

ICES ANNUAL SCIENCE CONFERENCE

15-18 September 2026

Theme session B: Ecosystem-based management & fisheries management

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Extreme Environmental Conditions Are Associated with Poor Recruitment of an Estuarine Sportfish

Manuel Coffill-Rivera

Across the world, changing ocean conditions are altering the productivity and distribution of fish stocks. These impacts can be especially observed in coastal and estuarine systems where multiple environmental drivers shape multi-scale processes. Understanding these is of the utmost importance to resource managers, given that many economically relevant species rely on these habitats. Substantial evidence has shown how environmental variables can drive the recruitment dynamics of fishery species. Therefore, there is a need to account for these linkages as many fishery species are demonstrating population declines and environmental conditions continue shifting towards novel states. The goal of this study was to investigate environment-recruitment relationships of a recreationally relevant fish species (spotted seatrout *Cynoscion nebulosus*) in Alabama, USA. To achieve this, an integrated stock assessment of the spotted seatrout resource was conducted to derive recruitment deviations from the expected stock-recruit relationship and compare them to environmental variables derived from a regional hindcast model to investigate possible linkages. We demonstrate how poor recruitment of spotted seatrout is strongly associated with negative salinity anomalies at multiple temporal scales (annual and settlement season), and negative temperature anomalies to a lesser extent, suggesting that fresher and cooler conditions result in poor recruitment. When paired with the stock assessment, these results demonstrate how proper management actions can improve stock condition despite environmental variables driving poor recruitment. As changes in ocean conditions persist and are directional, the establishment of environment-recruitment relationships could be fundamental for monitoring and forecasting changes in recruitment and population productivity of economically relevant species that many communities rely upon.

Linking environmental change to temporal and spatial trends in Pacific Hake maturity at age

Eric Ward

Effective management of marine species requires capturing the spatiotemporal variability driving population dynamics. While ideal assessments would model this variability internally, data limitations often necessitate modeling spatial variability to develop stock assessment inputs. We illustrate this approach by incorporating environmental drivers into maturation rates for Pacific Hake (*Merluccius productus*), a transboundary species in the California Current. Despite long-term monitoring, assessments have historically used static maturation ogives, potentially ignoring phenotypic plasticity under changing conditions. We developed spatiotemporal generalized linear mixed-effects models using the sdmTMB package to analyze a 2009–present histological dataset. We investigated a number of model structures, including a null model of constant maturation, models that included random spatiotemporal change, and a mechanistic model using subsurface temperature indices from GLORYS ocean reanalysis. Our results indicated that temporal variation outweighed spatial trends, and the mechanistic model was most supported. Maturation was significantly driven by ocean temperature, and we identified an important non-linear relationship. While moderate warming generally led to younger age-at-maturity, extreme temperatures during marine heatwaves in 2016 and 2019 resulted in delayed maturation, revealing a concave (parabolic) response to temperature. Integrating these time-varying ogives into the assessment model revealed that management quantities, such as spawning biomass, were highly sensitive to the day of year used to project maturation rates. Models projected to peak maturation estimated higher biomass than those

projected to mid-survey dates. By contrasting these results with the status quo, we demonstrate that incorporating environmentally-driven parameters can operationalize climate-informed science, providing a scalable framework to enhance the adaptive capacity and long-term resilience of fisheries management.

When environment-recruitment relationships work for the wrong reasons

Matthew Robertson

Despite over a century of fisheries research focused on identifying environment-recruitment relationships, robust and long-standing relationships remain elusive, and the prevalence of ephemeral relationships has raised doubts about their utility for explaining recruitment. However, what if these relationships are shadows of other life-history processes? To explore this question, we simulated populations where the environment affects natural mortality, a life-history process often assumed to be constant, to determine whether spurious environment-recruitment relationships arise. Specifically, we produced a series of simulations in which the environment affects only one life-history process, while estimation models were misspecified with respect to which process was environmentally driven. Our simulations show that misspecified models consistently produce false detections of environmental effects on recruitment when the environment affects only natural mortality. These results indicate that previously identified environment-recruitment relationships that later broke down may have been artifacts of environmental effects acting on other life-history processes that were assumed to be constant. Focusing exclusively on recruitment may therefore obscure the true pathways through which environmental variability influences population dynamics. Ultimately, sound scientific advice in the face of marine ecosystem complexity requires hypothesis driven model comparisons and transparent model assumptions.

Season Matters: Uncovering seasonal mechanisms driving European Sardine population dynamics using integrated state-space model

Maxime Olmos

Shedding light on the mechanisms underlying changes in population dynamics requires reflecting on the notion of scale. A mismatch between the scale of the study and the scale of the relevant ecological processes can lead to an inability to identify the processes driving the population dynamics, and then to bias in estimated quantities for management and conservation. When considering temporal scale, seasonality is an important feature as it represents the regular and periodic changes in a state within a year and is driven by periodic climatic condition. In population dynamics, seasonality determines many demographic processes, such as reproduction, growth and survival. These inter- and intra-annual cycles, along with other seasonal variations in abiotic factors and associated biotic interactions, shape the dynamics of wild animal populations, but are rarely considered in assessment models for management.

Short-lived species such as European Sardines transition between life stages are subject to strong seasonal fluctuations and rapid changes in their dynamics likely driven by intrinsic factors (density- and size-dependent mechanisms) and extrinsic factors (strong sensitivity to climate variability).

This work aims at better understanding the seasonal changes in sardine population dynamics, with a focus on variations in abundance and size structure. We have developed an integrated state space model, including a seasonal population dynamics model and a seasonal growth

model, to investigate the relative influence of intrinsic and extrinsic factors on successive transition rates along the life cycle of sardines.

In the model, year is composed of two seasons due to the seasonal environments: a productive season (April to September) characterized by higher temperature and high plankton productivity, increasing food availability for sardines, and unproductive season (October to March) characterized by reduced light and colder temperatures, which limit plankton productivity and make food scarce. The seasonal population dynamic model tracks abundances for each year and season and allows to infer both interannual and seasonal changes in mortality. The growth model tracks weight at age for each year and season and allow to infer both interannual and seasonal changes in growth for each age. These integrated population models integrate heterogeneous data for each season combining spring and fall surveys and seasonal fisheries data.

Our study revealed (i) seasonal differences in the variability of growth and natural mortality, (ii) higher growth during the productive season, especially at younger ages, and (iii) alternating seasonal patterns in natural mortality, indicating density-dependence for ages 1 and 2. Finally, we found that natural mortalities and growth of sardine were related to environmental variability such as sea surface temperature, zooplankton, large-scale environmental indicators, and those relationships were season-specific.

A new state space stock assessment model for Sardine in the Bay of Biscay to account for non-stationarity in productivity

Klervi Verbrugghe

Although the impacts of global change on fish population productivity have been widely demonstrated, most stock assessment models still assume population productivity to be stationary. This assumption can lead to biased estimates of stock status and management advice in a context of rapid environmental change. Accounting for climate-driven variability is therefore essential to deliver more robust scientific advice and to support fisheries management under an ecosystem-based approach.

The sardine stock in the Bay of Biscay is particularly sensitive to intra-annual environmental variability. Fluctuations in temperature, primary productivity, and other oceanographic conditions strongly influence recruitment, growth, and survival. Despite this, the current assessment model used for this stock assumes constant natural mortality and does not explicitly model non-stationary productivity. In addition, the current stock assessment exhibits several limitations, including strong retrospective patterns, large uncertainty in parameters estimates and difficulties in fitting survey data, especially age-1 data.

We developed a new assessment population dynamic model that explicitly incorporates non-stationarity in productivity. The new model is a state space model and allow key demographic processes to vary in time while simultaneously estimating fewer parameters. In particular, quantities which are unobserved, such as recruitment, natural mortality, fishing mortality and fishery selectivity are considered to be random variables with a specified probability distribution. Such a state space framework aims at estimating these latent time series, facilitate predictions, and reliably quantify the uncertainties of these estimates and predictions.

Our model improves (i) the ecological realism in population dynamic, (ii) reduces the retrospective pattern by allowing time varying key demographic rates such as natural mortality and fishing selectivity, (iii) improves parameter estimates and uncertainty quantification, and (iv) enhances fit to the data.

