DTU Aqua
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The correlation between spatial distribution of fisheries and resources - integrated spatial and bio-economic fisheries management evaluation (MSPTOOLS)

By J. Rasmus Nielsen, Marie-Christine Rufener, Kasper Kristensen and Francois Bastardie

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Colophon

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Preface

The present report is based on the MSPTOOLS project funded with 2 million DKK by the European Maritime and Fisheries Fund and the Danish Fisheries Agency.

DTU Aqua, Lyngby Denmark, November 2019

Contents

Summary

To achieve the goals of the EU Common Fishery Policy (EU CFP) of ecological and economic sustainable fishery and to meet the demands for protection of sensitive habitats under the EU Marine Strategy Framework Directive (EU MSFD), as well as to meet the demands from other marine sectors on occupation of specific sea areas for other uses under the EU Marine Spatial Planning Directive (EU MSPD), it is necessary to establish adequate management strategy evaluation (MSE) tools to evaluate the impacts of the different uses of the sea in a multi-disciplinary and multi-sectoral context. Such tools are needed to evaluate scenarios of different management strategies in order to inform managers and stakeholders about the impacts and relative performance of different management options in achieving the policy objectives. This demands implementation of MSE tools which encompass the dynamic variability in distribution and abundance of fish resources with high resolution in time and space. Also, this demands integration of bio-economic MSE tools which can evaluate fishing patterns and fisher's decision making, i.e. human behaviour, in allocating their fishing effort with high resolution in time and space. Consequently, these tools must be highly spatial explicit and enable small scale time specific resolution in order to efficiently and realistically evaluating the integrated biological and economic effects of spatial management, and contribute to improving spatial management strategies also taking into account the footpring of the marine capture sector including energy use and efficiency to catch the available fishery resources.

The MSPTOOLS project provides new and improved quantitative methods for evaluating stock abundances and distributions with high resolution in time and space by integrating different types of quantitative information as well as by linking biological and bio-economic models and evaluation tools. This has involved development of better tools, methods and integrated models to describe the resources, the fisheries and sensitive habitats/species distribution in relation to each other and identify sustainable fishing areas and conservation areas.

The model developments under the project have resulted in a row of manuscripts published and submitted to high ranking scientific peer-reviewed journals and symposia, and those manuscripts are summarised in the present report with proper reference to the main manuscripts. The first summary highlight the main results that were obtained in Rufener *et al*. (2019a;b) which describes a statistical framework (hereafter LGNB) that was developed to combine commercial fisheries and scientific survey data, to ultimately improve the understanding of the spatio-temporal abundance dynamics of marine harvested species. This framework served, in fact, as the main basis for all other MSPTOOLS work packages. The second summary presents preliminary results to an economic extension that was included in the proposed framework where there was made coupling of a Data Development Analysis (DEA) to the LGNB model in order to evaluate the cost-effectiveness of the commercial fisheries and scientific survey, with respect to their sampling size and accuracy in estimating abundance trends. Detailed results of this summary are reported in Rufener *et al*. (In Prep.1). The third summary provides the methodology and outline of the coupling process between the LGNB and the bio-economic management strategy evaluation tool DISPLACE. This, furthermore, includes a critical commenting on the main hurdles encountered in this process, and how this will be used to investigate the actual benefit of the coupled LGNB-DISPLACE framework within a set of hypothetical management scenarios.

Further results of this summary are stated in Rufener *et al*. (In Prep.2). The fourth summary presents the dissemination of the second and third MSPTOOLS working tasks at the annual ICES Working Group on Spatial Fisheries Data (ICES WGSFD) meeting, and how the working group could benefit from the LGNB-DISPLACE framework. Finally, the fifth summary presents an initial pilot study under the MSPTOOLS project to combine fishery-independent research survey information on catch rates as well as commercial fishery catch and effort information from the targeted Danish Norway pout fishery in integrated analyses with very high spatial resolution to evaluate spatial fisheries management measures in form of a specific fishing closure. The results of this summary is published in ICES Journal of Marine Science (Bigné *et al*. 2019).

The model improvements provided by the project has a high impact and news-value to both the current and future advisory and scientific stock evaluation development work within the scientific and management advisory communities under the International Council for Exploration of the Sea (ICES). As such the models, their improvements and their implementation provides significant new fisheries and marine spatial management scientific knowledge, as well as improved management advisory methods, directly to and relevant also for the Danish fisheries industry and all stakeholders within the fisheries sector besides the ICES communities.

The MSPTOOLS work has to high extent been targeted towards model application and implementation of the methodological developments made under the project through the ICES management advisory system and community, as well as the ICES scientific community and network. The project has as such contributed significantly to a row of ICES methodological development working groups such ICES WGSFD, ICES WGFBIT, ICES WKTRADE2 and ICES WGECON, as well as provided contributions to major ICES assessment working groups such the ICES WGNSSK with published pilot studies. Under those ICES working groups, the method developments under the MSPTOOLS project have been directly presented, evaluated and discussed among other through direct project (financed) participation in those working groups. This has also included provision of specific recommendations regarding future data calls, methodological further developments and directions, application to management advice, as well as management strategies in general under ICES according to important stocks, habitats and fisheries (among other for Danish fishery).

Furthermore, the implementation of the models have been affiliated further through MSPTOOLS contributions to other EU projects covering the EU-COFASP ECOAST and EU-HELCOM ACTION projects, and not least conducting a full PhD Study co-financed between MSPTOOLS (1 year), EU-COFASP ECOAST (1 year) and a DTU Aqua internal PhD project (1 year) on further development of statistical models for coupling of commercial fishery and research survey data to describe fish stock distribution and abundance surfaces, as well as further development of a bio-economic fisheries model, in order to link the two models. This has involved direct cooperation between those projects and several contributions from the MSPTOOLS project to those projects with input to methodological reviews and improved methods. As such, the MSPTOOLS project has also been further implemented and disseminated through the international expert networks working under these international research projects, as well as implementation of the model developments under MSPTOOLS in the work conducted under those research projects.

There has been conducted three project workshops held in cooperation between the EMFF MSPTOOLS and EMFF ManDaLiS projects. One of the workshops was international and was held in association with and just after an International Conference Special Session: IIFET Conference, Seattle, USA, July 2018, (IIFET 2018 International Institute of Fisheries Economics and Trade, *https://www.xcdsystem.com/iifet/website/*). This Special Open Session was directly arranged by the MSPTOOLS and ManDaLiS Projects with invitation of stakeholders and including stakeholder perspectives. Besides initiative taking, planning, arranging, organizing, coordinating, announcing, leading and carrying through this special session directly under the MSPTOOLS and ManDaLiS Projects the projects produced the session abstract and a full scientific publication reporting of the outcomes of the session (Nielsen *et al*., 2018):

In accordance with several of the stakeholder perspectives and suggestions from the above workshops and the IIFET session there has directly in relation to the MSPTOOLS project been produced a follow up research project proposal and application (NORDFO) submitted to the EMFF project call in spring 2019. This project proposal has had a positive evaluation and is for the time being placed as number one at the waiting list for funding under the EMFF in 2019 for which final decision is pending.

1. Background and Structure of the Project

To achieve the goals of the EU Common Fishery Policy (EU CPF) of ecological and economic sustainable fishery and to meet the demands for protection of sensitive habitats under the EU Marine Strategy Framework Directive (EU MSFD), as well as to meet the demands from other marine sectors on occupation of specific sea areas for other uses under the EU Marine Spatial Planning Directive (EU MSPD), it is necessary to establish adequate management strategy evaluation tools to evaluate the impacts of the different uses of the sea in a multi-disciplinary and multi-sectoral context. Such tools are necessary to evaluate scenarios of different management strategies and effects of different management options in order to inform managers and stakeholders about the consequences and impacts of different management options.

In this context, it is among other necessary to develop and implement a robust and efficient framework tool for integrated evaluation of spatial management strategies in relation to fishing impacts that promotes sustainable and gentle, low impact fisheries towards target species, by-catch species, and sensitive marine benthic habitats, under concurrent consideration and evaluation of the cost efficiency and the energy efficiency of the fisheries. This involves development of better tools, methods and integrated models to describe the resources, the fisheries and sensitive habitats/species distribution in relation to each other and identify sustainable fishing areas and conservation areas.

To do this it is necessary to implement management strategy evaluation tools which encompass the dynamic variability in distribution and abundance of fish resources with high resolution in time and space. Also, it is necessary to integrate bio-economic management strategy evaluation tools which can evaluate fishing patterns and human behavior in fishing effort allocation with high resolution in time and space. Consequently, these tools must be highly spatial explicit and enable small scale time specific resolution in order to efficiently and realistically evaluating the integrated biological and economic effects of spatial management, and contribute to improved spatial management strategies also taking into account energy efficiency.

Furthermore, it is necessary to develop methods that to higher degree can integrate different types of available quantitative information from commercial fishery and from fisheries research surveys to better describe distribution and abundance patterns of target and by-catch fish species. This should be seen in context of a substantial proportion of EU's fish stocks lack a quantitative assessment or a robust abundance estimate and are therefore regarded as data-limited. The goal of the present project and report is, accordingly, also to provide and improve quantitative abundance estimates and improved tuning data time series for stock assessments of data-limited stocks which is a prerequisite to the implementation of the Common Fisheries Policy (CFP) and to promote sustainable fisheries. Specifically, the project addresses in this context Article 2 of the CFP stating that the objective is to achieve exploitation levels that restore and maintain populations above levels which can produce the maximum sustainable yield (MSY). This cannot be achieved without quantitative assessments and/or robust quantitative abundance estimates for the stocks.

