Integrating spatial processes into ecosystem models for sustainable utilization of fish resources

INSPIRE

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INSPIRE Overview

Process-based understanding of changes in commercial fish spatial distributions, and to disentangle the role of natural drivers and various anthropogenic impacts, is a challenging research topic with high relevance to resource management. The four-years BONUS INSPIRE project fills in the most persistent gaps in knowledge of the spatial ecology of the major commercial fish and thereby support the effectiveness of the relevant policies and ecosystem-based management of the Baltic Sea. The project would serve as a *„framework axis project*" which other Baltic Sea research could be related to.

INSPIRE is designed to substantially advance our knowledge on the major commercial fish species – cod, herring, sprat and flounder, which represent key elements of the Baltic Sea ecosystems. The specific objectives of INSPIRE are to:

i. Quantify processes generating heterogeneity in spatial distributions of fish;
ii. Quantify and map potential hazards to the connectivity between identified key habitats, and assess the impact of anthropogenic and climatic environmental changes on habitat connectivity;
iii. Quantify the population dynamics and interactions of the fish species in a spatially explicit context;
iv. Develop spatially explicit advice for ecosystem-based fisheries management.

INSPIRE proposes pilot ecosystem integrated surveys to resolve the habitat requirements of different life-stages of fish species by combined use of traditional methods and application of modern advanced analysis techniques. The surveys are conducted in close collaboration with local fishermen.

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1. Scientific and/or technological results

Spatial distributions

The work encompasses a comprehensive data collection programme, and statistical as well as process-oriented analyses on the spatial distributions of the focal species at different spatial scales. Focus is put on the distributions and their properties at different points in time, including environmental (habitat) impact factors, trophic interactions and fisheries.

Objectives:

1. Develop a novel database on distribution of early life stages of cod and flatfish (especially flounder)
2. Develop data-based maps for the spatial distribution of cod, herring, sprat and flounder (both early life stages and adults) including time series of spatial overlaps

Coastal sampling of cod and flounder and distribution of flounder ecotypes

Extensive gillnet and beach seine surveys to monitor the distribution and habitat preferences of the main life stages of cod and flounder at pan-Baltic scale were undertaken (D1.1, D7.3, D7.5). The complete dataset is stored in common databases hosted by DTU Aqua and freely available *via* Stefan Neuenfeldt (e-mail stn@aqua.dtu.dk). The experience gained during the survey was used to produce guidelines for future sampling (D1.7, D7.8). During the surveys, samples were also collected to study flounder egg (specific gravity) and spermatozoa (mobility at different salinities) characteristics. The dual response of the gillnet survey CPUEs to salinity and water depth suggested the existence of two distinct flounder ecotypes, demersal and pelagic. The abundance of the two respective ecoytpes was related to different biotic and abiotic factors. The habitat availability for the pelagic spawning flounder decreased over the last 20 years in the central part of the Baltic Sea likely due to increased hypoxic areas (D1.5, D7.6, D7.8, Orio et al. 2017). Egg and spermatozoa analyses confirmed the existence of both coastal- and deep-sea spawning flounder ecotypes in both ICES subdivisions (SD) 25 and 28. Spawning individuals of the coastal spawning ecotype occurred also deep (65-80m depth in SD 28) suggesting that flounder population mixing with hybridisation may occur.

NE Baltic Sea as habitat for sprat

Dedicated hydro-acoustic and experimental trawling surveys and sampling of eggs and larvae were performed in the open Baltic Sea SDs 28-32 to investigate the importance of northern Baltic Proper as a reproduction area for sprat and the feeding overlap between herring and sprat. The analyses evidenced the major importance of the southern part of the area in May for reproduction. In June the sprat eggs distribution was more even in all survey area, however sprat larvae were found mainly in the southern part of the area evidencing either a transport to the south or a higher mortality in the north (D7.3, D7.5). The spatial dynamics in the taxonomic composition of herring and sprat stomachs broadly resembled that of the availability of prey with the interspecific diet overlap being higher in the Gulf of Finland than in the Baltic Proper (D7.6, Ojaveer et al. 2018).

Species distribution maps
Historical data (e.g., zooplankton, tagging information, herring and cod larvae, fish stomach content, acoustic survey and international trawl survey data) were standardized and collated into common databases for further analyses (D7.3, D7.5, D7.6). From these collated data, distribution maps for eggs, larvae, juveniles and adults of cod, flounder, sprat and herring, based on INSPIRE surveys and long-term monitoring data were created. At the local scale, the distribution of different stages of herring larvae was analysed in the Greifswald Bay (Germany) to describe the relationship between the distribution of larval herring and environmental variables to make predictions in order to identify essential fish habitats (D1.2, Polte et al. 2017).