This new model also opens avenues for further research. Specifically, our model indicates that the observed decline in mean age of the population is most likely attributable to elevated mortality at age 1. We also demonstrate that sardine demography exhibits density dependence,

with significant effects of population density on natural mortality at both age 1 and age 3. Furthermore, we find that natural mortality rates in sardine are linked to large-scale environmental indices such as the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation.

Finally, to support continued development and evaluation, a benchmark request has been submitted to the International Council for the Exploration of the Sea (ICES) to compare alternative assessment approaches and identify the most appropriate methodology for this stock.

Circulation-driven dispersal and retention affect blue whiting recruitment dynamics in the Northeast Atlantic Ocean

Costanza Cappelli

Blue whiting (*Micromesistius poutassou*) is a central prey and predator in Northeast Atlantic food webs and supports one of the largest commercial fisheries in the Atlantic. Recruitment varies markedly among years, motivating ecosystem-informed approaches that can improve single-species assessment and advice. Recent work shows that wind stress curl variability in the year prior to spawning co-varies with blue whiting recruit per spawner, but the physical-biological link remains uncertain. Here we test the role of regional circulation and transport in shaping the survival of blue whiting early life stages by combining two complementary approaches. First, we estimate volume transport across the Ellett Line, a long-running monitoring section that crosses blue whiting main spawning grounds west of the British Isles, and we use the derived flow indices in statistical models to assess their relationship with blue whiting recruit per spawner over the 28 years (1993-2020) of available hydrographic data. Second, we build an agent-based model (ABM) to simulate egg and larval drift from the spawning areas, and we quantify dispersal and retention focusing on years of exceptionally high and low recruit per spawner. We find that both effective transport to known northern nursery areas and retention in productive spawning regions can enhance early survival, depending on the spawning location. We propose that large-scale ocean-climate variability (e.g., changes in subpolar gyre circulation driven by wind stress curl) modulates these transport mechanisms, thereby influencing whether early life stages are delivered to favourable habitats or lost to suboptimal areas. Our findings provide a mechanistic link between climate-driven circulation changes and fish recruitment variability, underscoring a potential benefit of incorporating oceanographic processes into ecosystem-based fisheries management strategies and recruitment forecasting.

Recruitment variability of the Gulf of Riga herring stock: a long-term perspective

Elvita Eglite

The dynamics of fish recruitment have long been a focus in fisheries science, particularly under rapid climate warming and food-web change. Several studies have shown that the environment may have a stronger effect on fish recruitment than spawning stock biomass. The Gulf of Riga (GoR) herring (*Clupea harengus*) is a small, spring-spawning Baltic herring stock in the eastern Baltic Sea, where strong year classes have historically followed sequences of mild winters since the 1980s. Although the GoR herring stock remains one of the healthier fish stocks in the Baltic Sea, it also exhibits strong variability in year-class strength. Using multiple methods to detect nonlinear, nonstationary, and interactive relationships, we re-evaluated the drivers and their interactions responsible for multiannual recruitment dynamics in a long-term GoR herring time series (1977-2025). Due to the shallowness of the GoR, changes in air temperature directly

shape the gulf's temperature regime, and conventional stock–recruitment relationships fail to capture the full variation in the herring recruitment. Significant relationships were found between year-class strength, water temperature, and zooplankton abundance. Until the 1990s, surface water temperature (0-20 m) and *Eurytemora affinis* abundance in May successfully predicted recruitment. Yet, after the emergence of several very rich year classes past the 2000s, this relationship weakened. In the more recent period (1996-2025), recruitment variability was most strongly linked to young-of-the-year feeding and survival, with age-1 growth rate emerging as the key predictor alongside environmental variables. Our findings suggest that year-class strength strongly depends on feeding conditions during the post-spawning season. Potentially, in good feeding years, competition for food between older herring and young-of-the-year decreases, and the latter have a better chance of surviving. Overall, recruitment control in the GoR appears time-varying and ecosystem-dependent, supporting the use of ecosystem information and time-varying predictors in assessment and stock management.

Evaluation of environmental – productivity linkages and adaptive harvest control rules for eastern Bering Sea walleye pollock

Paul Spencer

Rapidly changing ocean conditions in the north Pacific have prompted development of stock assessment models and management procedures that account for non-stationary trends in stock productivity and impacts on shifting fishing rate and biomass reference points. For eastern Bering Sea walleye pollock (*Gadus chalcogrammus*), recruitment and stock productivity are linked to temperature through effects on prey availability, with reduced productivity and lower optimal harvest rates expected under warmer conditions. However, environmental-recruitment relationships often have high variability, and some stocks may exhibit productivity shifts without clear correlations to available environmental indicators. To address this uncertainty, we developed a suite of harvest control rules (HCRs) for Alaska stocks, including approaches that explicitly incorporate climate covariates and others that adapt to changing productivity without direct environmental linkages. Simulation testing under projected future conditions indicated that climate-enhanced HCRs produced similar yields as the current static HCR, while maintaining higher biomass levels and reducing the frequency of fishery closures (triggered when biomass falls below 50% of the reference point). Although reference points are re-estimated as new data becomes available and thus have some inherent time variation, the application of stationary assessment models to non-stationary stocks may underestimate shifts in productivity. Additionally, we compared climate-enhanced HCRs and adaptive HCRs that respond to updated estimates of current stock productivity without an explicit link to climate. Either form of adaptive HCR can improve alignment between management advice and evolving productivity for eastern Bering Sea walleye pollock, while stabilizing fishery performance under changing ocean conditions.

Evaluating the relative performance of using random effects versus environmental covariates in single-species stock assessment models

Melissa Karp

Environmental-driven shifts in fish population dynamics have challenged the reliability of stationarity assumptions in traditional single-species stock assessment models. A key debate in fisheries science revolves around the relative utility of using random effects versus explicit environmental indicators to account for this variability. Relying solely on random effects and process error adjustments may "mask" the underlying biological and environmental drivers of

stock condition. Thus there is a critical need to determine when environmental covariates should be explicitly modeled versus when random effects are sufficient for providing robust management advice. This study uses a simulation-estimation approach to evaluate the effectiveness of different modeling strategies for incorporating environmental variability within the single-species stock assessments. Our objectives are twofold: (1) compare the accuracy and predictive performance of models using random effects versus explicit environmental covariates, and (2) evaluate parameter identifiability when both random effects and environmental covariates are included in the model. We use two R packages {ecosystemdata} and {ecosystemom} to generate simulated observations from an ecosystem operating model (OM; Ecopath with Ecosim), which explicitly includes environmental drivers of recruitment for a focal fish stock. We then fit single-species stock assessment models for our focal stock based on generated input data and “true” biological information from the ecosystem OMs. We fit four estimation models using the NOAA Fisheries Integrated Modeling System (FIMS), a next-generation, community built, stock assessment platform, that differ in their structural assumptions around how recruitment is modeled: (1) random effects only, (2) environmental covariate (traditional regression approach), (3) environmental linkages informed by a dynamics structural equation model, and (4) null model (average recruitment assumption). Model performance is evaluated based on the Relative Error (RE) in key management quantities—spawning stock biomass (SSB), fishing mortality (F), and recruitment—in addition to diagnostics for retrospective bias (Mohn’s Rho) and prediction skill (Mean Absolute Scaled Error, MASE). This simulation study is ongoing and the presentation will focus on experimental design and preliminary findings from pilot runs. This goal of this research is to provide information to guide the incorporation of ecosystem linkages into FIMS, ensuring that the next generation of management advice is both ecologically grounded and statistically robust.

A single framework for synthesising forecasts seamlessly across time scales

Michael Spence

Mechanistic ecosystem models, based on describing ecological processes rather than statistical correlations, can be used to qualitatively assess the long-term effects. Due to the robustness of mechanism, they can describe the effects of phenomena that have not occurred such as long-term effects of climate change. However, due to the complexity of the ecosystem, they are not very good at quantitative or short-term predictions and therefore cannot be used for tactical advice.

On the other hand, statistical models, such as single-species assessment models, that describe the system using statistical correlations are much better at describing the current state of the system and forecasts on a shorter-time scale, making them ideal for tactical advice. However, they often ignore more interactions with the ecosystem that can happen over longer time periods, such as multispecies and climate effects and so the long-term predictions are not as robust.

Combining these different classes of models in a coherent way is a difficult problem. In this talk I will introduce a framework that combines predictions from different types of models to make predictions across different time scales, potentially providing a basis for coherent tactical and strategic advice. I demonstrate the method using five stocks in the North Sea along with four ecosystem models to make predictions seamlessly across different timescales.