By improving knowledge about data-limited fish stocks, the project minimises the risk of yield reductions that result from an increased precautionary buffer applied when quantitative stock assessments or robust abundance estimates are lacking. Similarly, the risk of overexploitation is minimised with the aim to prevent a subsequent potential long-term stock rebuilding period with reduction in quotas. The project has involved close collaboration with and feed-back from stakeholders within fisheries and management to ensure that the selected case studies under the project are relevant to management and the fisheries industry.

The project provides new and improved quantitative methods for evaluating stock abundances and distributions with high resolution in time and space by integrating different types of quantitative information as well as by linking biological and bio-economic models and evaluation tools. These model improvements provided by the project has a high impact and news-value to both the current and future advisory and scientific stock evaluation development work within the scientific and management advisory communities under the International Council for Exploration of the Sea (ICES). As such the models, their improvements and their implementation provides significant new fisheries and marine spatial management scientific knowledge, as well as improved management advisory methods, directly to and relevant also for the Danish fisheries industry and all stakeholders within the fisheries sector besides the ICES communities.

On basis of the results of the project and methodological developments, there has among other through ICES working groups (e.g. ICES WGSFD, ICES WGFBIT, ICES WKTRADE2, ICES WGECON, and ICES WGNSSK (Norway pout)) with project participation been made specific recommendations regarding future data calls, methodological directions, and advice and management strategies in general.

Overall, the project follows, provides improved evaluation methods of, and contribute to the evaluation of the objectives of the EU CFP (Common Fisheries Policy) with the objective of economic and ecosystem sustainable fishery according to MSY including evaluation of management measures with closed fishing areas (MPAs), improved information to fisheries management according to stock abundance (qoutas) of target and by-catch species - also involving the landing obligation objectives, - and evaluation of spatial management measures to reduce benthic impacts of fisheries (sensitive habitats) including selective spatial avoidance in the fishery. This also involves the EU MSFD (Marine Strategy Framework Directive) with respect to protection of sensitive habitats (e.g. NATURA 2000 protected areas) and sensitive habitats for fisheries to achieve Good Environmental Status (GES) – e.g. in relation to benthic impacts. Finally, it involves the EU MSPD (Marine Spatial Planning Directive) in relation to common and sustainable use of marine space, e.g. spatial and seasonal limitations in fisheries in relation to other activities.

In order to meet the above needs and requirements, the specific objectives of the project were the following:

Specific Objectives
The overall objective of the project is to provide a tool that can couple different types of data and link and further develop three advanced existing models:

- Bridging the gap between commercial fisheries and scientific survey data: exploring the full range of information to model the spatio-temporal dynamics of harvested species. That includes integrating commercial fisheries and scientific survey data.

- Improving the evaluation of fisheries management strategies by an advanced coupling of species spatio-temporal dynamics to fishing agents by linking and further development of existing models:
    - One model is a bio-economic individual vessel- and trip-based fisheries model which describes the fisheries effort, catches and economic outcome with very high resolution in time and space; it is a simulation model used for management strategy evaluation for all EU stocks and fisheries involving important Danish fishery;
    - The second is a statistical fish occurrence model which uses research survey and fisheries data on integrated basis to estimate the underlying distribution, density and overall abundance of the resources (target and by-catch fish and shellfish stocks) with similar high resolution in time and space;

On this basis further specific objectives are to:

- Evaluate fisheries impacts on selected key fish stock sustainability on local and regional scale;
- Evaluate examples of fisheries impacts on existing NATURA 2000 areas, sensitive benthic habitats, as well as areas suggested by management and stakeholders taking into consideration the biological connectivity between areas / species;
- Identify optimal fishing areas in relation to discard-reduction;
- Evaluate economic efficiency (sustainability) and energy efficiency of scenarios of effort allocation in space and time for selected gears / fishing methods / fisheries in relation to fish stock sustainability for selected stocks.

Structure of the report

According to this, the present report is structured as follows: First, the report presents the methodological developments, model improvements and case specific implementation of the models with references to the scientific reports and journal papers produced under the project. This is followed by an overview of the further dissemination of the model developments and implementation made among other through national and international stakeholder workshops and international scientific conference sessions directly arranged and made under the project as well as through the ICES advisory network.

2. Results of the project for integrated spatial and bio-economic fisheries management evaluation

2.1 Coupling commercial fisheries and survey data: a practical solution to boost the amount of information in data-poor contextommercial fisheries and research survey data

By Marie-Christine Rufener, Kasper Kristensen, J. Rasmus Nielsen, and Francois Bastardie

2.1.1 General Overview

Quantitative fish stock assessment methods have become increasingly complex. However, the quality of available data may still restrict their applicability, being a particular concern in data-poor situations and where management decisions rely on either commercial fisheries or scientific survey data. In the current study, we addressed this issue by proposing a flexible statistical tool that can compare and integrate both datasets simultaneously, while estimating and predicting abundances for a given space and time period. Here we give a summary of this full study reported in detail in a scientific paper (Rufener *et al.* 2019a) produced under MSPTOOLS. Because of the different sampling designs and procedures, distinct levels of biases arise between these data (e.g., different spatio-temporal coverages and size/age spectra of fish), and which were accounted for in our model framework. Specifically, we identified and accounted for three main differences, namely: difference in fishing effort, fishing catchability, and trawled distance. Spatio-temporal correlations were additionally considered, as their dependencies are inherent to this type of data. Moreover, we gave special attention to the correction of the preferential sampling nature of the commercial data, as this is a more serious issue that can lead to considerable biased estimates. We developed the model in Template Model Builder (TMB) where we specified a log-Gaussian Negative Binomial Process (hereafter “LGNB” model) to model count-related data with an overdispersed nature. To demonstrate its applicability, we applied the model on a cohort basis for the Western Baltic cod. We tested the LGNB model alternatively on (i) survey data, (ii) commercial data, and (iii) combined data to contrast their differences and evaluate the improvements in regards to the spatio-temporal abundance estimates and predictions. Our results from the survey model (option i) and commercial model (option ii) revealed considerable differences in cod’s spatio-temporal dynamics. Nevertheless, as expected, complementary information on its dynamics from the combined model (option iii) was reached, and yielded more precise abundance estimates. In addition, our results revealed that accounting for the preferential sampling bias of the commercial data leaded to substantial improvement in the model performance, as well as more precise abundance estimates. This confirms that the predictive modelling was greatly improved by joining the datasets and will likely enhance future stock evaluation and management advice in both data-poor and data-rich contexts. Moreover, the current tool represents a valuable benchmark for fishery-based bio-economic management evaluation tools, provided that ecological-economic systems can be reliably mocked at a spatio-temporal scale that our model support and which indeed matters for robust management and policy makers.

2.1.2 Bridging the gap between commercial fisheries and scientific survey data: insights from the western Baltic cod fishery

In many instances the quality and quantity of data dictates the analytical approaches that can be used for fisheries stock assessment. Most of the existing quantitative methods are heavily data driven and have been representing a challenge particularly for data-limited fisheries (Honey *et al.*, 2010). An intuitive alternative to overcome data shortages is to combine different fisheries data sources, *i.e.*, commercial fisheries and scientific survey data, and develop quantitative methods that can cope with their particularities.

In line with the second working package of MSTPOOLS, we approached this issue by designing a flexible and robust statistical model in Template Model Builder (TMB; Kristensen *et al*., 2016), which belongs to the general class of point-process models (log-Gaussian Negative Binomial Process, hereafter "LGNB model"). The LGNB model is essentially a *hierarchical* model where both latent and observation processes can be included. As such, it can estimate and predict the abundance of fisheries target species while simultaneously accounting for the data-specific bias sources, in addition to environmental covariates that could shape a species spatio-temporal abundance and distribution.

As the sampling design underlying each data type follows their particular objectives, distinct levels of biases arise between them. For example, scientific survey data are usually considered of superior quality due to their statistically grounded sampling designs that also covers large marine areas (Fig. 2.1.1). Nevertheless, because they rely on expensive research campaigns, data are solely collected during a few weeks per year (Board, 2000; Rufener *et al.,* 2019a), which results in a certain degree of temporal bias. In contrast, commercial fisheries data forms the backbone of many stock assessment models and provide information all year long. However, because they are commercially driven, skippers deliberately choose fishing grounds that maximizes their target catches, and hence sampling locations tend to be aggregated in space (Fig. 2.1.1).

The cornerstone in the development of such a model, thereby, is to account for such biases in order to provide the most reliable and robust abundance estimations. In our proposed LGNB model, we acknowledged and accounted for three bias sources that occur between both data sources, namely: difference in sampling effort, fishing catchability and trawled distance. As temporal and spatial dependencies are inherent to these data, the LGNB model was built such that their respective correlations are also accounted for. Additionally, we proposed an innovative approach to correct for the spatial bias that arise from the spatially aggregated sampling that typically occur in the commercial data (also referred to as *preferential sampling*; Diggle *et al*., 2010). To do so, we extended the observation process by including one additional parameter (α), which basically links the observation process to the amount and positon of the sampling unit (herein on a haul level).