At the Baltic-wide scale, large changes in distribution of some stocks were evidenced, such as for the Eastern Baltic cod and the Baltic sprat (D1.2, D7.5, D7.6). At high stock size, adult cod is distributed over large area, whereas at low stock sizes the population contracts into the most favorable areas in terms of abiotic conditions, supporting thereby the existence of density-dependent habitat selection (D1.3, D7.6, Bartolino et al. 2017). Analyses of vertical distribution revealed a clear day/night pattern, proving the existence of an overall migration of adult cod to the pelagic habitat during night at the population level (D7.6). The distribution maps were used to quantify the overlap between predator-prey and between competing species. Temporal drop in the occurrence of cod in the distribution area of sprat and herring, and in the occurrence of large cod in the distribution area of small cod was observed. A decline in prey occurrence in the areas occupied by cod was also observed, evidencing that lower feeding opportunities of cod on fish prey occurred during the past 20 years (D1.4, D7.6). A strong link between extent of hypoxic areas and cod condition was also evidenced likely operating through habitat contraction, decline in benthic prey and direct effects on cod physiology. These factors can partially explain the decline in cod condition (Casini et al. 2016).

Habitat availablity as key for cod distribution
A Bayesian network model developed for the Baltic Sea indicated that habitat type plays a very important role in cod distribution, and that the interplay to other environmental conditions is non-stationary temporally and spatially. Fisheries management that is able to accommodate shifting ecological and environmental conditions relevant to biotopic information will be more effective and realistic (D1.6; D7.8, Kininmonth et al. 2017).

Passive movements, active migrations, and habitat connectivity
The work involves statistical and process-based analyses of movements of the focal species at different temporal and spatial scales and in different life-stages. Besides quantifying these movements, emphasis is put on the characterization of obstacles for the transport or movement between nursery and feeding habitats, between feeding and spawning habitat, and between early life stages habitats and nursery grounds.

Obejctives:

1. Develop and test estimates of drift pattern for early life stages of cod and flounder.
2. Estimate net migration rates of adult cod, herring and sprat between ICES sub-divisions.
3. Develop a mechanistic test for importance of migrations compared to fishing, predation and reproduction in relation to changes in the spatial distributions of cod, herring and sprat.

Bearing in mind the need of the main stakeholder of BONUS INSPIRE (ICES) and in agreement with BONUS secretariat, the work was mostly focused on cod, due to the urgent need to advance the respective knowledge base on Eastern cod ecology under the conditions of lack of analysitcal stock assessment in ICES. Therefore, this section mostly deals with cod. For clupeids, several relevant elements are given under the section 'Scaling from individuals to populations'.

Spawning areas of the Eastern Baltic cod population

Advanced knowledge in spatial distribution patterns of cod early life stages and variations in Baltic Sea circulation are a prerequisite to investigate the spatial stability and mixing of cod populations/stocks. A hydrodynamic model combined with a Lagrangian particle tracking technique was utilized to provide long-term knowledge of environmentally-related survival probability and drift of eastern Baltic cod eggs and yolk-sac larvae. The extent of Baltic cod eggs represented as virtual drifters is primarily determined by oxygen and salinity conditions and the ability to obtain neutral buoyancy in the water column, which define the habitat requirement to which species' physiology is suited. Eggs initially released as drifters in the westernmost spawning grounds were more affected by sedimentation than those released in the eastern spawning grounds. For all spawning areas temperature dependent mortality was only evident after severe winters. Egg buoyancy in relation to topographic features like bottom sills and strong bottom slopes could appear as a barrier for th transport of Baltic cod eggs and could potentially limit the connectivity of Baltic cod early life stages between the different basins in the central and eastern Baltic Sea (Hinrichsen et al. 2016).

Survival and dispersal variability of early life-history stages of flounder

A hydrodynamic model coupled with a Lagrangian particle tracking technique was utilized to simulate spatially and temporally resolved long- term environmentally related (i) size of habitat suitable for reproduction, (ii) egg/yolk-sac larval survival, (iii) separation of causes of mortality, and (iv) connectivity between spawning areas of Baltic flounder with pelagic eggs. It appeared that the spatial extent of eggs and larvae represented as modelled particles is primarily determined by oxygen and salinity conditions. The reproduction habitat most suitable was determined for the Gdansk Deep, followed by the Bornholm Basin. Relatively low habitat suitability was obtained for the Arkona Basin and the Gotland Basin. The model runs also showed yolk-sac larval survival to be to a large extent affected by sedimentation. Eggs initially released in the Arkona Basin and Bornholm Basin are strongly affected by sedimentation compared with those released in the Gdansk Deep and Gotland Basin. Highest relative survival of eggs occurred in the Gdansk Deep and in the Bornholm Basin. Relatively low survival rates in the

Gotland Basin were attributable to oxygen-dependent mortality. Oxygen content had almost no impact on survival in the Arkona Basin. For all spawning areas mortality caused by lethally low temperatures was only evident after severe winters. Buoyancy of eggs and yolk-sac larvae in relation to topographic features appear as a barrier for the transport of eggs and yolk-sac larvae and potentially limits the connectivity of early life stages between the different spawning areas (Hinrichsen et al. 2017).

