate that these shifts will not only persist but intensify, increasing pressure on existing regulatory and institutional frameworks. As species move across jurisdictional boundaries and stock management areas, they disrupt governance arrangements, allocation systems, management plans, and on-the-water fishing practices. Along the east coast of the United States, warming ocean temperatures have been associated with widespread latitudinal and inshore-offshore species distribution shifts. Climate projections indicate these changes will continue, reshaping how species are distributed across national (U.S. / Canada) and regional (U.S. fishery management council regions) jurisdictions. Such shifts challenge governance systems that were designed around relatively stable species distributions. In response, frameworks are emerging to integrate distributional change into fisheries management and governance processes. We highlight our collaboration with the Mid-Atlantic Fishery Management Council to synthesize distribution change information, develop and apply indicators to signal when management attention is warranted, and embed these indicators into fisheries governance processes. Central to this effort is the rigorous evaluation of indicators and the development of clear guidance for how and when they should trigger governance action. By translating indicators of species distribution change into a structured decision-relevant framework, this work aims to make climate information operational and actionable within fisheries governance systems. The framework developed for the Mid-Atlantic region may serve as a model for other regions confronting similar challenges. We discuss ongoing collaborations with the Department of Fisheries and Oceans Canada to advance complementary approaches for transboundary and shifting stocks. Together, these efforts demonstrate species distribution information can be used to help fisheries governance systems remain effective and adapt within the context of changing marine ecosystems.

From Project Outputs to Mission Outcomes: A Theory-of-Change Monitoring Framework for Assessing Climate-Relevant Marine Actions

Harald Hasler-Sheetal

European research and innovation investments are generating an expanding portfolio of climate-biodiversity relevant marine actions (projects), ranging from ecosystem restoration and pollution reduction to low-impact fishing practices. However, assessing how these distributed activities collectively contribute to large-scale environmental and climate objectives remains a methodological challenge. Traditional project-level reporting is poorly suited to capture cumulative, cross-sectoral change in complex marine social-ecological systems.

This presentation introduces the monitoring framework designed to evaluate how diverse initiatives contribute to basin-scale transformation under the EU Mission “Restore our Ocean and Waters by 2030”. The framework responds to a key gap: the absence of an operational structure linking individual project achievements to systemic environmental progress.

The approach is built around a nested Theory of Change, structuring monitoring across four interconnected levels: project, thematic cluster, sea-basin, and Mission scale. Rather than assuming direct attribution, the framework traces *contribution pathways* (e.g. pathway to impact) from activities and demonstrators to intermediate outcomes such as governance uptake, behavioural shifts, or replication potential, and ultimately to long-term ecological objectives. This structure enables aggregation without losing causal meaning, a critical requirement for evaluating climate-biodiversity related interventions that unfold over long temporal and spatial scales.

To interpret these pathways, we integrate PESTEL analysis as a cross-cutting diagnostic tool, systematically capturing the political, economic, social, technological, environmental, and legal conditions that influence whether innovations are implemented, scaled, or constrained. Embedding contextual intelligence alongside quantitative indicators allows monitoring to explain divergence between expected and observed outcomes, particularly in regions experiencing rapid climatic and socio-economic change.

By shifting the emphasis from isolated performance metrics to structured synthesis and contextual interpretation, our framework provides a scalable methodology for understanding collective progress in climate-sensitive marine systems. It offers a practical model for evaluating how distributed scientific and innovation activities (projects) interact with governance and environmental dynamics, supporting more coherent assessment of transformation across regional seas.

Our presentation, includes interactive-engaging elements and highlights lessons from implementing the framework in the Atlantic-Arctic and Baltic-North Sea basin and discusses its relevance for future climate-environmental marine initiatives that must evaluate change not only within projects, but across interconnected ecosystems and policy landscapes.

From ocean change to diet change, combining climate projections and community evidence to guide nutrition-sensitive adaptation in Mexican fishing communities

Marina Banuet Martínez

Adapting fisheries and food systems to climate change often leads to trade-offs and unexpected effects that can increase risks to nutrition and well-being. Understanding these impacts in local settings is important for giving effective climate-smart advice, but there are still few tools that connect climate-driven changes in seafood production to local diet and nutrition, especially in the Global South. In this study, we introduce an interdisciplinary, mixed-method framework that integrates climate projections, species-specific habitat suitability and