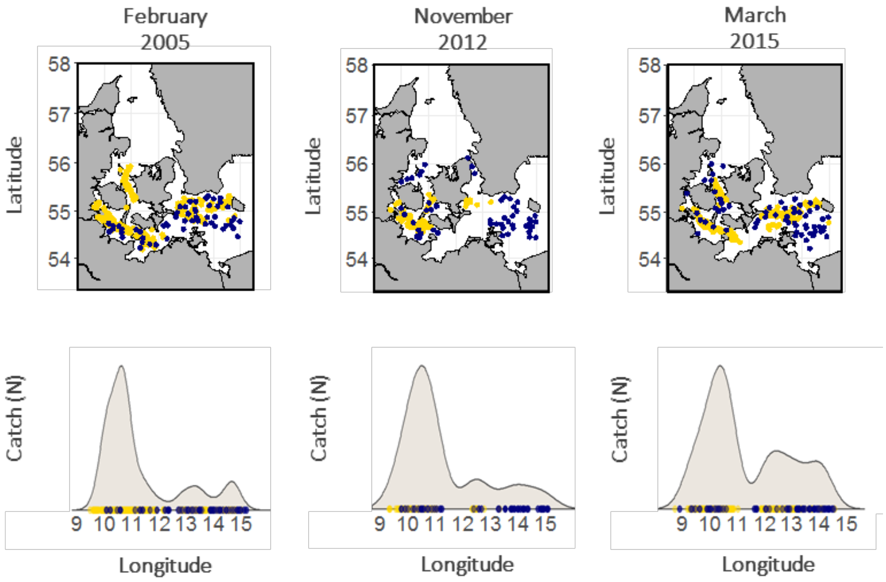

Figure 2.1.1: Example to illustrate the difference in the spatial and temporal positions of the scientific survey (blue dots) and fisheries commercial hauls (yellow dots,) during three different time frames for the Western Baltic cod stock. Lower panels represent the time-specific underlying cod abundance and highlights that commercial fisheries data tend to sample over areas with higher abundances.

The interpretation of this parameter is such that when estimated values are >0, a positive preferential sampling is indicated, implying thus that areas with high fish densities are being preferentially sampled. Conversely, values <0 indicate a negative preferential sampling, where low densities areas are preferentially sampled. Provided that the fishermen continuously adapt their fishing technologies and tactics, it should be expected that the sampling effort also changes throughout the year. To attend such changes, we provided some extra flexibility into the α-parameter such that three different levels of preferential sampling can be considered:

- Fishing effort remains relatively constant throughout the considered time-series. In this case, the model estimates only a single α-parameter, and is henceforth denoted as the MSA model (model-single-alpha);
- Fishing effort changes throughout the time series. In this case, the model estimates multiple α-parameters, one for each time-period in which the sampling effort highlights a considerable change in the effort. This case is henceforth referred as the MMA model (model-multiple-alpha);
- No preferential sampling occurs (e.g., as in the survey data). In this case the model does not estimate any α-parameter, and is referred as the MNA model (model-no-alpha);

For the purpose of this summary, we will solely focus on the Western Baltic cod stock. Yet, further case studies and examples are exposed in Rufener *et al.* (2019a).

Data for the fishery-dependent and -independent data were obtained from the Danish National Institute of Aquatic Resources (DTU Aqua) and the Database of Trawl Surveys (DATRAS; *http://www.datras.ices.dk/*), respectively, and covered only the trawl fisheries occurring in the

2005-2016 period. Due to the high data quality of the Western Baltic cod, we were able to apply the LGNB model on a cohort basis for which we defined an age-8+ group. In order to include the most recent data that were available (i.e., 2016), we choose to apply the model from 2008-2016 also as a mean to include the full range of the cohort.

For the sake of simplicity, we considered only three groups of fixed-effects, including a year-quarter effect to capture the intra and inter-annual variability, and two environmental predictors (depth at seabed and type of sediment). We then fitted the LGNB model to three data input options: (i) survey data, (ii) commercial data, and (iii) combined data (survey + commercial). In each option we tested for all possible combinations of the fixed effects, including a quadratic term for the depth effect and interaction terms. Moreover, we tested each option against the three preferential sampling correction methods in order to evaluate the improvement in the model performance. Lastly, we used the Akaike Information Criteria (AIC; Burnham & Anderson, 2002) to select the best model within each option; the smaller the value, the better the model.

2.1.3 Results

Across all three data options, the worst fit (highest AICs) was obtained for those model in which no preferential sampling correction was considered (MNA, Table 2.1.1). The lowest AIC were generally achieved for the MSA models. However, in most instances the MSA models for the commercial data could not be properly converged, and therefore we choose the lowest AICs within the MMA models. In this case, the final selected model for the survey data included the time-period and depth effect in its structure (m2 in Table 2.1.1). This model, in particular, states that the cod cohort is significantly and positively related to depth while its abundances decreases towards the end of the time-period. In turn, for the commercial and combined model, the final selected model was m5 and m6 (Table 2.1.1), respectively, which included the sediment type besides the time-period, depth (commercial model) and a quadratic depth term (combined model) as fixed effects. The interpretations for both models are similar, where the cod cohort is significantly and positively related to both depth and sediment type, with particular preference towards deeper waters and sandy bottom. However, unlike the survey model, no clear abundance pattern could be traced form the time-period effect.

The estimated α-parameter indicated clearly a preferential sampling in the commercial data. Particularly, 72% of the multiple estimated α-parameters were above 2. However, the survey data, as expected, did not reveal any preferential sampling as its estimated parameter was close to zero. When comparing the predictive abundance maps between the survey and commercial data, the results suggested that both dataset provided different information on cod's spatio-temporal dynamics (left and mid panels in Fig. 2.1.2). Nevertheless, these differences were usually well complemented by the combined model (right panel in Fig.2.1.2).

Table 2.1.1: AIC values for the Western Baltic cod 2008-cohort models. The final selected model is highlighted in bold for each input data. The asterisk for survey data refers to cases that were not applicable. Acronyms stand for: I=intercept, T=time-period, B=bathymetry (seabed depth), S=sediment type, and PSC=Preferential sampling correction.

PSC	Model		Commercial	Survey	Combined
MNA	m1	I + T	516088.0	22057.1	538242.4
	m2	I + T + B	516007.2	21933.6	538118.7
	m3	I + T + B^2	515997.1	21942.2	538112.3
	m4	I + T + S	516070.4	22064.7	538225.5
	m5	I + T + B + S	516008.5	21952.6	538126.7
	m6	I + T + B^2 + S	516000.2	21961.9	538121.7
	m7	I + T + B:S	516022.1	21972.1	538139.4
MSA	m1	I + T	456709.3	22044.8	479146.0
	m2	**I + T + B**	456238.7	**21933.4**	478597.3
	m3	I + T + B^2	456221.6	21942.0	478574.6
	m4	I + T + S	456643.2	22050.5	479084.0
	m5	I + T + B + S	456028.5	21953.4	478392.6
	m6	I + T + B^2 + S	455978.0	21962.5	478337.4
	m7	I + T + B:S	456022.3	21972.5	478382.1
MMA	m1	I + T	458938.1	*	481159.4
	m2	I + T + B	458254.4	*	480515.1
	m3	I + T + B^2	458350.8	*	480492.6
	m4	I + T + S	458860.5	*	481093.6
	m5	**I + T + B + S**	**458021.3**	*	480302.0
	m6	**I + T + B^2 + S**	458080.1	*	**480248.0**
	m7	I + T + B:S	458133.2	*	480307.6

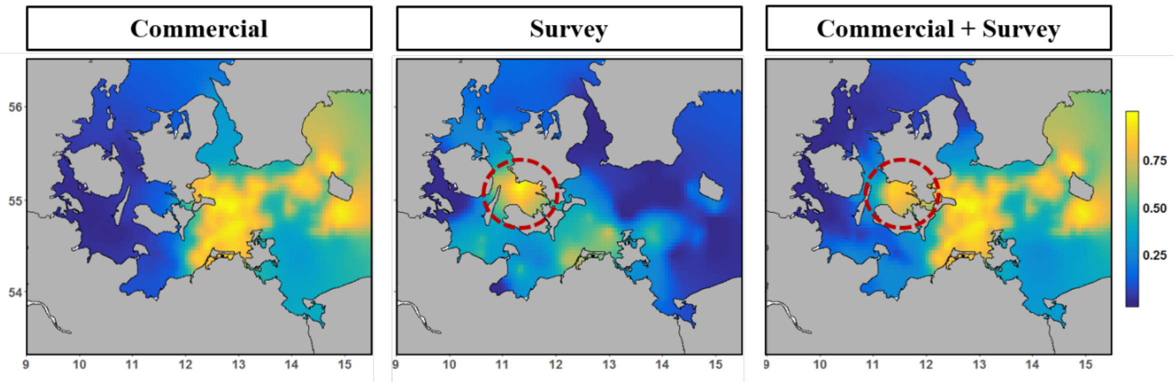

Figure 2.1.2: Snapshot of the 2008-cohort of the Western Baltic cod abundance predicted by the LGNB model during the first quarter of 2008. For better visualization, abundances have been standardized. Red circle higlights the complementarity in the combined model.