Mixing of eastern and western Baltic cod

In the Baltic Sea, two genetically distinct cod populations occur, the "Eastern" Baltic cod in ICES SDs 22-32 and the "Western" Baltic cod in SDs 22-24. Since 2006, cod abundance has increased 5-fold in the Arkona Basin in the eastern part of the "Western" cod's management unit (SD 24), but remained constant in SD 22, presumably due to mixing of the two stocks. The spatio-temporal dynamics of stock mixing were analysed using shape analysis of archived otolith, and the impact of "Eastern" cod's immigration on recruitment by hydrographic drift modelling. The spatial resolution of stock mixing suggests immigration occurring north of Bornholm and propagating throughout the Arkona Basin. An age-related trend in immigration was evident, which started with age-4 cod followed by progressively older individuals. The immigration cannot be attributed to spawning migration, as no seasonal trend in stock mixing was observed. Albeit considerable, the immigration of "Eastern" cod does therefore not seem to contribute significantly to "Western" Baltic cod's recruitment (Hüssy et al. 2015).

Connectivity of larval cod in the transition area

Connectivity of pelagic, early life stages via transport by ocean currents is of particular interest, as it may affect survival chances of offspring, recruitment success and mixing of stocks across management units. Based on drift model studies, the transport of larvae showed a high intra- and inter-annual variability, but also some general, consistent patterns of retention within and dispersion to different management areas. Good agreement of drifter end positions, representing potential juvenile settlement areas, with actual catches of juveniles from bottom trawl surveys suggests that the drift simulations provide reasonable estimates of early life stage connectivity between cod populations in the investigated areas. High exchange rates of drifters between management areas suggest that cod populations are demographically correlated (Huwer et al. 2016).

Migration of cod

Tag-recapture data-points indicate that only a small fraction (<10%) of the tagged population is conducting trans-basin migrations with the net displacement being independent of the time at large. This means that adult migrations probably do not contribute to whole Baltic scale re-distributions of cod. Furthermore, it implies that regional stock recovery might not lead to recovery of cod in the whole Baltic Sea, but rather to regional regulation of stock size due to density-dependent processes. The spatial pattern of landings has changed substantially (but consistently with cod distribution): the fishery of cod has shrunk to the southern and southwestern areas while the importance of north-eastern areas has increased in sprat and herring fishery (D2.3, Hinrichsen et al. 2016).

Species interaction of cod and sprat on small scales
Information about species interactions at a spatial scale comparable to the perceptive abilities of the involved species is crucial for the establishment of predictive, food consumption models at the population level. Nevertheless, such information is sparse due to methodological constraints. We studied the diel, vertical dynamics of species interactions between cod and its major clupeid prey sprat in the Bornholm Basin during late winter. This was accomplished by combining acoustic information on diel vertical fish distribution, time of ingestion of individual sprat estimated from cod stomach content data and observed vertical profiles of salinity, temperature and oxygen content. Cod predation took place primarily at dusk and dawn during ascent and descent of sprat associated with school dissolution and formation. Cod resided close to the bottom outside these temporal predation windows. Sprat schools were located at the same depth or deeper than cod during light hours, whereas dispersed sprat at night were situated higher in the water column. These vertical dynamics could be explained by fitness optimization using bioenergetics and trade-offs between temperature, oxygen saturation of the water, and predation risk. The study thus forms the first step to providing a mechanistic background for the aggregate functional response of cod at basin scale and beyond (D2.6).

Scaling from individuals to populations
The work aims at quantifying the impact of individual scale movements on population scale spatial distributions. Besides the scaling from individuals' movement to populations' dispersion in space, the focus is on local scale mortality, for example hazards due to hot spot fisheries, predation on aggregations of juveniles, or climatic extremes such as severe winter storms. The question to be addressed is whether such local events shape larger, regional scale population abundance and recruitment strength and thus spatial distribution patterns.

Objectives:
1. To develop methods to scale individual movements of cod, herring, sprat and flounder (early life stages) to population distributions.
2. To perform process-studies collecting basic knowledge on regional hazards for population dynamics of Baltic herring and cod

Cod
For the first time, a drift study has been performed in which fertilized cod eggs have been released in historically important Baltic cod spawning grounds. These eggs drifted at levels of neutral buoyancy until they entered the first feeding state. The end positions of this drift study were the starting positions for the subsequent drift study, where first feeding stage larvae drifted until they reached the age of settlement (90 days). Then after checking for suitable habitats, either the drift ended successfully or the particles were not counted as settled juveniles (D3.1, D7.6, Hinrichsen et al. 2017). The study has shown that also particles representing eastern Baltic cod juveniles settled to a relatively large extent in the western Baltic cod management area and may significantly contribute to western Baltic cod recruitment. Therefore, it could be suggested that not only immigration but also larval and juvenile transport could contribute to recruitment in the western Baltic Sea. However, it is also evident that the stock component in the Gotland

Basin only to a minor degree contributed particles to nursery grounds in other ICES subdivisions (D3.1).