Quantifying Food-Web Dynamics to support fisheries management advice

Benjamin Planque

Effective ecosystem-based management relies on understanding and quantifying species interactions that can affect fisheries management and conservation goals. This presentation introduces a food-web assessment model that reconstructs the dynamics of fish, marine mammals, and fisheries in the Norwegian and Barents Seas over recent decades, based on available data and expert knowledge. The outputs of the assessment are time-series of biomass, feeding interactions, and catches, with known levels of uncertainty. These are used to address key assessment and management questions:

- How did natural mortality of commercial fish stocks change in the last decades?
- Can multiple fisheries management and marine mammal conservation goals be achieved simultaneously?
- Do changes in marine mammal biomass impact fish stocks? By how much?

Results show that natural (predation) mortalities, though very uncertain, have varied in recent decades sometimes far from the rates commonly assumed in stock assessment models. The results also indicate that today's management and conservation goals can, in principle, all be met at the same time. Finally, the results highlight that marine mammals have had a much stronger, and also more uncertain, impact on fish than vice versa.

These results have direct implications for setting quotas, balancing conservation objectives, and managing multispecies trade-offs. They can be used to support integrated ecosystem assessments and to evaluate multiple management objectives simultaneously, help identify where goals align, where they conflict, and what trade-offs are involved. For decision-makers this approach offers a practical and transparent tool to include ecological considerations in management design.

Integrating Dynamic Energy Budget theory into a population dynamics model to explore energetic demands of a declining marine mammal, the northern fur seal (*Callorhinus ursinus*), under climate change.

Anna Sulc

Marine ecosystems globally are changing rapidly and experiencing unprecedented environmental conditions which result in the alteration of their dynamics. These rapid changes lead to a wide scale of impacts on marine food webs ranging from changes in abundance and productivity of a population to the modification of trophic interactions. However, most fisheries stock assessments do not account for these dynamics and still consider a single-species approach. To provide more reliable fisheries management advice, models must consider predator-prey interactions to better assess tradeoffs between fisheries yield and ecosystem resilience to ensure sustainable management going forward. CEATTLE, a climate-enhanced multispecies stock assessment model, considers predator-prey dynamics between different species of groundfish but omits interactions with other predators, such as marine mammals, in the ecosystem.

The northern fur seal (NFS) (*Callorhinus ursinus*) is a top predator in the Eastern Bering Sea (EBS) marine ecosystem playing an important ecological and economical role through consumption of large amounts of commercially valuable Walleye Pollock (*Gadus chalcogrammus*). The NFS is also culturally important, as they are harvested by local native communities for subsistence and tradition. Local populations have experienced ongoing declines since the mid 1990s that are hypothesized to be driven by food availability, specifically for lactating females whose ability to find food during an energetically intense time period is a strong driver of offspring growth and survival.

Here we develop a Dynamic Energy Budget (DEB) model for NFS, a bioenergetic theory that captures how an individual acquires and uses energy and essential nutrients for life processes such as development, growth, maintenance, and reproduction across its entire life cycle via

reservoirs and fluxes. The DEB framework supports exploration of growth under optimal conditions as well as the consequences of food limitation on development and survival. Given the importance of pup growth and survival for NFS, we focus on gestation and lactation dynamics while accounting for species-specific traits such as size dimorphism, molt, and seasonal weight gain. This individual-level model is coupled with an age-structured population dynamics framework and forced with projected food availability from CEATTLE across a range of climate scenarios through 2100. We use this integrated framework to evaluate how shifting prey availability may affect mother-pup dynamics and long-term population trajectories, and to quantify the potential for conflict between NFS predation demand and pollock fishery removals. By embedding a bioenergetic predator model directly within a stock assessment context, this work contributes towards efforts to implement ecosystem based fisheries management in the EBS and provides a template for incorporating marine mammal trophic dynamics into fisheries decision-making more broadly.

From the individual to the stock: how to integrate biophysical models with stock assessment models.

Luz María García-García

Understanding the link between environmental variability and fisheries is a significant challenge with impacts on key development stages, such as egg and larval phases, and hence on recruitment. At IEO, we have experience in developing biophysical models that combine hydrodynamic and biogeochemical models with Lagrangian Individual Based Models (IBMs) to simulate fish early life stages (ELS, eggs and larvae) evolving in a 3D environment to explore the dispersal, growth and survival, serving as essential tools to study population recruitment and connectivity. To date, robust models have been developed for sardine, anchovy, hake, and octopus under the framework of the DEMON project and the Galician Marine Science Programme. The development of these biophysical tools is data-intensive and requires deep biological knowledge. The IEO has a long historical experience in fisheries studies and stock assessment, with fisheries scientists participating in the evaluation of stocks of many commercial species within ICES.

However, the integration of the biophysical models with stock assessments is scarce. To address this, a Workshop entitled “From the individual to the stock” was organized in A Coruña, Galicia, in November 2025. This forum focused on how the knowledge generated through biophysical IBM modeling can be effectively integrated into the fisheries stock assessment process.

This presentation shares the discussions, conclusions and recommendations of this workshop. A primary conclusion is the recognition of biophysical IBMs as the most robust tool for understanding the complex dynamics of fish ELS within a changing oceanic environment. By explicitly simulating growth and survival conditioned by prey density, temperature and advection, these models allow for testing critical ecological hypotheses that traditional stock assessments cannot address. For data-limited species such as the Galician octopus, biophysical IBMs represent the only viable tool to assess the impact of oceanographic forcing on paralarval survival and connectivity, providing the necessary mechanistic framework to develop a spatially-explicit analytical assessment. For species like hake and sardine, these models are essential for generating variable Recruitment Success Indices (RSI) based on larval abundance or larval survival to explain interannual variability and enhance short-term recruitment forecasts, moving management beyond stationary historical averages. Ultimately, the workshop remarked that while biophysical IBMs are not suited to predict absolute

recruitment values, they are key for validating connectivity hypotheses and simulating "what-if" management scenarios under diverse climate scenarios.

To ensure biophysical IBM modelling research translates into effective fisheries management, researchers must explicitly address operational stock assessment needs, which can only be achieved by a sustained multidisciplinary collaboration.

Causal models as a scientific framework for next-generation ecosystem and climate-linked stock assessments

James Thorson

Rapid changes in marine ecosystems highlight the need to account for time-varying productivity in stock assessment models used to support fisheries management. Common approaches incorporate annual variation or regress processes such as recruitment, natural mortality, or growth on environmental variables. While the latter represents a step towards biological realism, it often fails to account for interactions among variables and may yield biased inferences when key drivers are correlated or unmeasured. We introduce a novel framework, Structural Causal Enhanced Stock Assessment Modelling (SCEAM), which integrates a Dynamic Structural Equation Model (DSEM) into a state-space stock assessment. SCEAM encompasses and extends the full range of existing time-varying approaches within a single framework, enabling direct comparison among them. We applied SCEAM to walleye pollock in the Gulf of Alaska to improve recruitment forecasting, comparing three causal models of increasing complexity to recruitment modelled as random deviations around a mean, a first order autoregressive process, or regressed on a single variable. We found that a causal model with intermediate complexity best balanced fit, parsimony, and predictive skill. This configuration reduced unexplained variance of recruitment by 69% and improved one-year-ahead forecasts. Key variables included juvenile body condition and juvenile and larval catch rates. Our study represents the first application of a structural causal model embedded within a fisheries population model. SCEAM offers a unified, hypothesis-driven approach to integrating multiple non-independent variables. We therefore propose that SCEAM can serve as a general scientific and statistical framework for building next-generation ecosystem- and climate-linked fisheries stock assessment models.

Assessing the Effects of Size-Selective Fishing on Population Structure and Community Dynamics in the Northern Humboldt Current Ecosystem Using an Individual-Based Ecosystem Model

Juliane Niewiar

Fishing pressure not only reduces the population size of target species but also alters their demographic structure, often resulting in juvenilized populations as a consequence of size-selective fishing practices. However, the ecosystem responses to fishing strategies that employ different catch size regulations are still poorly understood. The Northern Humboldt Current System (NHCS) is a highly productive fishing region, relying predominantly on its anchoveta (*Engraulis ringens*) fishery. The fishery of the fast-growing Humboldt Squid (*Dosidicus gigas*) has increased notably in recent years. In contrast, the slow-growing hake (*Merluccius gayi*) has been overexploited for decades, exhibiting a juvenile-biased demographic structure. In this study, we employed the multispecies, individual-based model OSMOSE to assess the impacts of different minimum catch size regulations for anchoveta, hake, and Humboldt squid on their demographic structure and on the community dynamics of the NHCS.