2.1.4 Concluding Remarks

By extending the time series and widening the spatial frame, the combined LGNB model was able to capture a more refined description of the spatio-temporal dynamics of the Western Baltic cod stock, and thus boosted our understanding of its dynamics. In overall, the combined model showed that the estimation and prediction of cod's abundance was greatly enhanced, and provided a good balance between the spatial prediction of both datasets. Furthermore, the results presented herein have shown that accounting for the preferential sampling of the commercial data is of utmost importance, and yielded more precise abundance estimates.

Besides being flexible in regard to the input data and the different levels of bias corrections, the LGNB model represents a valuable tool to support fish stock assessment, as well as to calibrate bio-economic models such as DISPLACE (Bastardie *et al*., 2014). The latter case is especially interesting, as it was used to attend the aims within third working package of the MSPTOOLS. It should be noted, however, that further improvements on the LGNB model will still need to be considered. This is particularly true for the description of the fishermen's prevailed sampling (hence spatial bias correction), since it depends on many behavioral aspects (*e.g*., fuel consumption, fishing regulations, distance to port, etc.), rather than solely on the sampling position as defined in the current LGNB approach.

2.2 Cost-effectiveness of the Danish fishery-dependent and -independent sampling programs

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2.2.1 Context

Fisheries management represents a complex interrelated system of costs and benefits, that demands multi-layer initiatives linked with monitoring and research programs (ICES, 2016). When setting total allowable catches (TACs) or determining the overall status of a stock, for example, data from well-designed survey programs (fishery-independent) are preferably used. However, due to their costly nature, samplings can only be conducted for a reduced time period, and has consequently implications on the sampling size and temporal coverage. Commercial fisheries data (fishery-dependent), on the other hand, are much cheaper to gather and provide data all year round (hence, larger sampling size). They are, thus, generally included in the assessment routines as a mean to tune the overall time-series (Maunder & Punt, 2004).

The costs of the fishery-dependent data collection involve basically only the staff labor related to the monitoring program and processing of the biological samples. Conversely, fishery-independent data demands additional capital investment for the operating costs (*e.g.* deployment and maintenance of the fishing vessel, fuel, etc.), besides the costs associated to the scientific and technical staff labor, and those to the processing of the biological samples. In Denmark, for instance, monitoring the Kattegat-Western Baltic Sea in 2018 was held at a total cost of DKK 1,759,117.00, of which DKK 270,710 were from the on-board observers (fishery-dependent data), and DKK 1,488,407.00 from the scientific surveys. Despite the lower costs and larger sampling size, fishery-dependent data have a serious caveat since they are a by-product of the commercial fisheries. As such, estimated abundances might not necessarily reflect the true abundance due to hyper-stability relationship, increased fishing effort, and/or fishing power (Dennis *et al*., 2015).

There is, therefore, a clear trade-off between estimating accurately abundance shifts and the sampling costs (hence, sampling size). Even though a sampling methodology that maximizes the abundance accuracy and minimizes sampling costs is often stated, the cost-benefit of these data are rarely explicitly assessed. Indeed, of the few existing studies, the cost-effectiveness is mostly conducted for the fishery-independent data (e.g., Liu *et al*., 2009; Dennis *et al*., 2015; Xu *et al*., 2015; Bellanger & Levrel, 2017). Yet, considering that both data sources are used in stock assessment routines, evaluating their trade-offs from a combined data perspective would not only represent a great benefit for the overall management process, as it would be more intuitive. Such an evaluation framework would also allow managers to assess what are the added value of including fishery-dependent data into standard stock assessment routines.

Within this context, the following summary will shortly present a cost-effective evaluation framework developed by Rufener *et al*. (In. Prep.2), and which aimed to evaluate the trade-offs between abundance accuracy, sampling size and cost under both individual and combined data perspectives. The framework was built upon the statistical LGNB model developed for the second working package of MSPTOOLS, and further coupled to a Data Envelopment Analysis (DEA) to address three questions of interest: 1) Which data is the most cost-effective, 2) Which data is the most risk-averse, and 3) which data has the optimal balance between cost and a set of uncertainty measures related to abundance estimates. As a case study, we used data from the Danish commercial trawl fisheries and international survey sampling programs carried out in the Kattegat/western Baltic Sea, with focus on cod (*Gadus morhua*), plaice (*Pleuronectes platessa*) and herring (*Clupea harengus*).

2.2.2 Study System and Simulation Framework

Among the commercially important fish species for the Danish fisheries, we selected cod, plaice and herring occurring in the Western Baltic and Kattegat waters to test our simulation framework. To estimate their abundance, we used the spatio-temporal LGNB model developed by Rufener *et al*. (In review). The model essentially provides a statistical approach to combine both fishery-dependent and –independent data, while filtering out their relative bias contributions. It can be applied on either each data individually or combined, and represents thus a valuable approach to conduct a cost-effectiveness analysis for different levels of data combination. For simplification purposes, we considered only the at-sea sampling program for the fishery-dependent data, and the first and fourth quarter Baltic International Trawl Surveys (BITS) for the fishery-independent data. For the latter case, we focused solely on the sampling conducted by the R/V Havfisken research vessel.

To simulate abundances for different data types and sampling sizes, we adapted the LGNB model such that a predefined fraction of hauls (sampling unit) could be randomly selected within the total pool of hauls of each data. We defined five fractions to select the hauls, namely: 0%, 25%, 50%, 75% and 100%. This individual haul selection is referred as a *scenario*, and the combination of the three data-specific scenarios (i.e., commercial, survey Q1, and survey Q4) leads to a so-called *sampling strategy*. Figure 2.2.1 summarizes a graphical example of the simulation framework, where a sampling strategy of 25% of the fishery-dependent, 75% of the first quarter survey, and 0% of the fourth quarter fishery-dependent data is used to estimate the abundance for a given species (we shall denote this by 025_075_0, with the first to last position indicating the selected fraction within the fishery-dependent data, first quarter fishery-independent data, and fourth quarter fishery-independent data, respectively).

The different scenario combinations yielded a total of 124 sampling strategies (5^3, excluding the case where no data is selected in none of the datasets), of which some were specific to the fishery-dependent data and others to the fishery-independent data. We used the 1_1_1 strategy (100% of all data sources) as the *baseline strategy*, where its abundance estimate was used to contrast the deviations from the strategy-specific abundance simulations. Each sampling strategy was then simulated 500 times, resulting in 500 abundance estimates per sampling strategy. For each species, we simulated the sampling strategies for two years (2016 and 2015) to further evaluate inter-annual differences.

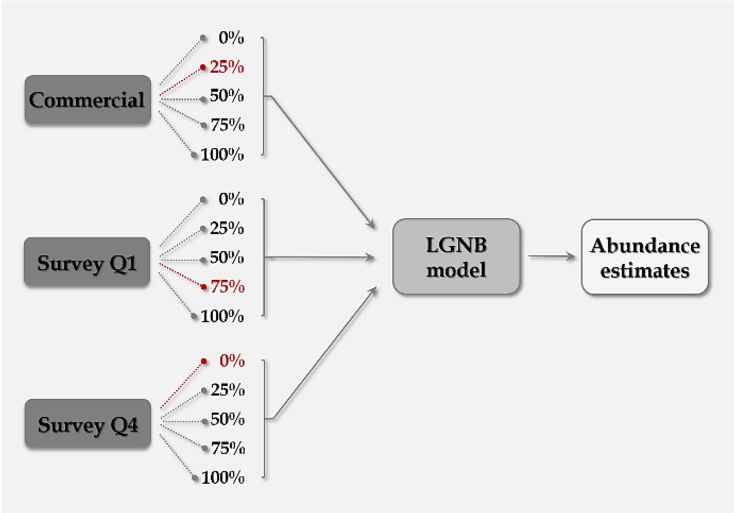

Figure 2.2.1: Schematic illustration of the simulation framework, with the red highlighted numbers denoting a hypothetical scenario selected within each data source. The combination of the three data scenarios leads to a sampling strategy, herein denoted as 025_075_0.

As a proxy for the individual sampling program costs, we used economic data derived from research budgets that were undertaken in 2018, and which were supplied by DTU Aqua. All costs were calculated in Danish crowns (DKK), and covered both fixed and variable costs. The overall research cost in 2018 were (i) DKK 270,710 for the at-sea sampling program, (ii) DKK 731,910 for the first-quarter survey, and (iii) DKK 756,498 for the fourth-quarter survey. Considering that fisheries costs are usually evaluated at the level of days spent at sea, costs of the individual sampling strategies were converted on a daily basis (total costs divided by the amount of days spent at sea). To further relate the daily costs to the actual amount of sampling (i.e., sampling strategy), we assumed that the amount of days spent at sea would be proportional to the sampling size. In this sense, a reduction of 25% of the fishery-dependent data, for example, would imply on an equivalent reduction of its sampling cost.