Maximum Catch Potential modelling, and stakeholder knowledge to develop practical indicators for planning climate-smart fisheries and community food systems. We used two climate scenarios (SSP1-2.6 and SSP5-8.5) and species projections from two Earth System Models to look at future trends of dietary and commercially important seafood species. We then combined these projections with qualitative climate disruption scenarios and interviews to capture behavioural responses to climate impacts on fisheries, economies, and social systems. Quantitatively, community-specific portion-size estimation, retrospective dietary recalls, and nutrient composition were used to estimate scenario-sensitive changes in seafood consumption, diet diversity, and the contribution of seafood to recommended intakes of key nutrients. Our results show that several key species are likely to decline sharply by 2050 in both scenarios, while others may remain stable or increase, pointing toward uneven vulnerability and possible resilience. Qualitative data show diets may shift toward more finfish and less shellfish, likely affecting the contribution of seafood to nutritional requirements. In all scenarios, the share of seafood in meeting key nutrient needs is expected to drop over time, and overall diet diversity will decrease. There will also be changes in food categories, with less total protein and a move away from animal and processed protein sources. We will share these results with community partners to find adaptation options that connect fisheries, economic, and food system responses with nutrition-focused, climate-smart management. Coupling catch potential projections with mixed-method evidence on dietary responses enables climate-smart fisheries and food system planning that is anticipatory rather than reactive, and that also considers nutrition, livelihoods, and well-being under accelerating ocean change.

Contraction, convergence, and emergence of fishing métiers in a rapidly warming multispecies fishery

Rikki Taylor

Multispecies fisheries form the backbone of global fisheries, yet technical interactions among species pose a significant challenge for sustainable management. Climate change exacerbates these challenges, as species respond heterogeneously via shifts in growth rates, reproduction, and trophic interactions. When these environmental and biological conditions shift, fishers adapt by altering their fishing strategies (métiers), which consequently serve as valuable indicators of ecosystem change. We analysed 36 years of logbook data from a multispecies demersal trawl fishery in Australia's south-east, one of the world's fastest warming marine regions. We identified métiers using multivariate clustering techniques and tracked their temporal and spatial dynamics using centre of gravity analysis. The fishery has undergone substantial reorganisation, transitioning from numerous single-species métiers towards fewer mixed-species operations. As traditional key commercial species have declined, new commercial opportunities emerged, most notably Ocean Jacket (*Nelusetta ayraud*), which shifted from discarded bycatch to commercially valuable byproduct. Spatial analysis revealed widespread poleward distribution shifts, with 11 of 19 métiers moving south at rates of 2-14 km per year, with declining single-species métiers exhibiting the greatest rates of movement. Together, these findings demonstrate the capacity of métier analysis to capture and communicate long-term fishery change, equipping managers to reallocate effort, facilitate emerging opportunities, and support sustainable practices in multispecies fisheries.

An Integrated Approach to Ecosystem Based Climate Scenarios Through the Incorporation of Socioeconomic Data

Kiera Morrill

Our study is part of a multidisciplinary national effort by NOAA Fisheries, known as the Changing Ecosystems and Fisheries Initiative (CEFI), to understand changing conditions in the Northwest Atlantic and the associated impacts to regional fishing industries throughout the US. The goal is to ensure reliable delivery of comprehensive ocean forecasts and projections, produce climate informed advice for economic and ecological outlooks, risk assessments, and to enhance climate informed decision making. Our study utilized Oral History Interviews, a form of unstructured interviews, as a tool to capture the nuances and subjectivity present in regional fishing groups as well as their associated similarities and differences. Interdisciplinary thematic coding was applied to interview data across varied relevant subjects. Themes ranged from tangible and concrete adaptations such as those related to Climate, Ecosystem, or physical locations, as well as a range of subjective domains such as Market variability, and Policy or Adaptation strategies. Those codes were then broken down into more specific details in order to understand the individual situations described in the interviews then disaggregated into specific contextual details and parameterized as scenarios in the Northeast US Atlantis ecosystem model to be used in climate projection models. By linking to an ecosystem model we evaluate how successful various strategies are for responding to changing environments and socioeconomic conditions. Additionally, it aims to represent a collaborative effort for guidance on marine resource management and community adaptation. Including socioeconomic data addresses a fundamental gap: the fishing community is adapting unevenly to accelerating environmental change, particularly in the Northeast. By addressing socioeconomic strategies among resource users, we can contextualize the trends seen in climate model projections to produce a more cohesive view of both changing ecosystems and the resilience efforts being made to navigate them.

Mapping management on ramps for climate and ecosystem information

Michael Drexler

Climate change is already having—and will continue to have—far-reaching and multiscale impacts on fisheries, fisheries management, and fishing communities. In response, calls for fisheries to be climate-ready and climate-resilient have become almost ubiquitous across spheres of marine management. As fishery managers are preparing for and responding to climate change, the inclusion of climate and ecosystem information within the management process is often identified as central to these efforts. However, it has proven difficult to define and conceptualize on ramps for climate and ecosystem information in management—that is, where and how information can, could, and should be used.