We observed an increased stock size and a more mature demographic structure for anchoveta and hake in fishing scenarios restricted by larger catch sizes relative to current ones. These alterations in population structure also affected the community composition of the NHCS through trophic propagation. Our results emphasize the important position of anchoveta in the NHCS food web, as its biomass was negatively associated with the biomass of its predation competitors, such as squat lobster (*Pleuroncodes monodon*) and jack mackerel (*Trachurus murphyi*). In contrast, varying the minimum catch size of the fast-growing Humboldt squid neither altered its population structure nor affected the community composition. Our findings suggest that adjusting catch size regulations can be an effective mechanism to ensure sustainable fishing, particularly for depleted fish stocks with slow life histories, such as hake. Moreover, fishing strategies that benefit the anchoveta stock may result in a decrease in other commercially important species, such as jack mackerel. These insights can contribute to the development of ecosystem-based management strategies for fish stocks by improving our understanding of how target species and the community in the NHCS respond to size-selective fishing scenarios.

Ecosystem dynamics shape effective population size response to fishing: implications for single-species advice

Marine Beneat

Single-species fisheries advice is usually based on abundance- or biomass-based indicators, yet these may not fully capture changes in population resilience under exploitation. In particular, effective population size (N_e) reflects the rate of genetic diversity loss, and thus the erosion of adaptive potential, whereas census population size (N) tracks demographic decline. The ratio N_e/N can therefore indicate whether genetic diversity is being lost more slowly or more rapidly than abundance. This distinction is important for risk interpretation in stock assessment and forecasting contexts, but it is usually examined in mono-specific models that omit ecological interactions.

Previous mono-specific models predict a decline in N_e with increasing fishing mortality due to reduced recruitment, but an increase in N_e/N as abundance declines faster than genetic diversity. However, population dynamics can be driven by ecological processes such as competition and predation, which are occluded in mono-specific models. We used OSMOSE, a spatially explicit, size-based multispecies individual-based model, to simulate harvested fish populations under contrasting fishing pressures and quantify responses in N_e (estimated from life-history traits), N , and N_e/N . In this framework, emergent trophic interactions generate time-varying natural mortality and reproductive conditions through predation, competition, and environmentally constrained bioenergetics, resulting in less predictable life-history variation and N_e/N ranges than those observed in monospecific model populations.

Our results challenge the expectation of a consistently positive linear relationship between N_e/N and fishing mortality. Instead, they show that genetic diversity loss and abundance decline under exploitation are species-specific, potentially compromising sustainability beyond what abundance-based indicators alone would suggest. To interpret these patterns, we investigated the links between fishing mortality, natural mortalities, fecundity, generation length, variance in reproductive success and N_e , thereby improving our understanding of N_e and N_e/N dynamics. For single-species applications, we sought indicators to distinguish between species that lose genetic diversity faster from species that primarily experience abundance decline. Overall, our findings suggest that robust single-species advice would benefit from accounting for ecosystem dynamics when evaluating relative losses in genetic diversity and recovery potential in abundance and genetic diversity, as neglecting these processes may misrepresent stock resilience to exploitation.

Integrating predation mortality into Pacific hake assessment

Raquel Ruiz Diaz

Pacific hake (*Merluccius productus*) is the largest commercial fishery on the U.S. West Coast and a keystone species in the California Current ecosystem. Current stock assessments, conducted annually under the Pacific hake/Whiting treaty, rely on catch-at-age single-species models that assume time-invariant natural mortality, potentially biasing population estimates. Here, we address this gap by applying the multispecies model CEATTLE (Climate-Enhanced Age-based model with Temperature-specific Trophic Linkages and Energetics) to explicitly quantify predation mortality for Pacific hake. We expanded CEATTLE to incorporate predators with diet-limited information (lacking prey-at-age data) and partition natural mortality into predation from key predators and residual sources (e.g., disease, senescence), producing more robust, age- and time-varying mortality estimates. Our model includes predation by Arrowtooth flounder (*Atheresthes stomias*), Sablefish (*Anoplopoma fimbria*), California sea lions (*Zalophus californianus*), and hake cannibalism. Cannibalism emerged as the dominant source of predation mortality, but predation from other included predators was also relevant, particularly for age-1 and age-2 hake. Accounting for predation modified population estimates and revealed increased competition for age-2 hake between the fishery and predators, especially sea lions. CEATTLE outputs can be directly compared with single-species assessments and used to derive multispecies biological reference points. By explicitly quantifying predation mortality, our approach provides a more realistic representation of ecosystem dynamics and fisheries interactions. This work demonstrates that multispecies assessments are not only feasible but also operationally relevant, offering actionable insights that can guide management decisions, improve stock sustainability, and support ecosystem-based fisheries management strategies.

Considering Ecosystem Risk in the Management of New England Fisheries

Maxwell Grezlik

The New England Fishery Management Council (NEFMC) has approved and begun implementation of a Risk Policy Framework as a step toward Ecosystem-Based Fisheries Management. The framework is designed to incorporate ecosystem considerations into single-species management advice by explicitly accounting for environmental, ecological, and socioeconomic risk factors when setting Acceptable Biological Catch (ABC).

We present the development of climate- and ecosystem-informed indicators to support this framework, focusing on species-specific thermal habitat suitability as a measurable risk factor. Thermal tolerance ranges were derived from long-term bottom trawl survey observations and a comprehensive literature review. These tolerance estimates were paired with temperatures from an ocean reanalysis product to quantify temporal changes in realized thermal habitat for managed stocks.

For each species, we developed indicators that track the proportion of the stock's distribution occurring within, approaching, or exceeding thermal thresholds annually and seasonally. These indicators provide a standardized and transparent method to evaluate exposure to warming and potential shifts in productivity or distribution. By translating environmental change into stock-specific risk metrics, the approach allows climate signals to be considered in managers' evaluation of risk alongside traditional assessment outputs.

Within the NEFMC Risk Policy Framework, a formal pathway exists for integrating environmental variability and long-term change into single-species management decisions. This integration occurs without replacing the existing assessment process, as adjustments to ABC control rules

are made when risk is elevated.

Our work demonstrates a scalable and operational model for integrating climate and ecosystem risk into routine fisheries management while maintaining the structure of single-species assessment frameworks. This approach is transferable to other management bodies.

Defining Biological Reference Points in a Dynamic Ecosystem

Jerelle Jesse

Biological reference points (BRPs) are a fundamental aspect of fisheries management that determine stock status and play a vital role informing rebuilding plans and catch advice. BRPs are often informed by assumptions that imply stationary population dynamics, however, climate change can influence stock productivity with persistent directional changes. Failure to account for non-stationarity may lead to management decisions that are ineffective at meeting objectives such as achieving optimum yield, avoiding overfishing, or rebuilding a depleted stock. Traditional BRP methods need to be reconsidered to accurately represent the anticipated future productivity of the stock, but best practices for defining BRPs in the context of climate change are still being developed. This study provides a comprehensive review of adapting BRPs under climate change by summarizing current practice, identifying alternative methods, and using case studies to document BRP revision processes. We characterized current approaches to defining BRPs for U.S. stocks by creating a database detailing assessment characteristics, BRP estimation methods and assumptions, and biomass and fishing mortality targets and limits. Examining approaches across different regions in the U.S. identified shared methodologies (e.g., use of FMSY proxies) and offers an opportunity to collaborate on solving shared challenges. Next, we developed a list of alternative methods for estimating BRPs under conditions of non-stationarity. Commonly employed methods included truncation approaches such as moving windows or regime shift analysis. Other methods included time-varying parameters or inclusions of ecosystem covariates in stock assessment models or stock-recruit relationships. Less commonly employed methods included dynamic B_0 or linkages to ecosystem models. While each of these methods provides a means of accounting for non-stationarity, there is no consensus on which approach performs best. Additionally, we documented the BRP revision process of Northeast U.S. groundfish stocks impacted by climate change. Case studies focused on identifying challenges and impacts of BRP redefinition and included the trigger for change, decision context, methodological updates, and outcomes for the stock. Together this work reveals common barriers, trade-offs, and lessons learned for integrating climate into single species BRPs. As management frameworks evolve to address non-stationary dynamics, this work informs best practices to support sustainable fisheries management in the context of climate change.