The cost-effectiveness of the sampling strategies was evaluated through a Data Envelopment Analysis (DEA; Charnes *et al*., 1978). In short, DEA constitutes a non-parametric approach to estimate efficiency through linear programming techniques. The idea of the method is that the efficiency of the Decision Making Units (DMUs, hereby sampling strategy) is evaluated through multiple efficiency measures, termed as inputs and outputs. Based on the best practice DMUs, the DEA establishes a *best practice frontier*, from which the relative efficiency of a DMU can be estimated by measuring its position relative to the frontier. This results in an efficiency score that can take-up values between 0 and 1, with 1 indicating full efficiency and smaller values the degree of inefficiency. To account for the uncertainty of the estimated efficiencies, we applied a bootstrapping technique that is embedded within the *Benchmarking* R-package (Bogetoft & Otto, 2018).

For the present study, four sets of inputs and outputs were used to describe the efficiency of the sampling strategies. Particularly, we considered the sampling costs, the abundance variance, and both maximum and median abundance bias. Maximum and median bias were calculated in relation to the abundance estimate provided by the baseline strategy.

Based on different input and output combinations, we applied the DEA to evaluate three different cases:

- Case 1: Identify the most cost-effective sampling strategy
    - Input: variance & median bias
    - Output: cost
- Case 2: Identify the most risk-averse sampling strategy
    - Input: variance & maximum bias
    - Output: cost
- Case 3: Identify the sampling strategy with the optimal trade-off between variance, bias and cost
    - Input: cost, variance, and median bias
    - Output: constant value of 1

2.2.3 Preliminary Results

In the following we will present preliminary results that were obtained from our cost-effective framework. The results are preliminary, as recently improvements on the LGNB model were done to improve the abundance estimates. Details on this can be read in the next section.

The simulated abundances revealed different estimates across species, year and sampling strategy (Fig. 2.2.2). In general, using the individual data sources yielded abundance estimates that were either underestimated or overestimated when compared to the baseline strategy (red, blue and beige boxplots). However, opposite effect occurred for specific data combinations. For example, sampling strategies using a set of fishery-dependent and fourth quarter fishery-independent data (light blue boxplots) achieved reasonable abundance estimates for both cod and plaice in 2016. Similarly, for herring this tended to occur in 2016 when combining fishery-dependent and first quarter fishery-independent data (light green boxplots). This was also true for some isolated cases concerning the combination of the three data sources (grey boxplots), as seen for cod in both years, and for plaice and herring in 2016. Despite these overall tendencies, the results were not consistent across years and we hypothesize that this could be due to the different amount of hauls between the years (Tab. 2.2.1).

Table 2.2.1: Number of hauls per data type, species and percentage of haul selection.

Species	% of haul selection	Commercial		Survey Q1		Survey Q4	
		2016	2015	2016	2015	2016	2015
Cod	1	72	30	60	48	65	53
	0.75	54	22	45	36	49	40
	0.5	36	15	30	24	32	26
	0.25	18	8	15	12	16	13
	0	0	0	0	0	0	0
Plaice	1	90	35	57	47	56	53
	0.75	68	26	43	35	42	40
	0.5	45	18	28	24	28	26
	0.25	22	9	14	12	14	13
	0	0	0	0	0	0	0
Herring	1	121	81	57	48	56	53
	0.75	91	61	43	36	42	40
	0.5	60	40	28	24	28	26
	0.25	30	20	14	12	14	13
	0	0	0	0	0	0	0

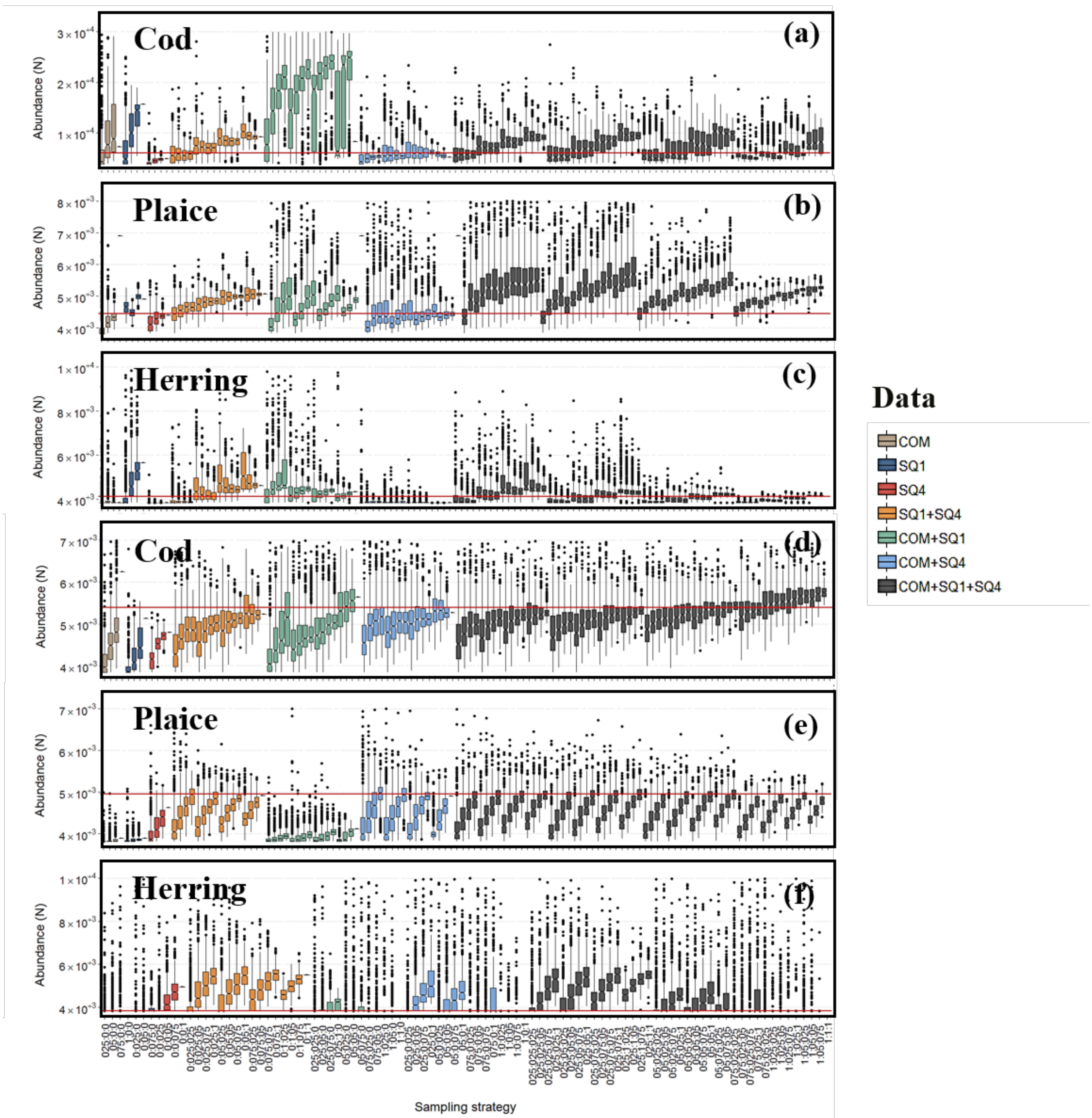

Figure 2.2.2. Boxplots of the simulated abundances for each sampling strategy contrasted to the abundance of the baseline strategy (red line). Panels a-c and d-f refers to 2016 and 2015 simulations, respectively. Data acronyms stands for: COM=commercial data, SQ1= first quarter survey data, SQ4= fourth quarter survey data.

When evaluating the coefficient of variation (cv) of the final simulated abundance as a function of the number of hauls, all levels of data combination demonstrated a decreasing trend across species and years (Fig. 2.2.3). As expected, this implies that a higher amount of hauls reduces the variability in the abundance estimates. Ideally, a sampling strategy with a cv of 10% -15% is sought (Stamatopoulos, 2002), and this was a general tendency for all types of input data and species, despite the minor differences between the years. Surprisingly, for some input data such a result could be obtained even when using a considerable small amount of hauls. For example, plaice in 2015 achieved cv's of approximately 3% for only 9 hauls (fishery-dependent data, beige line) and 12 hauls (first quarter fishery-independent data, dark blue line).

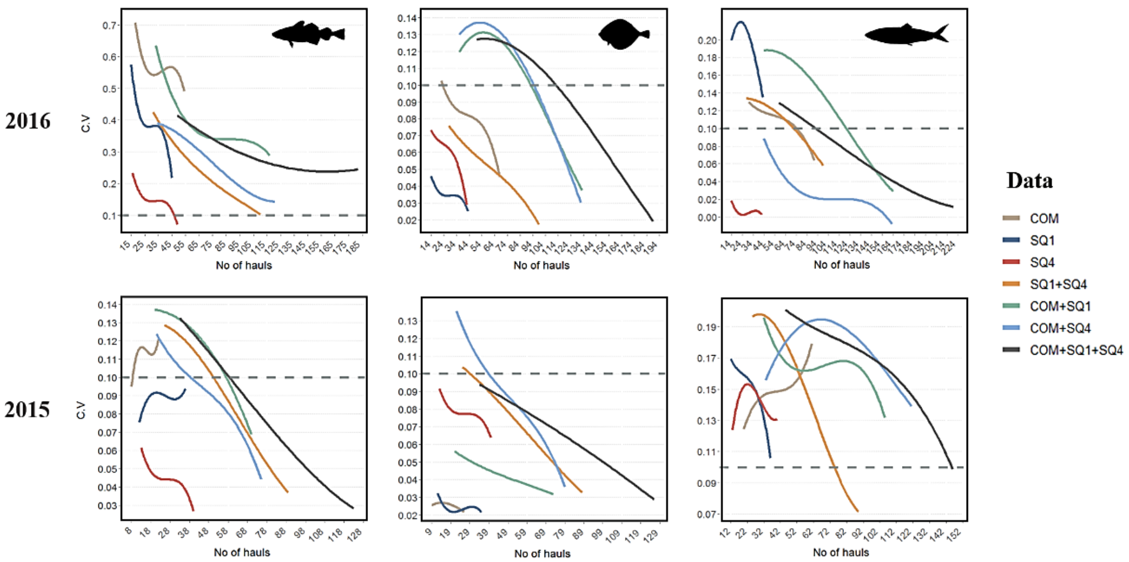

Figure 2.2.3: Coefficient of variation as a function of sampling size. Panels from left to right refers to cod, plaice and herring, and dotted grey line denotes a conservative c.v. of 10%. Data acronyms are the same as in Figure 2.2.2.