Sprat

Analysis based on the database on hydro-acoustic surveys of sprat evidenced that sprat tended to aggregate in deeper waters in spring season while moving towards coastal waters and aggregating at 30-70m depth during feeding (D3.2). The main factor determining aggregation and distribution pattern of sprat in May was winter severity. The main factor determining aggregation and distribution pattern of sprat population in September-October was water temperature in 50-100m depth layer, but in recent 7-year period distribution supposedly is determined by several factors simultaneously. In last two decades sprat distribution is shifted northward coinciding with an increase in winter temperatures and population size. The investigated area of Eastern central Baltic is supposedly important for the reproduction of sprat as the proportion of sprat spawning stock biomass significantly increases in years of rich year-class formation. A hypothesis is put forward that Gotland Deep basin is the centre of distribution of sprat stock in the Baltic Sea (D3.2)

Herring

For most herring populations in the Baltic Sea frequenting coastal zones and inner coastal waters for spawning and larval retention, this means that important drivers and stressors of recruitment dynamics are acting on the scale of regional basins or estuaries. This renders stocks vulnerable against (anthropogenic) alterations of coastal zones and regional climate regimes. Generally, reproductive success and year class strength of Baltic herring populations is strongly determined by the survival of early life stages such as eggs and larvae in local nursery areas. However, the explicit mechanisms by which local stressors might affect overall recruitment are currently not well understood. The importance of early life stage ecology for recruitment of a population was exemplarily studied on two distinct Baltic spring herring populations: the Gulf of Riga spring herring (representing the gulf herring) and the Western Baltic herring (representing the sea herring). A synthesis was made as to which genericaly drive recruitment of Baltic spring herring populations (D3.3, Moll et al. 2018). In the very shallow NE part of the Gulf of Riga, high summer temperatures, which likely exceed the physiological optimum, may negatively affect larval survival. Therefore, the observed simultaneously high growth and mortality rates primarily resulted from a rapidly increasing and high water temperature that masked potential food-web effects. The investigation suggests that the projected climate warming may have significant effect on early life history stages of the dominating marine fish species inhabiting shallow estuaries (Arula et al. 2015, 2016). In the long-term perspective (since the 1950), hydroclimatic factors (significant were winter water temperature and annual sum of sun hours) appeared to be superior to biotic variables in explaining the inter-annual variability of recruitment abundance (D3.3).

Amongst others, the role of small- and meso-scale drivers and stressors for the recruitment strength was investigated including effects of regional climate regimes and food availability on larval growth as well as consequences of single storm events on herring egg mortality. Against the general ocean paradigm assuming that spatial distribution of larval fish is entirely driven by

hydrodynamics, research on habitat use of differing larval stages in a Western Baltic nursery area could demonstrate that along the early life history stages habitat selection is significantly driven by active habitat selection. An ontogenetic loop in habitat use during larval ontogeny indicated an active habitat selection and revealed a key role of shallow littoral waters for larval herring retention (D3.2, Polte et al. 2017).

We have also used elemental fingerprinting in herring otoliths to detect differences in the chemical composition based on varying water chemistry in particular spawning areas along the Southwestern Baltic Sea coast. Cluster analysis revealed a distinct chemical separation between juvenile herring caught in the vicinity of the Island of Ruegen (south-western Baltic Sea) and other potential nurseries. This novel approach will increase our understanding of the contribution of particular coastal nursery areas to overall western Baltic herring productivity (D3.2).

Stock Assessments

The work includes incorporation of knowledge on the processes shaping heterogeneity in spatial distribution of exploited species into analytical assessments for cod, herring and sprat. Also, analytical assessment for flounder, accounting for stock structure and spatial distribution of this species, as a basis for quantitative management of this species, was performed. Besides the stock assessments, input is generated to estimate indicators of good environmental status according to the Marine Strategy Framework Directive.

Objectives:

1. to include and quantify the effects of migrations and spatial and temporal changes in exploited fish distribution (cod, herring, and sprat) on stock assessment,
2. to provide assessment of the status of flatfish in the Baltic Sea, as a basis for quantitative management of these stocks.

Cod dynamics and alternative assessment

The eastern Baltic cod stock was assessed with two models, in which natural mortality in recent years was allowed to increase (or be dependent on weight of cod, which drastically declined in recent years). The applied models were the age-structured CAGEAN and difference stock-production model, as they allowed for easy implementation of functional dependence in natural mortality (M). It was shown that the assessment models with M related to growth perform much better that the standard assessment models in which M is assumed constant; they are better both in diagnostics of the model quality and in consistency with the trends in survey indices of stock size (D4.1, D7.5). In addition, a stock similar to eastern cod with natural mortality increasing in recent years was generated. It appeared that the assessment of such stock using constant natural mortality performs similarly badly as recent ICES assessments in terms of model diagnostics. The obtained results strongly suggest that natural mortality of cod in recent years markedly increased (Horbowy, 2016).

Spatial effects on clupeids

Herring and sprat were assessed according to former assessment units (AUs), used up to 1990s. Such assessments better reflect both biological characteristics of stocks and spatial overlap of clupeids with predator (cod), then the standard assessment performed presently by ICES. Assessments of herring show similar trends in biomass development in AUs and similar are trends in fishing mortality. The biomass of herring in SDs 25-27 is about two times higher than the biomass of herring in SDs 28-29+32. Opposite is estimated for fishing mortality. The sum of biomasses by AUs is very similar to biomass of the central Baltic herring stock estimated by ICES. Trial assessments indicate that the AU of herring in SDs 28-29+32 should rather not be decomposed into smaller units. The merging of two AUs (herring in SDs 25-27 and herring in SDs 28-29+ 32) into one AU of the central Baltic herring stock seems to be justified from assessment point of view. However, spatial management of the stocks could be recommended; then data and assessment by former AUs would be needed (D4.1).