A probabilistic extension of Risk Tables to support the inclusion of ecological concerns into single species stock assessment framework

Enrico Nicola Armelloni

Risk analysis complementing single species stock assessment is emerging as a feasible strategy to operationalize ecosystem-based fisheries management. The Risk Table (RT) developed by North Pacific Fishery Management Council is a real-world example of a qualitative score for model quality and broad ecological concerns used to support catch advice. We extend this framework, grounding assessment and ecosystem risks into a logic process that can reveal hidden threats and facilitate management understanding of ecological concerns. Building on a compiled RT we combine stock assessment model scoring (Assessment-related risk; AR) to a

probabilistic evaluation of ecological and management scenarios (Process-related risk; PR). AR relies on quantitative diagnostic metrics aggregated into a hierarchical composite indicator for model performance and data quality, producing a transparent score that can be generalized to any single species stock assessment model. PR encodes the narrative described by the RT into a conceptual map. The identified relationships are formalized into a Bayesian Network (BN) informed with best available science including existing food web models, theoretical formulations, and expert knowledge. BN utilities are compared to historical reference conditions to identify probability of not reaching management target. The final risk weights the PR scenarios utilities by the AR score. The framework is demonstrated for common cuttlefish in the Adriatic Sea (northern Mediterranean Sea). We apply AR to the most recent stock assessment used for advice, suggesting a moderate risk due to some diagnostics failure and uncertainties regarding recreational fisheries input data. PR represents changes in expected weight at age under projected warming, food-web changes under alternative demersal trawlers effort regimes informed by an existing Ecopath with Ecosim model, and alternative competition hypotheses. PR for future scenarios was medium to high and did not decrease along with fishing effort reductions despite a slight positive effect of warming on metabolic performance, suggesting that a lower fishing pressure on the demersal species assemblage may increase competition. The result of our case study suggests that there are medium-to-high risks due to model and data quality as well as potentially unfavorable future ecological conditions, currently not addressed within the actual stock assessment framework. In addition to tabular risk provisions, our method clarifies the sources and pathways of risk and exposes model limitations. The transparency of assessment scores and conceptual schemes is meant to strengthen communication. The inclusion of food web models in the single species stock assessment framework supports the credibility of future risk. Our results can be used either to recommend a precautionary buffer to scientific advice or support the need for management measures beyond demersal trawlers effort reduction.

Integrating Ecospace-Derived Empirical Selectivity into Stock Assessments to Estimate *Karenia brevis* Induced Mortality in Red Grouper (*Epinephelus morio*)

Francesca Forrester

Harmful algal blooms of the dinoflagellate *Karenia brevis*, commonly known as red tide, can represent a significant source of episodic mortality for shallow-water reef fish in the Gulf of America/Gulf of Mexico. For Red Grouper (*Epinephelus morio*), these events have been integrated into stock assessments since 2006 and have been traditionally modeled as a bycatch fleet with 100% discard mortality. While previous assessments assumed constant and full selectivity-at-age, the 2025 assessment transitioned to using empirical selectivity-at-age to better capture the disproportionate impacts of red tide across different age classes. This study utilized outputs from an Ecospace module of the West Florida Shelf (WFS) Ecopath with Ecosim model to derive age-specific mortality data for Red Grouper (ages 0–5+). By parameterizing differing selectivity for red tide events in 2005, 2014, 2018, and 2021, the model allowed for the estimation of mortality across age bins rather than relying on a constant selectivity across all age classes.

Results indicate that red tide events led to substantial population losses, with estimated removals of 5.94, 5.04, 2.13, and 6.68 million individuals across the four red tide years included in the model. These findings demonstrate that incorporating age-structured empirical data refines our understanding of how red tide can affect recruitment and biomass, providing a more robust framework for the sustainable management of Gulf of America/Gulf of Mexico fisheries.

Accounting for episodic mortality events in the estimation of fishery reference points for groupers in the Gulf of America

Skyler Sagarese

Stock assessments for red grouper (*Epinephelus morio*) and gag grouper (*Mycteroperca microlepis*) in the Gulf of America (Gulf) of the United States routinely account for red tide mortality in the assessment period (i.e., the historic period fitted to observed data) and in short-term projections for deriving catch advice where necessary. However, it remains unclear how to account for red tide events in the longer term when estimating reference points. In this simulation exercise we evaluate how reference points for Gulf red grouper and gag grouper are affected by episodic events of severe red tides causing mass mortality. Given the uncertainty surrounding future red tide events in both space and time (and intensity), various scenarios of red tide mortality occurrence and severity are simulated with bounds derived from previous stock assessment estimates of red tide mortality. Simulation results suggest that ignoring future red tide mortality in stock assessment projections will result in the overestimation of sustainable fishing mortality rates and long-term depletion of the stock below targeted spawning stock biomass (SSB) thresholds. Importantly this overexploitation results in negligible increases in long term landings due to the reduced population abundance counteracting the increased fishing mortality rates. Our results also suggest that, due to the significant impact of red tide mortality, the population actually needs to spend a significant amount of time above target SSB levels in order to provide a buffer for episodic mortality events. We demonstrate this approach using the 2025 Gulf red grouper assessment, and thereby provide guidance for fisheries managers on the important tradeoffs and dynamics to consider when determining reference points in the context of episodic mortality events.

Evaluating Methods for Estimating Episodic Mortality in Gulf of America Grouper Assessments using SSMSE

Lisa Ailloud

Red tide blooms, caused by the dinoflagellate *Karenia brevis*, are a major environmental stressor in the Gulf of America (Gulf), significantly impacting important fish stocks like red grouper and gag grouper. Accurately accounting for this additional source of mortality in our Gulf assessments has been a persistent challenge, with questions remaining about the risks of mis-specifying red tide mortality and which modeling approach performs best given inherent uncertainties. Within the Stock Synthesis (SS) Management Strategy Evaluation R package SSMSE, we developed a custom management procedure (MP) enabling estimation of environmental mortality and the necessary feedback within SSMSE. We modeled red tide episodic mortality events in the Operating Model (OM) and Estimation Model (EM) using the bycatch fleet option in SS, as implemented in recent stock assessments, and explored the impact of misspecifying the timing (years) of red tide events. Our SSMSE modifications and custom MP were validated by confirming that the EM accurately estimated the OM truth when both models were structured identically. When the OM and EM were mismatched, the red tide mortality was generally underestimated. The worst performing scenario occurred when red tide mortality was present in the OM but omitted from the EM. Our preliminary results suggest that, in the absence of precise information regarding the exact timing and magnitudes of red tides, it may be advisable to allow SS to estimate some level of extra mortality every year to account for red tides or other stressors such as hypoxia and cold snaps.

Incorporating seasonal and spatial dynamics into ecological reference points for Atlantic Menhaden

David Chagaris

Atlantic menhaden (*Brevoortia tyrannus*) are a small pelagic fish that support the largest commercial fishery on the U.S. east coast, where approximately 145,000 mt are landed each year with a valued over \$40 million USD. They are also important prey for many marine predators, including resident and migratory fishes, marine mammals, and birds. Ecological reference points (ERPs) were adopted by the Atlantic States Marine Fisheries Commission (ASMFC) in 2020 with the objective of sustaining both menhaden and their predators. The ERPs were developed using a simplified ecosystem model of the Northwest Atlantic Continental Shelf (NWACS) and a modeled tradeoff relationship between menhaden harvest and the biomass of a predator, striped bass (*Morone saxatilis*). Recently, seasonal and spatial dynamics were added to the NWACS ecosystem model to account for seasonal predator-prey overlaps and environmental drivers in an effort to improve estimates of key parameters that govern the menhaden-striped bass tradeoff relationship. Incorporating these processes resulted in improved model diagnostics and fits to timeseries. In addition, a spatially explicit NWACS model was developed along with a genetic algorithm procedure to estimate predator-prey parameters, dispersal rates, and habitat preference functions that drive spatial distributions. While the addition of seasonal-spatial considerations generally improved model fits to data, the resulting tradeoff relationships and ERPs were highly variable. This demonstrates the potential of the NWACS model to capture ecosystem dynamics as well as the challenges that remain and future research needs to ensure the ERPs remain viable in the future and continue to address the evolving needs of managers.