Similar to the simulated abundances, different results also emerged from the DEA across species and years (Figures 2.2.4-2.2.6). For all DEA cases and species, the efficiency of the 2015 sampling strategies was usually smaller than those of the 2016 data. Furthermore, across species, years and DEA cases, the highest efficiency scores tended to correspond to those strategies with the smallest abundance bias (i.e., abundances closest to the baseline reference in Fig. 2.2.2). For example, for cod 2016 data (Fig. 2.2.4), the most cost-effective sampling strategies (highest scores in DEA-case 1) were predominantly achieved for the strategies including either both fishery-independent data (orange circles), or for the fishery-dependent data combined to the fourth quarter fishery-independent data (light blue circles). When comparing to Figure 2.2.2 for the same year, these cases also corresponded to those with smallest abundance bias. Similar pattern could also be traced for plaice and herring. Plaice 2016 data, for example, highlighted that using either fishery-dependent combined to first-quarter data (light green circles) or to fourth-quarter fishery-independent data (light green circles) yielded the highest cost-effectiveness for the DEA-case1 (Fig. 2.2.5).

When considering the risk-averse strategies (DEA-case 2), some of the highest efficiency scores highlighted in the DEA-case 1 could be also highly risk averse. Yet, when considering the optimal trade-off between cost, bias and variance (DEA-case3), the same strategies could be still efficient, despite being risk-averse. Herring, for example, demonstrated high cost-effectiveness for sampling strategies involving either the fourth-quarter fishery-independent data (red circles), or those where fishery-dependent data is used together with the fourth quarter-fishery independent data (light blue circles) (Fig. 2.2.6). These strategies, however, were also amongst the most risk averse (DEA-case 2 in Fig. 2.2.6). Nevertheless, regardless their risk, they provided still a good trade-off between the considered efficiency measures (DEA-case 1 in Fig. 2.2.6).

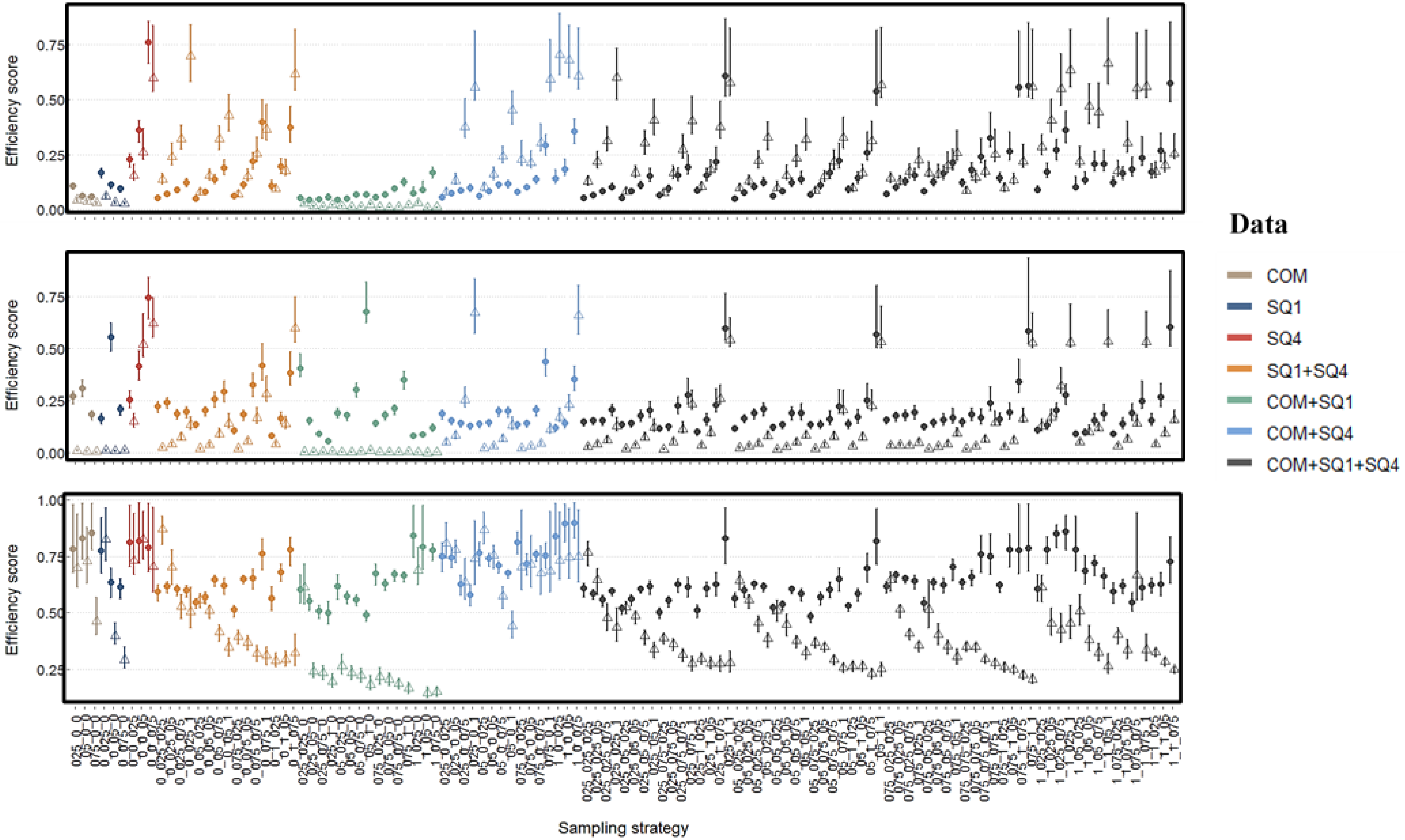

Figure 2.2.4: Bootstrapped efficiency scores with 95% confidence intervals for cod, with upper to lower panels highlighting respectively the DEA case 1, case 2, and case 3. Filled circles and open triangles refers to the 2016 and 2015 results, respectively. Data acronyms are the same as in Figure 2.2.2.