In general, assessments of sprat show similar trends in stock biomass and fishing mortality developments in the considered AUs (sprat in SDs 22-25, sprat in SDs 26+28, and sprat in SDs 27,29-32) and sum of biomasses by AUs is close to ICES estimates of sprat biomass in the Baltic Sea. The biomass of sprat in SDs 26+28 is the biggest; in most years it was close to the sum of biomasses of other sprat stocks. Fishing mortality of this stock has been the highest in recent years. Merging of three AUs of sprat into one AU of sprat in the Baltic Sea seems to be justified from assessment point of view. However, differences in intensity of exploitation (fishing mortality) of the stocks is substantial (fishing mortality being higher in the north-eastern areas) and spatial management could be considered. Such management would require assessment and data by former AUs (D4.1).

The estimated Maximum Sustainable Yield (MSY) reference points indicate that exploitation of stocks in recent years was consistent with MSY approach, except sprat in SDs 26+28, for which fishing mortality exceeded F_{msy}. New way of estimating reference points taking into account density dependent effects was proposed and used for sprat (Horbowy and Luzeńczyk, 2016), indicating higher F_{msy} than the one used by ICES.

Flounder stock identification

Flounders were differentiated by egg and spermatozoa characteristics, to be used as reference material. Genetics, morphometrics and otolith microchemistry were applied to develop tools for separating demersal and pelagic spawning flounder and enable allocation of catch to different spawning types of flounder in different SDs. Although it was possible to correctly classify 74% of flounder based on morphometry, it required use of 18 morphological characteristics and hence was quite time consuming. Results from the otolith chemistry revealed that further studies are needed before the findings can be used for stock separation. Following obtained results, the flounder stocks were redefined taking into account share of stock components as: flounder in SDs 24-25 (mainly pelagic component), flounder in SD 26 (mainly pelagic component), flounder in SD 28 (mostly demersal component), and flounder in SDs 27 and 29-32 (mostly demersal component) (D7.8, D4.3).

Further work on stock separation may be based on the probability distribution model (Orio et al. 2017) in combination with the proportions of the different types in the survey revealed by the genetic study; then the proportion of the two types of flounder in different areas can be estimated. Furthermore, the developed genetic protocol with 16 msats and results from the 1000 flounders can be used as control for future investigations of proportion of flounders types in different areas and/or fisheries.

Assessment of flatfish stocks
A variety of assessment models and methods for estimation of MSY reference points have been tested and applied. The set of analyses comprised age-based methods, different stock-production models, including state space models with random effects, length based approach as spawning potential ratio, equilibrium yield and biomass curves as basis for MSY parameters estimation. The methods were applied to stock structure defined on the basis of newly collected data within INSPIRE surveys.

Important elements of flounder fishery are discards. They could not be directly included into the assessments as time series of reliable discards estimates are very short. However, extensive analysis was conducted to test effects of different discards ratios on assessment results and management conclusions. For these analyses a few discards models were considered and applied. The general conclusion was that inclusion of discards increase estimates of biomass in similar rate as discards rate but has little effect on estimates of fishing mortality. Trends in biomass estimates with modelled discards included were similar to trends in biomass estimates without discards (D4.3).

The conducted analyses indicate good state of flounder in SDs 24-25; all models indicate that stock biomass is high, while fishing mortality is low and below F_{msy}. Similarly, SPiCT assessments indicate good status of flounder in SD 26; stock biomass is above B_{msy}, fishing mortality is below F_{msy}. On the contrary, state of flounder in SD 28 has been poor in recent years; stock biomass has been below B_{msy}, and fishing mortality has been above F_{msy}. The biomass of flounder in SDs 27,29-32 declined but has been stable and above B_{msy} in recent years, while fishing mortality has been below F_{msy}. No assessment or evaluation model has indicated immediate danger for the stock (D4.3).

Ecosystem-based management

The work involved suggesting critical revision of the existing management for Baltic cod, herring and sprat, taking into account possible modifications and extensions when spatial heterogeneity is accounted for. The work also supports implementation of MSFD by linking indicators in a spatially explicit context.

Objectives:
1. Document and publish the importance of including spatial heterogeneity into ecosystem-based management in the Baltic
2. Report on the importance of spatial heterogeneity in defining Baltic-specific MSFD indicators
3. Develop proposals to include significant regional processes in Baltic ecosystem-based fisheries management

Early warning indicators

Potential early warning indicators for the Eastern Baltic cod stock development were examined (D5.1). Indicators of recruitment environment, like depth at 11 psu isohaline, was sugested as an “early warning” of potentially good or bad conditions. It apeared that cod body condition has decreased from the mid 1990s and suggests high natural mortality. The rescaled Baltic International Trawl Survey BITS index may be considered an early warning indicator of cod stock size. Increased hypoxic bottom areas have caused changes in cod feeding level. The combined consequences of declining growth, reduced condition, and spawning at smaller sizes on individual egg production and viability of offsprings have remained unclear (D5.1).