Precautionary data-limited assessment tools and harvest control frameworks for deep-sea fisheries in ABNJ – tools to support the Ecosystem Approach

Wendell Medeiros-Leal

Deep-sea fisheries in Areas Beyond National Jurisdiction (ABNJ) target species characterized by low productivity, high longevity, and limited resilience to exploitation. These life-history characteristics, combined with sparse data availability, pose persistent challenges for generating robust stock status assessments and implementing ecosystem-based fisheries management objectives within Regional Fisheries Management Organizations (RFMOs). Conventional approaches often fail to adequately reflect the vulnerability and recovery dynamics of deep-sea species, increasing the risk of prolonged depletion, evidenced by UN FAO estimates that 28 and 36% of deep-sea fish stocks are overfished or have status “unknown”, respectively. Within the UN FAO Deep-sea Fisheries Project under the GEF-funded Our Common Oceans Program, ICES is contributing to the development and testing of life-history-informed data-limited assessment tools and harvest control frameworks tailored to deep-sea species. This work expands existing ICES data-limited approaches by explicitly incorporating life-history traits, exploitation patterns, and available fishery-dependent and fishery-independent information into assessment methods and harvest control rules that are robust to uncertainty and aligned with management objectives. Selected case-study species managed by RFMOs across the Atlantic, Pacific, Southern, Indian Ocean, and the Mediterranean Sea will be used to evaluate the approaches, including adaptations of existing ICES data-limited methods and dynamic harvest rate rules. Through iterative methodological development and simulation testing, the project seeks to identify assessment tools that better capture deep-sea vulnerability while remaining operational in data-constrained contexts. By aligning life-history-informed assessment approaches with precautionary harvest

strategies, this work strengthens single-species advice frameworks in support of ecosystem-based management objectives for vulnerable deep-sea fisheries in ABNJ.

Integrating Marine Ecosystem Services in Fisheries Management

Yajie Liu

Ecosystem-based fisheries management is often seen as something we can simply add on top of single-species management by collecting more data and building better models. This review argues that this view is misleading. Bringing ecosystem services into single-species advice exposes deep conflicts between management goals, stakeholder interests, and different types of benefits from the sea. These conflicts cannot be solved just by improving science inside a system that mainly prioritises catch.

Provisioning services (fish landed, income) dominate because markets, economic tools, and institutions are designed around them. This creates a “provisioning service paradox”: many “ecosystem-based” successes are celebrated because they increase or stabilise catches and revenues, while cultural, regulating, and supporting services remain secondary. In high-capacity systems (e.g. Iceland, Norway, Denmark, USA), more data and modelling rarely shift the core objective away from harvest. In low-capacity settings, urgent needs for food and income make it even harder to consider other services.

Outcomes differ strongly by context. Ocean productivity, habitat type, and who uses the ecosystem determine which services matter and what trade-offs are acceptable. Upwelling systems can trade off harvest and carbon storage; many coral reef systems are constrained by their roles in coastal protection and biodiversity. Industrial, tourism-based, small-scale, and Indigenous fisheries are built on different value systems: some see nature mainly as economic capital, others emphasise identity, spirituality, and reciprocal relationships.

Three mechanisms help explain why integration looks so different across cases and why simply “ecosystemising” single-species advice is unlikely to work. (1) Governance–science fit: advanced tools without supportive institutions, or strong institutions without ecosystem science, both fail; copying tools from data-rich to data-poor regions often does not work. (2) Service substitutability: managing a “portfolio” of species works when services can substitute for each other, but not for unique cultural values or when high catches depend on ecologically degraded states. (3) Time horizons: short political cycles and immediate livelihood needs favour quick gains in catch over slow benefits from habitat recovery.

We argue that the key task is not to fine-tune single-species reference points, but to change how decisions are made. This means: (i) clearly identifying which services can be traded off and which cannot; (ii) designing governance that fits local capacity and respects different value systems; and (iii) creating institutions and funding that support long-term commitments.

Multi-species “portfolio” strategies for catch, targeted protection of culturally and ecologically important places and species, and community-based, long-term finance offer more realistic ways to bring ecosystem considerations into fisheries management.

Including human dimensions expertise can improve catch advice for sustainable fisheries management

Andrea Chan

Managing fish stocks to meet societal and sustainability goals requires managers to balance competing social, environmental, and economic objectives. Fisheries operate in social-ecological systems, where fish populations interact with human systems primarily through variable fishing activities, which must be characterized and understood if the system is to be

successfully managed. In the movement towards ecosystem-based fisheries management, a great deal of research effort has been devoted to developing new approaches to incorporate ecosystem information into single-species assessment and advice. However, less attention has been devoted to the integration of human dimensions data and expertise in fisheries management processes, leading to overly simplistic and shortsighted catch advice. In 2022, NOAA Fisheries published a report identifying case studies where human dimensions expertise was incorporated in some portion of the catch advice process (i.e., data collection, data processing, stock assessment models, projections of abundance and catch, evaluation of harvest control rules, and the delivery of scientific advice to managers and stakeholders). In 2024, we conducted a survey of recent ICES Benchmark/Assessment Working Group Chairs to identify similar case studies of human dimensions integration in the production of fishing opportunities advice. We compare these ICES case studies with the previously identified NOAA Fisheries case studies, highlighting the range of ways in which human dimensions information may be, or already is, incorporated. Notably, traditional and experiential knowledge from fishers can provide information on spatiotemporal changes in fishing practices. Social scientists can synthesize knowledge of drivers of fisher behavior to help investigate trends in catch and bycatch time series, and support more realistic projection assumptions. The catch advice processes in NOAA Fisheries and ICES could benefit from regularly producing mixed fisheries projections and stock-specific trends in human dimensions indicators, respectively. By moving towards transdisciplinary scientific practices and integrated analyses, the NOAA Fisheries and ICES communities can provide more holistic catch advice in a dynamic world. Given that our recommendations are broadly applicable across fisheries catch advice processes, other fishery management organizations around the world should evaluate these ideas in the context of their management frameworks.

From net to web: a socio-ecological system analysis of brown shrimp fisheries in the Wadden Sea

Tjitske Kooistra

The Wadden Sea, a shallow coastal sea bordering the Netherlands, Germany and Denmark, is a Natura2000 area and UNESCO World Heritage Site with unique ecological and cultural values. A recent cumulative impact assessment of the Dutch Wadden Sea highlighted brown shrimp fisheries as having the highest risks of ecological impacts. The system is also experiencing unprecedented climate-driven warming. Long-term ecological time series collected in the western Wadden Sea on various taxa have formed the foundation of several tools used to inform ecosystem-based management such as cumulative risk assessments. Here, we build on this recent management advice by identifying and incorporating feedback loops and indirect (food web) impacts of shrimp fishing using a simple socio-ecological system (sSES) approach developed by the EU Marine SABRES project. We present how this sSES tool can be used to assess the ecological and social impacts of policy measures, and the additional value of this tool in communicating implications with stakeholders. Ultimately, this approach of examining both cumulative (direct) and indirect impacts of pressures offers decision-makers a more nuanced insight on balancing human activities with their impacts on natural values in coastal marine systems such as the Wadden Sea.

How valuable is a dolphin? Evidence from the French Bay of Biscay closure

Francois-Charles Wolff

This paper provides a comprehensive economic and conservation evaluation of a large-scale spatio-temporal fishing closure implemented in the Bay of Biscay in 2024 and 2025 to reduce incidental bycatch of common dolphins. Mandated under judicial and regulatory pressure following scientific advice, the policy represents one of the most extensive fishery closures ever adopted in European waters for marine mammal protection. We exploit this intervention as a natural experiment to quantify both its economic costs to the fishing sector and its benefits in terms of avoided cetacean mortality.

Our analysis combines highly granular transaction-level data from all French fish auction markets over the period 2016–2025 with detailed records of dolphin strandings along the French Atlantic coastline. To identify causal effects, we implement imputation-based difference-in-differences estimators that accommodate strong heterogeneity across markets, unbalanced panels, and unobserved time-varying confounders. This approach allows us to construct credible counterfactual outcomes for affected markets and to assess pre-treatment dynamics and placebo effects.