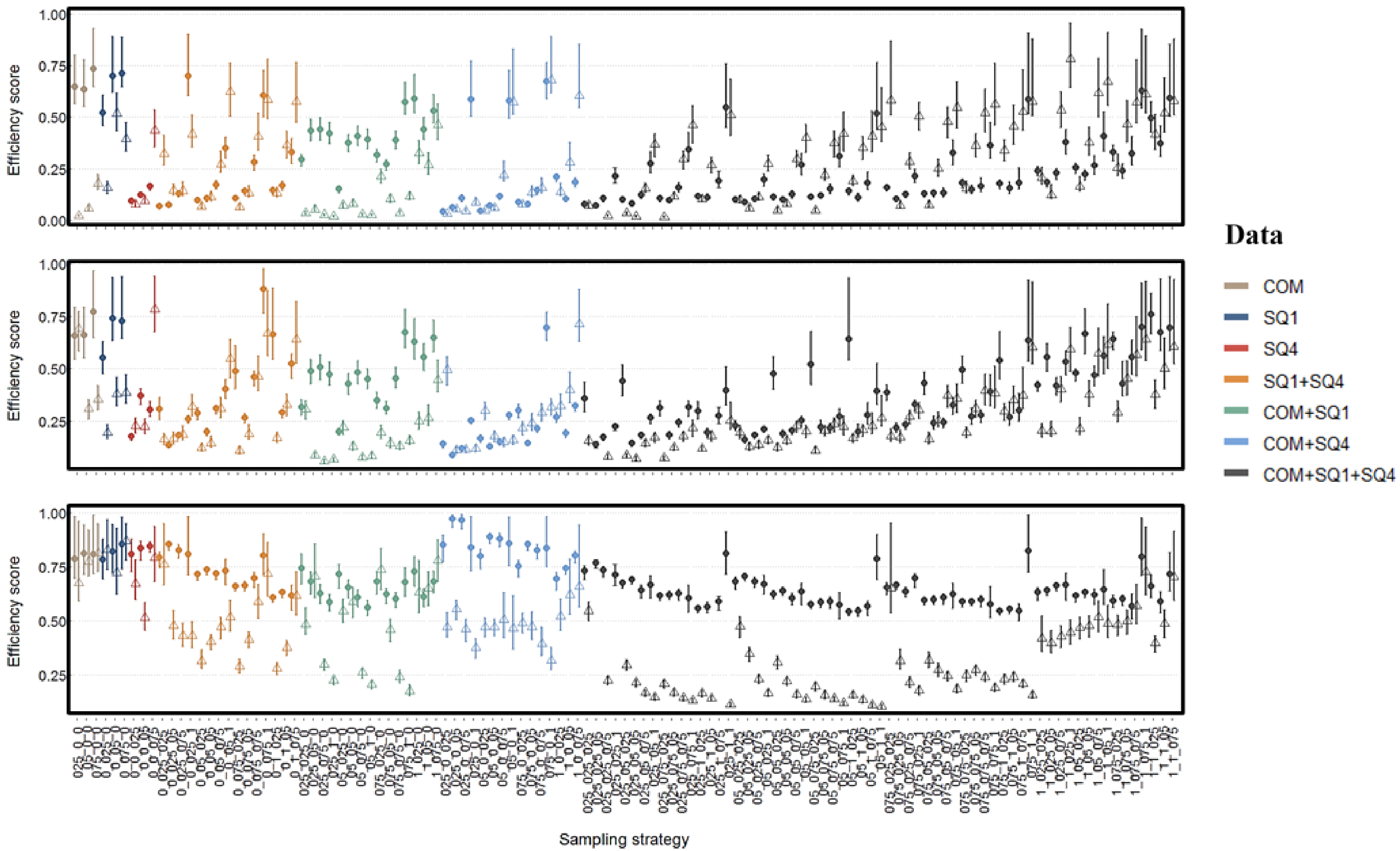

Figure 2.2.5: Bootstrapped efficiency scores with 95% confidence intervals for plaice, with upper to lower panels highlighting respectively the DEA case 1, case 2, and case 3. Filled circles and open triangles refers to the 2016 and 2015 results, respectively. Data acronyms are the same as in Figure 2.2.2.

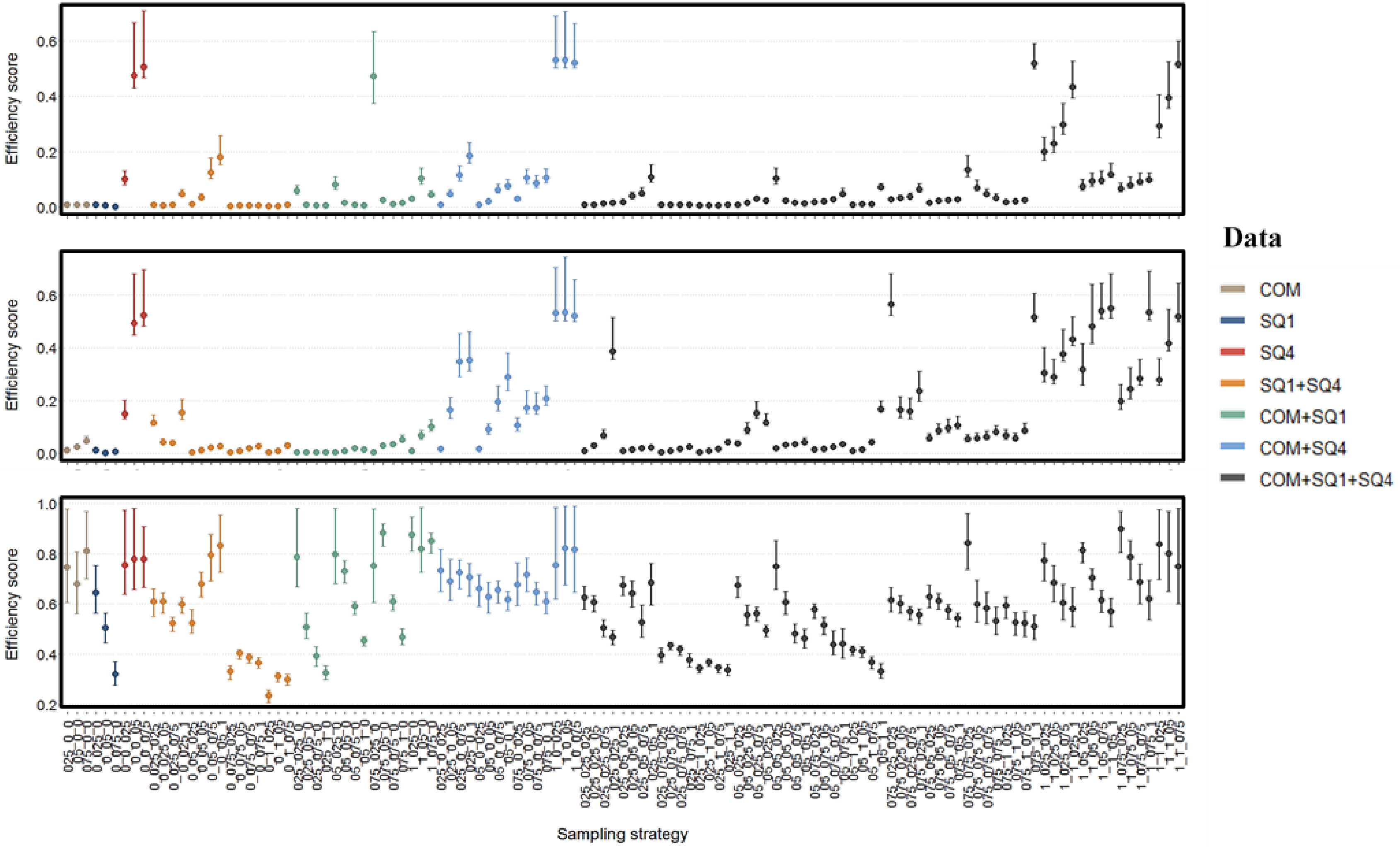

Figure 2.2.6: Bootstrapped efficiency scores with 95% confidence intervals for herring, with upper to lower panels highlighting respectively the DEA case 1, case 2, and case 3. Results are only shown for 2016 data, as bootstrapped efficiencies could not be computed for 2015. Data acronyms are the same as in Figure 2.2.2.

2.2.4 Concluding Remarks and Future Perspectives

The present study aimed to explore the cost-benefit of the Danish fishery-dependent and –independent monitoring programs. To our current knowledge, this represents indeed the first attempt to evaluate the overall trade-offs between both data sources, and despite the preliminary results, several practical conclusions can be drawn and future research suggested.

First, the proposed framework highlighted that careful considerations needs to be set when evaluating the cost-effectiveness of both data sources. In general, our results revealed that the conclusions depended not only on the evaluated species, as well as on the considered year. This could be likely related to the fact that the sampling sizes between years and species were not the same. Moreover, as inter-annual abundance fluctuations are naturally expected, the cost-effectiveness of a given sampling program might be driven by these abundance shifts. This is especially true for the fishery-dependent data, as the sampling locations can be drastically different from one year to another. Liu *et al*. (2009) proposed an alternative metric to evaluate the change in the performance statistics at different sampling sizes. Denoted as the *accuracy changing rate* (ACR), their metric essentially represents a ratio between the difference of the performance statistics and the difference in the sampling size:

$$ACR = \frac{(PS_1 - PS_2)}{(N_1 - N_2)}$$

where N_1 and N_2 are two different sampling sizes and PS_1 and PS_2 their corresponding performance statistics. In the present context, we could adapt the ACR such that the median/maximum bias could be evaluated in regards to the sampling size between different years. This could provide a practical solution to interpret differences between years.

Second, the cost-effectiveness is likely to be affected by the chosen reference sampling strategy. Herein, we considered as a reference the strategy including 100% of all three data source, and was consequently used to calculate the median and maximum bias of all sampling strategies. However, if another reference level is chosen (e.g., using only the full set of the fishery-independent data), the results can potentially differ from the present study. For upcoming research, we will evaluate the sensitivity of the results when using the full set of survey data as a reference.

Third, in this preliminary investigation, the abundances were calculated by taking the annual mean abundances that were predicted on a spatial grid (referred to as an *abundance field*). This approach, nevertheless, does not implicitly correct for the fishing catchabilities that were considered in the LGNB model; hence, estimated annual abundances might not correctly reflect the actual abundance. This is an issue we recently became aware of, and efforts to improve the LGNB model were already provided. At the current date, all simulations are being conducted to re-estimate the abundances.

Fourth, the used framework provides a set of flexibilities that makes it applicable to a wide range of case studies, including the general field of Ecology. By doing so, however, the results will mainly reflect the chosen data, and hence conclusions will be restricted to the specific applications. This is so, as the random haul selection results in different sampling positions (thus abundance signal) being selected in each simulation, and therefore different abundance fields will be predicted by the model. To obvious reasons, this will influence the calculated annual abundance that were used in the present study, and therefore results cannot be straightforwardly compared between different years, even within the same case study. One way to explore further our framework could be through a pure simulation study. In this case, one could simulate yearly abundance fields while keeping the sampling positions of all data types fixed across years. Albeit this is not necessarily a realistic assumption, comparisons across years would be much more intuitive to interpret.