Spatially explicit MSFD indicators

Altogether 15 species-based (herring, sprat, cod and flounder) spatially explicit indicators were identified and elaborated. These address the following three MSFD Descriptors: D1 Biodiversity, D3 Exploited fish stocks and D4 Food-webs (D5.2). In addition, composite indicator to evaluate status of the cod and herring stocks at the pan-Baltic scale was developed, by applying the recently developed Baltic Health Index framework. We also presented the indicator-testing framework, which can be used to identify responses of food-web indicators to manageable pressures while accounting for the biotic interactions in food-webs linking such indicators. The outcomes, essentially D3 indicators on spawning stock biomass and fishing mortality, were discussed in the light of potential precautionary reference and Good Environmental Status (GES). However, several indicators need further work not only to develop reference points and targets, which will ultimately result in achievement of GES, but also consider spatial scales for indicator aggregations (D5.2).

Regional management

Several spatially-explicit novel research results emerged, which will make valuable contribution for advancing the ecosystem-based managemnt in the Baltic Sea. The highlights include: (1) recent abundant presence of sprat in the NE Baltic Sea is likely facilitated by superior competitive feeding to herring; (2) the commercial extinction of the previously abundant autumn spawning herring in the early 1980s was likely due to too high fishing mortality; (3) spatial distribution and size composition of sprat and herring affect the individual performance in salmon and cod, suggesting the need for spatial management of sprat; (4) the presently implemented area closures of cod fisheries in Gdansk Deep and Gotland Basin are likely largely ineffective in enhancing the cod stock; and (5) the two subpopulations of flounder seem to use different areas following settlement (D5.3).

The Baltic Sea is chosen as a pilot case for taking into account biological interactions in the new fisheries management plans (D5.4). Its ecosystem has undergone major structural changes: decline in cod and herring biomass from the late 1980s to the 1990s and increase of sprat biomass. This has implied a mismatch in the spatial overlap between cod and sprat, affecting predator-prey

interactions. In ICES stock assessments, e.g. genetic analyses and practical reasons have led to mainly combining a number of stocks of sprat, herring and flounder. When comparing stock assessments by former ICES Assessment Units with the larger, present ones, the results have been mainly compatible, but with sprat there was spatial contradiction that should be taken into account (D5.4).

2. Summary of the produced scientific and technological foreground capable of industrial or commercial application, plan for the use and dissemination of this foreground and measures taken for its protection

The project did not produce any products explicitly relevant for industrial or commercial applications.

3. Further research needed in the field

Topics of general fisheries biology/ecology interest:

- ✓ the effects of the continuing climate change to the ecosystem and fish community, especially exploited fish stocks;
- ✓ a cost-benefit analysis on the optimal amount and accuracy of biological information needed to collect for the basis of stock assessments in heterogenous systems;
- ✓ a quantitative exploration of bottom-up and top-down processes shaping clupeid-zooplankton interactions, including predation by cod on clupeids;
- ✓ basic ecology of autumn spawning herring to identify why autumn herring hasn't recovered;
- ✓ Explanation of the increased appearance of cod in pelagic zone in areas with hypoxic bottoms;
- ✓ further investigations on the reasons for differences in survey catchabilities by assessment units;
- ✓ increase the understanding of the reasons for the decrease in cod condition by comparably investigating cod condition in offshore versus inshore areas;
- ✓ increase knowledge of benthic fish community ecology with specific focus on interactions between cod and flatfish
- ✓ investigation of the effects of parasitic infections in Eastern Baltic cod.

Some specific targets:

- ✓ factors affecting individual egg production and viability of offspring in Eastern Baltic cod: the role of factors like declined growth, reduced condition or spawning at smaller sizes
- ✓ the reasons behind the decrease of the growth rate of EB cod, length at maturity (L_{50}), and maximal length L_{max}: selective nature of fishery, and potential genetic changes and/or food shortage, increased competition with flounder and physiological/behavioural responses to increased hypoxic areas
- ✓ basic research to comparatively analyse spatial otolith microchemistry and genetic data of flounder in the Baltic Sea

Applied aspects:

- ✓ improvement of the understanding of the effects of spatio-temporal measures such as spawning closures with cod;

- ✓ further investigations on the differences of spawning stock biomass and recruitment relationships between ICES sub-divisins and potentially identifying criteria for defining area-specific good environmental status;
- ✓ derivation of biological reference points for former assessment units, including in the maximum sustainable yield context;
- ✓ further investigations on the methods to include stock spatial distribution and overlap in analytical stock assessment and management advice
- ✓ continued work on analyses of food-web indicators and criteruia for defining the health status of ecosystems;

Data:

- ✓ Collect historical trawl survey data from all Baltic countries and coastal areas not covered by trawl surveys

4. Promoting an effective science-policy interface to ensure optimal take up of research results

INSPIRE scientists have made the following relevant contributions to the development and implementation of 'fit-to-purpose' regulations, policies and management practices on international, European, the Baltic Sea region or national level aimed at safeguarding the sustainable use of ecosystem's goods and services:

1. Review of the ICES management options on Baltic Sea fish stocks in order to advice the European Commission implementing the EU Common Fisheries Policy (UT-EMI);
2. Analysis of effort allocation in European fisheries in the Baltic Sea in order to advice the European Commission implementing the EU Common Fisheries Policy (UT-EMI);
3. National advisory services (Estonia) on fisheries management options in the Baltic Sea (EU Common Fisheries Policy);
4. Contribution to the national process of MSFD to propose monitoring scheme and start to develop program of measures (UT-EMI);
5. Proposing management options of fishing effort distribution in the Baltic Sea in pelagic fisheries to elaborate a spatially explicit advice for ecosystem-based fisheries management (BIOR);
6. Advising about the Multiannual plan for the Baltic Sea fisheries (MIR-PIB);
7. National advisory services (Denmark) on fisheries options in the Blatic Sea with special focus on cod fisheries and the Common Fisheries Policy (DTU-Aqua);
8. Formulating management advice of the Baltic fish stocks to ICES and providing evidences of increasing natural mortality of cod (MIR-PIB);
9. National advisory services (Poland) on fish stock management, incl. reporting on indicators of balance between fishing capacity and fishing opportunities (MIR-PIB);
10. Advising in the development of indicators of the state of offshore fish community (SLU);
11. National advisory services (Sweden) on fisheries management options in the Baltic Sea with special focus on cod fisheries and the Common Fisheries Policy (SLU);

12. Proposals of methodology and data requirements for EU Member States for reporting on the EU Landing Obligation Proposed types of information, metrics and indicators that would be useful in reporting on the elements defined in the legislation (UT-EMI);
13. National advisory service (Sweden) on maritime spatial planning (SLU);
14. National advisory service (Sweden) on identifying Ecologically and Biologically Significant Areas (SLU).

INSPIRE scientists have made the following relevant contributions for designing, implementing and evaluating the efficacy of relevant public policies and governance on international, European, the Baltic Sea region or national level:

1. National discussions in Latvia on the fishing possibilities and distribution of the fishing effort in pelagic fisheries.
2. National discussions in Denmark and suggestions on limiting sprat fisheries in ICES SD 25 in order to increase living conditions for cod.
3. National discussions in Poland on developing measures to improve cod stock and fisheries in the Baltic Sea.

Participation in stakeholder committees:

In total, INSPIRE sceintists have 370 participations at various stakeholder committees. The priority was given to ICES, with substantial contribution to the following expert groups: Working Group on Baltic Fish Stock Assessments (WGBFAS), Working Group on Multispecies Stock Assessments (WGSAM), Workshop on Spatial Processes (WKSPATIAL), Working Group on History of Fish and Fisheries (WGHIST), Working Group on Atlantic Fish Larvae and Eggs Surveys (WGALES), Working Group on Integrated Assessments in the Baltic Sea (WGIAB), Workshop on Developing Integrated Advice for Baltic Sea ecosystem-based fisheries management (WKDEICE), Workshop on Biological Input to Eastern Baltic Cod Assessment (WKBEBCA), Workshop on Evaluation of Input data to Eastern Baltic Cod Assessment (WKIDEBKA) and Baltic Sea Advice Drafting Group (ADGBS).

International, national and regional stakeholder events organised:

1. BONUS BIO-C3/INSPIRE/COCOA/BAMBI summer school on ‘Modelling Biodiversity for Sustainable Use of Baltic Sea Living Resources’ (Holbæk, Denmark, 2016).
2. Theme session on ‘From genes to ecosystems: spatial heterogeneity and temporal dynamics of the Baltic Sea’ at ICES ASC 2015 in Copenhagen with Karin Hüssy (DTU-Aqua) as a co-convener on behalf of INSPIRE.
3. Theme session on ‘The emerging science of ecological multi-model inference for informing fisheries management’ at ICES ASC 2016 in Riga with Stefan Neuenfeldt (DTU-Aqua) as a co-convener on behalf of INSPIRE.
4. BONUS SYMPOSIUM on ’Science delivery for sustainable use of the Baltic Sea living resources’ (Tallinn, Estonia, 2017). For details, see D6.3.
5. National events organised
   - ✓ Open doors at survey vessel RV Aranda (Finland, 2015). Scientists presented fisheries research and stock assessment work to media and public;

- ✓ BONUS BAMBI/BIO-C3/INSPIRE seminar on 'The new challenges in management of the Baltic Sea' (Estonia 2016). Scientists presented research results to representatives from relevant national ministries.

6. Presenting work at the following important international science events:
   - ✓ ICES Annual Science Conferences 2015, 2016 and 2017;
   - ✓ The Baltic Sea Science Congresses in 2015 and 2017;
   - ✓ The 39th Annual Larval Fish Congress (Switzerland, 2015);
   - ✓ Fisheries Society of the British Isles Symposium on 'Fish Genes and genomes: Contributions to Ecology, Evolution and Management' (UK, 2016);
   - ✓ 7th World Fisheries Congress (Korea, 2016);
   - ✓ ICES/PICES Early Career Scientist Conference: Climate, Oceans and Society - Challenges & Opportunities (Korea, 2017)
   - ✓ PICES International Symposium: Drivers of dynamics of small pelagic fish resources (Canada, 2017);
   - ✓ International Flatfish symposium (France, 2017);
   - ✓ ASLO Aquatic Sciences Meeting (Hawaii, 2017).