We find that the closure reduced daily auction sales in treated markets by approximately 36,000–41,000 euros per market during the one-month closure window. After accounting for auction days lost due to insufficient supply and applying sector-specific value-added multipliers, the resulting annual economic cost is estimated to range between 18.7 million euros and 21.2 million euros. In parallel, a spatial difference-in-differences analysis of dolphin strandings indicates a statistically significant reduction in strandings south of the closure boundary relative to northern control areas. Translating strandings into at-sea mortalities using empirically grounded carcass buoyancy estimates suggests that the closure plausibly prevented around 625 common dolphin deaths per year under central assumptions, with substantial uncertainty bounds.

Combining these estimates yields a cost-effectiveness measure of roughly 30,000 euros per dolphin life saved, with lower values under more favorable assumptions regarding mortality reduction. While interpretation is complicated by uncertainty in stranding-to-mortality conversion and the presence of concurrent mitigation measures, the results offer a rare transaction-level benchmark for evaluating trade-offs between fisheries livelihoods and marine mammal conservation. More broadly, the paper illustrates how integrating administrative market data with ecological indicators and modern causal inference methods can inform the design, comparison, and targeting of bycatch mitigation policies.

Many Branching Paths: The multitude of ways we use ecosystem information in fisheries management

Chris Kelble

There has been an established scientific understanding of the need to implement Ecosystem Based Fisheries Management (EBFM) for decades. Among the most compelling rationales for EBFM is that our oceans are changing in ways that are affecting the productivity and distributions of many important fishery species. Thus, we need to incorporate ecosystem information in the scientific advice we are providing to fisheries management. Over the past 2 decades there have been numerous attempts to include environmental information in the fisheries management decision-making process and progress towards EBFM has been substantial. This includes multiple case studies where ecosystem information was critical to informing management decisions that prevented overfishing. However, ecosystem information is not comprehensively or routinely incorporated into our scientific advice for the majority of our fisheries.

In the USA, we have attempted to incorporate ecosystem information into fisheries management advice via a variety of pathways ranging from direct inclusion in stock assessment models to presenting ecosystem status reports that set the context for fisheries management decision-making. A recent review of stock assessment models in the USA from 2003-2023 found that just over 2% had an assessment parameter directly linked to an ecosystem factor. Ecosystem information has also been incorporated into the fisheries management advice process via ecosystem status reports (indicator assessment of the overall ecosystem condition), ecosystem and socioeconomic profiles (a synthesis report of stock-specific ecosystem indicator trends), risk tables (evaluate unanticipated ecosystem and environmental impacts on the stock), risk assessments (quantify the probability of undesirable events along with their consequences), and dynamic ocean management tools (use satellite data and species distribution models to predict bycatch potential). In this talk, we will review the various pathways for ecosystem information to be incorporated into the scientific advice provided to the fisheries management community and suggest some ways forward to increase the uptake of ecosystem information into fisheries management.

Incorporating ecosystem indicators into a single stock assessment framework: a case study using anadromous Dolly Varden

Xinhua Zhu

A warming climate in the western Canadian Arctic has affected river discharge, which provides important habitat for anadromous salmonids. Strong seasonal variations in weather and hydroclimatic conditions have been identified as environmental drivers of the timing of seasonal migrations of anadromous fish populations.

Subsistence fisheries in the western Canadian Arctic rely on stocks of anadromous Arctic Char and Dolly Varden to ensure food security and transmit cultural practices. In response to a decline in the abundance of anadromous Dolly Varden in the Rat River, Northwest Territories, an annual fisheries-dependent community-based monitoring program was initiated in 1995.

Experienced Gwich'in harvesters implemented this program to collect fisheries data, including catch-effort and biological information, during the upstream migration (late-July to mid-September). Additionally, several qualitative categorical variables regarding water level, debris, and water clarity were recorded to track the temporal changes in the environmental conditions and link them to the relative abundance index of migrating Dolly Varden. The assessment of temporal changes in weather and hydrometric indicators may contribute to a better understanding of impacts on the seasonal migration timing and population dynamics, although the qualitative environmental information is difficult to directly apply to quantitative stock assessment.

To incorporate the ecosystem indicators recorded by the harvesters into a stock assessment, our EAFM approach was to i) establish scenario-based causal models linking catch-per-unit-effort of Dolly Varden with the qualitative and quantitative ecosystem indicators, ii) estimate population dynamics parameters using a Bayesian state-space surplus production model, and iii) develop fisheries reference points delineating the historical and current stock status of the population among scenarios. The modelling indicated that the stock is currently in a healthy state. The outcomes will promote an integrated assessment plan for the stock that incorporates environmental considerations.

Complementing single-species advice: socially just effort optimization in mixed fisheries to address technical interactions and seabed impacts

Jochen Depestele

In mixed demersal fisheries selectively harvesting healthy stocks while avoiding overfished stocks is difficult. Multiple fleets and métiers exploit spatially overlapping stocks, and cumulative catches often do not align with catch limits. This mismatch can lead to overexploitation of the more vulnerable stocks as they continue to be caught after their quota is exhausted. Additionally, towed-gear demersal fisheries raise concerns about impacts on benthic habitats, which are largely unassessed at international and regional levels though should be managed nationally under the Marine Strategy Framework Directive (MSFD). Our study had two objectives: (1) reduce mismatches between realized catches and single-species catch limits, and (2) reduce seabed impacts at management-relevant scales. We developed a common analytical framework using fishing métiers as a unifying unit. We hypothesized that adjusting effort levels across appropriate métiers could simultaneously reduce catch mismatches and benthic impacts.

Using an optimization algorithm, we explored scenarios that reallocated fishing effort across métiers to meet these objectives. Total fishing mortality across 14 stocks was maximized while constraining each stock's mortality to MSY levels and limiting fishing pressure in each MSFD habitat type according to Relative Benthic State thresholds. The feasibility of effort changes was evaluated by their magnitude. Changes below 20% were considered socially acceptable and unlikely to threaten the economic viability of a métier. The framework was applied to demersal fish stocks in the Celtic Seas, using 2021 as the baseline year.

No scenario achieved all objectives simultaneously. Reaching optimal fishing mortalities (near MSY) required substantial effort reductions in several otter trawl and gillnet métiers with high cod catchability. Including habitat constraints further reduced fishing mortalities as effort in previously unconstrained métiers became limiting, particularly in the Western English Channel. All such scenarios required effort changes exceeding socially acceptable limits (>20%). When effort changes were restricted to socially acceptable bounds, the resulting fisheries closely resembled the current system.

Although no single solution satisfied all goals, the simulations demonstrate how management trade-offs can be quantified. The framework helped assess the potential of measures to achieve fisheries and conservation objectives jointly, and can clarify the magnitude of trade-offs required to prioritize one objective over another.

Operationalizing ecosystem indicators in the sea urchin fishery in Western Mediterranean Sea: from single species to ecosystem approach to management

Giovanni Romagnoni

The sea urchin (*Paracentrotus lividus*) fishery in the Western Mediterranean Sea has led to stock declines and even local collapses in areas of intense harvesting. Herbivorous sea urchins are considered keystone species in coastal rocky reefs, capable of triggering regime shifts from rich macroalgal beds to deserts of bare rock or barrens. The loss of macroalgal forests due to overgrazing and the depletion of sea urchin populations due to overfishing are thus two extremes of the same continuum of sea urchin abundance.

To permit a viable sea urchin fishery while simultaneously conserving marine forests, and given the hysteresis-prone nature of these systems, sea urchin populations should be kept within two critical thresholds, avoiding both too high and too low abundance. A conceptual framework has been proposed to identify the safe operating space between sustainable fisheries and marine forest conservation based on those upper and lower biomass thresholds. However, quantitative estimates of these thresholds are scarce, highly case-specific, and rarely applied in holistic ecosystem management, remaining largely theoretical to date. Here, we propose the integration of this framework into single species management approaches, exemplified with a modified

Kobe plot. The empirically estimated “habitat threshold” (i.e., density of sea urchins at which macroalgal forests collapse) could be used as an indicator of the higher limit of sea urchin biomass. This threshold could inform managers about the abundance level at which intensified harvesting should be triggered to preserve the ecosystem state, for example through harvest control rules, in particular for sea urchin species which are both the target species of the fishery and the primary driver of the ecosystem collapse.