Within the context of fisheries in the United States, we assessed how climate and ecosystem information and local ecological knowledge could be integrated into management processes and identified which approaches were relevant at specific management on ramps. We created diagrams of core management processes within U.S. federal fisheries, including for harvest specifications, framework actions, and fishery management plan amendments. These process diagrams were used to solicit input from focus groups composed of fisheries stakeholders, managers, and scientists. From the focus groups, we synthesized a set of existing approaches and inputs to integrate climate and ecosystem information and local ecological knowledge, which were then mapped to potential on ramps using our management process diagrams. For example, working with fishery managers, we explored how fishery performance reports, a tool used in one region, could be applied within the harvest specifications process in another region, finding that only small modifications to process would be needed to deliver this new input of information.

Generally, we find that the use of process diagrams to visualize on ramps can be informative to clarify how climate and ecosystem information and stakeholder knowledge can most readily be

integrated into existing management processes and what changes might be needed to do so. Our framework, which matches tools and approaches with potential integration points within the management process, can also provide a transparent sense of information gaps and opportunities. Finally, given the regionally specific management structure in the U.S., process diagrams illustrating specific on ramps can facilitate information sharing across regions by identifying differences in processes that can affect the application of a tool or approach from one region to another.

Bridging the Gap: R Packages for Integrating Climate and Ecosystem Information into Single-Species Fisheries Management Advice

Bai Li

Effective fisheries management requires a holistic perspective that extends beyond traditional single-species assessments. While ecosystem-based fisheries management has progressed significantly, single-species management is still seen as the best available science for hundreds of species. Single-species modeling frameworks are often tested using data from single-species operating models making them appear to be highly robust when we know that fisheries data never comes from an ocean with just a single species. A key challenge remains the technical difficulty of incorporating complex ecosystem and climate information into stock assessment models. To bridge this gap, we present two R packages developed as part of the National Oceanic and Atmospheric Administration Fisheries Integrated Modeling System (FIMS), which is a collaborative effort to build next-generation stock assessment tools. `{ecosystemdata}` provides functions to standardize outputs from ecosystem and climate models into a consistent format, featuring built-in tools to connect ecosystem data to external analysis such as Dynamic Structural Equation Models. This allows for robust time-series evaluation of ecosystem drivers prior to their inclusion in the assessment. Complementing `{ecosystemdata}` is `{ecosystemom}` that serves as an operating model by providing resampling functions that generate simulated observations from the standardized ecosystem model datasets. These packages in tandem allow scientists to test how single-species assessment frameworks perform under potentially thousands of ecosystem and climate scenarios within a simulation framework. Our current work focuses on linking climate input for Ecopath with Ecosim (EwE) and EwE output to assessments fit using the Fisheries Integrated Modeling System, with future plans to include other ecosystem models like Atlantis. In addition, we explore approaches to translate ecosystem knowledge into informative initial values and constraints for assessment parameters. By creating a repeatable pipeline from ecosystem models to single-species assessment tools, this work provides a practical pathway for scientists to evaluate how changing environments impact fish populations and to develop management advice that is resilient to ecosystem shifts.

Climate Attribution in Fisheries Stock Assessment and Management: Lessons from the Northeast U.S. groundfish stocks

Lisa Kerr

Climate change poses an unprecedented risk to fisheries ecosystems and economies globally. Ocean warming has led to observed geographic shifts and changes in the productivity of fish stocks. Due to the rapid pace of change in many of the world's oceans, there is a critical need to develop and apply scientific knowledge and tools that can help account for non-stationarity and integrate climate and ecosystem drivers into fishery stock assessment to improve management outcomes. We have applied a structured approach to identify and integrate the impact of

climate and ecosystem change on fish stock dynamics in the context of stock assessment processes in the Northeast U.S. This approach represents an advance in climate attribution within stock assessment and is expected to enhance assessment performance (e.g., through reduced retrospective patterns) and projection realism, supporting fisheries decision-making for long-term resource sustainability. In addition, there have been recent changes to a regional risk policy that have revised the approach for characterizing risk in fisheries management, including climate risk. Using management strategy evaluation, we tested the performance of different approaches for accounting for climate impacts on stock dynamics within the fisheries decision-making process, including: 1) allowing for time-varying dynamics in assessment, 2) attribution of climate impacts to a specific driver, and 3) accounting for climate risk in catch advice setting. We compare these approaches to understand the performance of more explicit attribution of climate impacts within assessment versus management. Accounting for climate impacts on stock dynamics within assessment, either implicitly through random effects or more explicitly through inclusion of environmental covariates, can improve management outcomes. Further incorporation of climate risk into the operation of harvest control rules could support more adaptive and responsive management as conditions change. It also offers a practical pathway for addressing climate-related risks in situations where fully climate-integrated stock assessments are not yet feasible. Evaluating the trade-offs among alternative adaptive management strategies for addressing climate uncertainty and associated risks can help identify the most effective and actionable next steps.