5. Collaboration with relevant research programmes and the science communities in the other European sea basins and on international level

The following international scietific collaborations were established and performed:

1. Partnership within the global research network 'Oceans Past Initiative';
2. Partnership with the EU COST Action 'Oceans Past Platform';
3. Participation in the global science initiative 'Indicators for the Seas (IndiSeas);
4. Pan-Baltic regional study on the Baltic Health Index (BHI), by involving cooperation from outside the Baltic Sea - Ben Halpern and the Ocean Helth Index team;
5. Membership of the LENFEST Fishery Ecosystem Task Force, led by Tim Essington and Phil Levin, to develop Ecosystem Management Plans for the US.

6. Lists of peer-reviewed publications arising from the project research and defended PhD dissertations

Published/accepted papers:

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3. Arula, T., Laur, K., Simm, M., Ojaveer, H. 2015. Dual impact of temperature on growth and mortality of marine fish larvae in a shallow estuarine habitat. Estuarine, Coastal and Shelf Science 167: 326-335.
4. Arula, T., Raid, T., Simm, M., Ojaveer, H. 2016. Temperature-driven changes in early life-history stages influence the Gulf of Riga spring spawning herring (*Clupea harengus* m.) recruitment abundance. Hydrobiologia 767: 125-135.

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Manuscripts

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52. Florin et al. Using genetics to identify management units of European flounder in the Baltic Sea. Manuscript.
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PhD Thesis:

1. Berndt, K. 2016 Fishing the gene pool: Genetic structure, admixture and behavioural complexity in fisheries management. PhD Thesis (main supervisor Anders Persson, LU).
2. Luzeńczyk, A. 2017. MSY (maximum sustainable yield) approach in fish stock management: an example of the Baltic Sea. PhD Thesis (supervisor Jan Horbowy, MIR-PIB).

7. Progress in comparison with the original research plan and the schedule of deliverables

No changes to DoW has occurred, the final product measured as the number of publications (see above) exceeded several times the research delivery indicated in DoW. Minor budgetary modifications have occurred in several partner institutes without negatiive implications to the workplan and science delivery.

There were some changes in the organisation of science and the timing of its delivery, driven both from project internalities (as new scientific evidences accumulated) and externalities (associated essentially to timing of ICES Annual Science Conferences). These were:

i) New item added: join BONUS BIO-C3/BAMBI/INSPIRE summer school in 2015 with both lecturers and early career scientists from INSPIRE project to attend the event.
ii) New item added: co-organise BONUS Theme session on 'From genes to ecosystems: spatial heterogeneity and temporal dynamics of the Baltic Sea' at ICES Annual Science Conference in 2015.
iii) New item added: dedicated flounder workshop (Poland, 2017), to discuss and agree the assessment methods to be used for flounder stock assessments/evaluations in order to achieve D4.3.
iv) Major shift in timing: move INSPIRE Training school from 2017 to 2016, and to held it jointly with other relevant BONUS projects (Denmark, August 2016).
v) Minor shift in timing: change timing of a few milestones and deliverables (e.g., 2nd, 3rd and 4th Integrating workshops; 1st, 2nd and 3rd annual meetings; BONUS symposium; D4.2; D4.3; D5.4).
vi) Change D4.3 from 'manuscript' to 'report' (as it appeared that the assembled scientific evidence was insufficient deliver scientific manuscript on the model and methods of assessment of flounder stocks).

8. Wider societal implications

The project has major implications on sustainable management of fish stocks and ecosystems of the Baltic Sea, contributing thereby to improved livelihoods of coastal inhabitants and assisting in implementation of various EU policies and legislative acts (such as the EU Blue Growth policy, Common Fisheries Policy, Marine Strategy Framework Directive). This has been achieved through elevating the general basic knowledge base in the field as well as testing and applying new methods in fish stock assessments. Importantly, the first ever assessment of flatfish in the Baltic Sea was carried out.

INSPIRE scientists originate from seven different Baltic countries. The knowledge generated in the project was disseminated both on national level and all-Baltic level. This parallel dissemination facilitates the uptake of new knowledge especially in the fishries management processes.

There were no direct gender issues associated with INSPIRE. The project provided a challenging opportunity for both men and women to participate. The team has a focus on a balanced participation of men and women, and it was prioritized that men and women were given equal opportunities.

Public at large was involved in several INSPIRE partner institute countries through dedicated national events, e.g., open doors at survey vessel RV Aranda (Finland, 2015) and BONUS BAMBI/BIO-C3/INSPIRE seminar on 'The new challenges in management of the Baltic Sea' (Estonia, 2016). In addition, various media channels (TV, radio, newspapers, journals, internet blogs) were actively used in several countries with in total of 34 occasions.