However, in the Western Mediterranean, the decline of the key herbivore and target species *P. lividus* leaves space to the competing, non-edible echinoid *Arbacia lixula*. In this context, a reduction of *P. lividus* due to fishing pressure or other causes (e.g., mass mortality events) may not necessarily allow the recovery of pristine macroalgal forests, as grazing pressure is maintained by *A. lixula*. We therefore recommend the use of an indicator that accounts for the abundance of both species as an ecosystem threshold, moving beyond the single-species, two-threshold approach. Monitoring the abundance of both sea urchin species would allow to tailor specific measures for each, specifically indicating when excessive biomass of one or both species needs to be controlled, with the dual goal of enabling macroalgae recovery and maintaining a sustainable fishery of *P. lividus*. The proposed approach aligns with the principles of ecosystem approach to fisheries and adaptive management, proposing a practical implementation of ecosystem indicators into single species fisheries management.

Modelling marine forests context-dependent thresholds to inform ecosystem-based management of small-scale fisheries

Mario Minguito-Frutos

High herbivory rates can lead to severe declines in ecosystem state and functioning of marine forests. The role of fishing in depleting populations of predatory species that control herbivorous populations, represents a key mechanism driving the collapse of marine forest. However, the resilience of coastal macroalgal habitats is further shaped by anthropogenic pressures, such as seawater warming and eutrophication, which modify fundamental ecological processes, including primary production and herbivory, at regional scales. Small-scale fisheries, due to their constrained spatial range, have the potential to target barren-forming species and their predators on temperate reefs, making them suitable candidates for effective implementation of ecosystem-based (or at least multi-trophic) fisheries management. Considering the natural spatial and temporal variability in temperate reef dynamics, effective fisheries management requires the conduction of ecosystem-based assessments at ecologically relevant scales (i.e., explicitly accounting for ecosystem-specific properties), which actively contribute to safeguard and/or promote the recovery of key macroalgal forest habitats. To investigate these dynamics, we developed a tri-trophic MICE model to explore how the effects of fishing pressure on both predators and herbivores may mediate the risk of ecosystem collapse in macroalgal forests across different ecological contexts. The model captures the dynamics of coastal rocky reefs and associated fisheries in the Mediterranean Sea, characterized by macroalgal assemblages dominated by *Cystoseira* spp., the herbivorous sea urchin *Paracentrotus lividus*, and the predatory sparid fish *Diplodus sargus*. Using a dedicated synthesis of field evidence, time series data, and bibliographic information, we have parameterized the model to represent how the ecological contexts of two contrasting regions, Catalonia in Spain and Sardinia in Italy, may alter the likelihood of barren-forming processes between these two regions. Simulation outputs provide: i) probabilistic estimates of context-dependent thresholds (i.e., critical sea urchin and predatory fish densities beyond which the system is likely to shift from productive and diverse marine forests to sea urchin barrens), and ii) estimates of ecosystem degradation risks, and marine forests recovery after barren formation, as a function of fishing intensity on herbivore sea urchins and predatory sparid fish. This work

helps explore trade-offs between fisheries productivity and conservation of Mediterranean marine forests, at relevant socio-ecological scales, in the face of overgrazing-induced collapses.

How Much is Too Much? Estimating ecosystem-level thresholds of overfishing

Jay Peterson

Single species fisheries management often focuses on estimating a maximum sustainable yield for an individual stock without taking into consideration predator-prey dynamics, environmental drivers, and other complex ecosystem interactions. When assessing stocks in isolation, cumulative effects across multiple fisheries can lead to a scenario where individual total allowable catches seem reasonable, but collectively it is not possible to sustainably harvest all species at their individual maximum yield without exceeding the system's capacity or compromising prey availability for non-target species of conservation concern. Single-species fisheries management will continue to be an important and necessary approach in many ecosystems. To help reduce risk, identifying an ecosystem-level reference point threshold of overfishing provides a holistic 'backstop' or 'cap' to ensure the total removal of biomass does not exceed the fundamental sustainable capacity of the ecosystem.

Here, we present a comparison of methods and preliminary results of calculated 'ecosystem caps' for multiple U.S. marine ecosystems, including sub-arctic, temperate, sub-tropical, and tropical ecosystems. The approaches considered are based on historical catches, satellite and *in situ* chlorophyll *a* and primary productivity estimates, trophic transfer efficiency, and ecosystem modeling. The various approaches and cap estimates have utility for management as indicators of system-level trends, the likelihood of ecosystem overfishing, and as context for discussing tradeoffs of various management approaches and decisions.

Ecosystem integration in single-species fisheries management advice: can AI lower the burden? Insights from an experimental approach

Margarita María Rincón Hidalgo

Single -species stock assessments form the backbone of most fisheries management advice worldwide, yet they operate in isolation from the complex ecological realities of fish populations. Integrating ecosystem considerations into these assessments is a recognized priority, but it remains a challenge. Fish stocks are influenced by a web of interacting factors — predator-prey dynamics, shifts in primary productivity, climate-driven habitat changes, and the cascading impacts of fishing itself — all of which are difficult to quantify and model simultaneously. Beyond the biological complexity, institutional frameworks and assessment workflows have been built around single-species paradigms, making structural change slow and difficult. Data gaps, model limitations, and the sheer volume of heterogeneous ecosystem information that analysts must synthesize further compound the problem. It is in this context that Artificial Intelligence presents a compelling opportunity: by enabling faster processing of complex, multi-source datasets, supporting pattern recognition across ecological variables, and assisting experts in navigating analytical workflows that would otherwise be excessively time-intensive, AI could serve as a practical bridge between the ambition of ecosystem-based management and the realities of operational fisheries advice. Incorporating ecosystem considerations into single-species fisheries management advice is widely acknowledged as necessary, yet few approaches have successfully translated into operational practice. This study investigates the potential of AI to facilitate this integration by enhancing both the efficiency and effectiveness of the assessment workflow. In a structured

experiment funded by the Exploratory Research program of the Joint Research Centre, EU Commission, fisheries and data scientists were tasked with integrating ecosystem aspects into a single-species stock assessment using standard data tools, first relying solely on their own prior knowledge of AI, and subsequently following targeted AI training. By directly comparing the two approaches, we examine how AI affects the time required, the quality of the outputs, and the ability of participants to establish a structured and reproducible workflow. We present the experimental design and summarize the findings, exploring whether — and to what extent — AI assistance can reduce the time burden of the integration process, improve analytical outcomes, and ultimately help bridge the gap between ecosystem-based management ambitions and the practical realities of operational fisheries advice.

Environmental impact ranking of the Portuguese multi-gear fleet

Pedro Leitão

Static fishing gears, such as nets, traps, and longlines, are widely used in artisanal and multi-gear fleets around the world, including in Europe, where their fishing effort is particularly high in southern countries. These gears are often perceived as less harmful than active gears such as bottom trawls; nevertheless, their environmental impacts can be high, including seabed damage and habitat destruction, high levels of bycatch and discards, including sensitive species, and ghost fishing.

In this study, the activity of a total of 25 métiers in the Portuguese coastal multi-gear fleet was mapped and their impacts evaluated, based on the information available in electronic logbooks and sales notes from 2014 to 2023 (fisheries-dependent data) and a literature review. Métiers were assessed based on catch and value per unit of effort (CPUE and VPUE) and four impact indicators: non-target species landed, amount of discards, presence of sensitive species, and ghost fishing. Impacts were scored as low, medium, or high, with different reliability levels based on data availability and specificity.

Gillnets and trammel nets emerged as the most used and impactful gears, representing over 50% of the fishing effort and exhibiting high levels of bycatch, discards, and ghost fishing. Conversely, traps and bottom longlines showed lower impacts but were also much less used, except for the common octopus (*Octopus vulgaris*) traps and the back scabbardfish (*Aphanopus carbo*) bottom longline, which together represent 40% of the fishing effort analyzed. Longline fisheries were generally scored higher in VPUE, followed by gillnet and trammel net fisheries, while trap fisheries were scored lower, except for the octopus and Nephrops fisheries. Geospatial analysis revealed strong overlapping fishing effort of different gears to target the same species. This was the case for European hake (*Merluccius merluccius*), John Dories (Zeidae), and monkfish (Lophiidae) fisheries. This overlap opens the possibility to transition to less impactful gears without changing fishing dynamics.

This study ranks the most impactful métiers and highlights knowledge gaps in most métiers, especially on high-effort, low-data métiers. It notes the importance of fisheries-dependent data for region-specific management strategies, such as area closures and effort reductions, to reduce adverse impacts promoting sustainable fisheries. Future work should be done to fill data gaps and expand monitoring to the small-scale Portuguese multi-gear fleet.