Fifth, when using solely the coefficient of variation (cv) as a relative index of variability, as presented in Fig. 2.2.3, it is difficult to determine whether the lowest cv corresponded in fact to the lowest abundance bias. This can be overcome by including an additional variability metric into Fig. 2.2.3 to highlight the “center of gravity” of a given data-related curve. To do so, we will investigate the amount of hauls that corresponded to the lowest bias in each data-specific sampling strategy, and indicate this explicitly in Figure 2.2.3.

Lastly, it is important to note that this study does not aim to propose current or any future level of expenditure for the Danish government, nor changes in any of the current sampling designs, or even suggest the use of one data in detriment of the other. Instead, we simply aimed to demonstrate a practical guidance tool that can be used to evaluate the costs and benefits of the fishery-dependent and –independent sampling programs.

2.3 **Improving the evaluation of fisheries management strategies by an advanced coupling of species spatio-temporal dynamics to fishing agents**

By Marie-Christine Rufener, J. Rasmus Nielsen, Kasper Kristensen, and Francois Bastardie

2.3.1 Context

Fisheries management constitutes a complex and time-consuming process that is driven by managers´ multiple and often competing objectives, divergent interests among stakeholders, and high uncertainty on the natural resources´ dynamics (Smith *et al*., 1999). Due to the continued improvement of computational power, management strategy evaluation (MSE) approaches have gained considerable ground among fisheries scientists in the later decade (Schnute *et al*., 2007; Bunnefeld *et al*., 2011). By relying on expensive simulation techniques that models several aspects of the adaptive management cycle, MSE has been providing critical lenses to compare alternative strategies under the multifaceted management objectives. As such, they constitute a valuable tool to clarify and balance trade-offs between these objectives, and consequently identify the best outcomes for a successful management implementation (Sainsbury *et al.*, 2000; Punt *et al.*, 2001; Holland, 2010).

DISPLACE (www.displace-project.org; Bastardie *et al.,* 2014) represents such an evaluation platform and was mainly developed to support marine spatial planning (MSP) and fisheries-related management issues through an underlying agent-based simulation model (Bastardie *et al.,* 2015; 2017). The model simulates individual fishing vessels (hereby fishing agents) as a function of individual incentives and the availability of fisheries´ resource, and further projects scenarios of alternative harvest control rules with the consequent redistribution of fishing effort.

Moreover, it allows a detailed evaluation of the fisher´s decision making process when confronted to particular management plan, together with the economic viability related to these decisions and conditions of the underlying stocks (Bastardie *et al*., 2014).

In its current set-up, the fishery resource availability is informed through scientific research survey data. For each quarter, stock, and size-group, the abundance is interpolated within a radius circle (*e.g*., 50 km) by means of the inverse distance weighted (IDW) method (Bastardie *et al*., 2014), resulting in a so-called *abundance field*. Despite the advantages of using research survey data are often stated, the samplings are usually conducted during a few weeks per year, imposing therefore serious limitations in regards to the temporal coverage and consequently hampering the precise capture of a species seasonal biological cycle and distribution pattern (Pennino *et al.*, 2016; Rufener *et al.* 2019a and references therein). In DISPLACE the initial abundance field of the relative stock distribution is provided on a semester basis, where the information on the first and second versus third and fourth quarter are pooled together (Bastardie *et al*., 2014). As the uncertainties associated to the time and space resource availability is likely to affect the outcomes of the fisheries management plan under concern, a higher reliability of the MSE simulations is expected be achieved when using more detailed and high resolution input information on the stock abundance fields. This, in turn, would provide both more reliable simulations and robust management advice.

To sidestep data limitations and capture a species´ full distribution range, Rufener *et al*. (2019a) proposed a flexible and robust abundance predictive statistical model (log-Gaussian Negative Binomial process model, hereby LGNB) where multiple fishery-related data sources can be combined. Briefly, the LGNB integrates both commercial fisheries and scientific survey data while accounting for spatio-temporal correlation and differences in fishing catchability and effort. In doing so, a complete picture of a fishery target species is provided, where its spatio-temporal abundance dynamics can be tracked according to the user´s pre-defined spatial and temporal scales (referring to chapter 2.1 in the present report for a preview).

In line with the third working package of MSPTOOLS, *i.e*., developing a set of analytical tools that could be coupled in an integrated framework, the present project aimed to integrate the LGNB model into DISPLACE. This is reported in detail in the scientific paper Rufener *et al.* (In Prep.2) to be submitted for a high ranking scientific peer reviewed journal in early 2020, and the current report with the same title is a summary of the results obtained from here. For the purpose of this project, a quarterly time-window for a 12-year period (2005-2016) and spatial resolution of 5 km was defined, meaning that the LGNB model provides much more refined information in both spatial and temporal terms than DISPLACE´s initial set-up. The ultimate goal of this integrated framework is to allow fisheries scientists and managers to perform robust and reliable evaluation of different spatial management strategies that fully cope with the EU´s CFP, MSFD, Blue growth, and EAFM objectives. Below the coupling procedures are shortly described, the main challenges highlighted, and the future perspective discussed.

2.3.2 Coupling LGNB model to DISPLACE

DISPLACE is built upon a set of interrelated functions that links the vessels dynamics to the population dynamics of commercial important fish species (Bastardie *et al*., 2014). A cornerstone of this simulation framework is the so-called *harvest function* that aims to mimic the stock depletion by the individual vessels. To do so, a Generalized Linear Model (GLM) using a Negative Binomial distribution is applied to model the landing-per-unit-effort (LPUE, rounded to the nearest integer). The LPUE is described as a function of vessel (v), métier (m), and the stock-specific abundance (s), with the latter being further expressed in terms of its size-specific availability and the métier-gear selectivity. Thus, for a given stock, the general model structure is summarized as:

$$LPUE_{s,v,m} \sim NB(\mu, k)$$

$$\log(\mu) = \eta = \beta_1 \text{Vessel} + \beta_2 \text{Métier} + \ \beta_3 (Availability\ x\ Selectivity)$$

where μ denotes the expected LPUE that is linked to the linear predictor η throguh a log-function, k is the overdispersion parameter, and β_{1-3} are the predictor-specific regressors.

The size-specific stock availability term in the above equation relates to the abundance fields that are informed by the scientific research surveys, and represents the key element for the LGNB model coupling to DISPLACE. In this sense, a first step for the coupling procedure is to replace the research survey informed abundance fields by those provided by the LGNB model. To align with DISPLACE´s default configuration of having the abundance fields on a stock and size-group level, the LGNB model had to be applied independently for each stock and on the same size-groups as defined in DISPLACE. For example, cod stocks from the Western Baltic Sea are divided into 14 size groups; meaning that 14 LGNB models had to be run for this particular stock (Fig. 2.3.1).

The simulation of the vessel dynamics in DISPLACE is done through an underlying fishing arena, which basically constitutes a spatial grid whose vertices (also called nodes) are used for the vessel movement and the fishermen´s decision (Bastardie *et al*., 2010; Bastardie *et al*., 2014). Thus, once having the stock and size-specific abundance fields provided by the LGNB model, the next step of the coupling consisted in extracting the abundances for the same spatial coordinates as those of the DISPLACE´s fishing arena nodes (Fig. 2.3.2). Provided that each DISPLACE node contains the information on the total abundance of a stock disaggregated into its respective size-proportions (Bastardie *et al*., 2014), the LGNB informed abundances had also to be converted into size-proportions per location (summing to 1 for each stock over all the stock-specific locations).

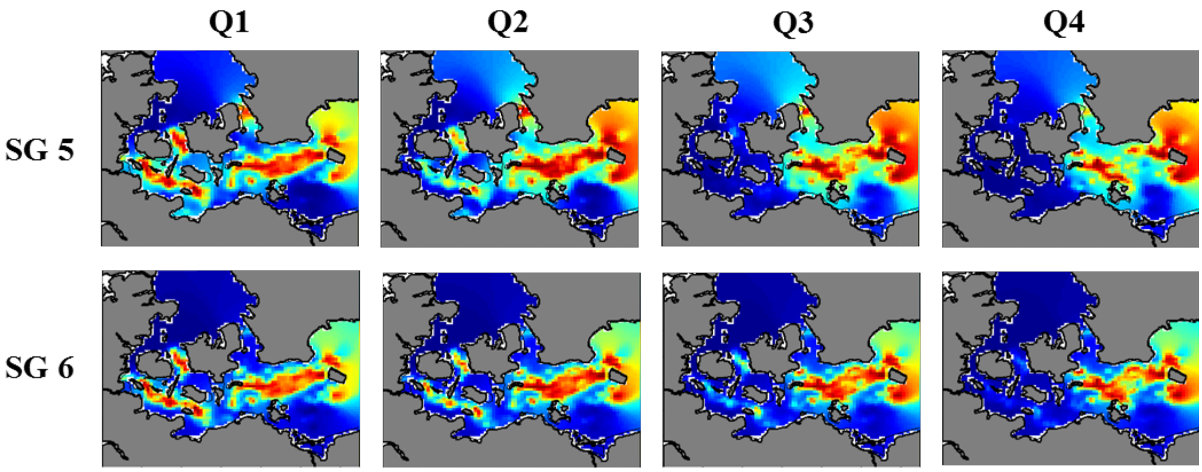

Figure 2.3.1: Illustration of the abundance fields provided by the LGNB model, highlighting an example for size groups 5 (200-250 mm) and 6 (251-300 mm) of the Western Baltic Cod stock for all quarters of 2016.

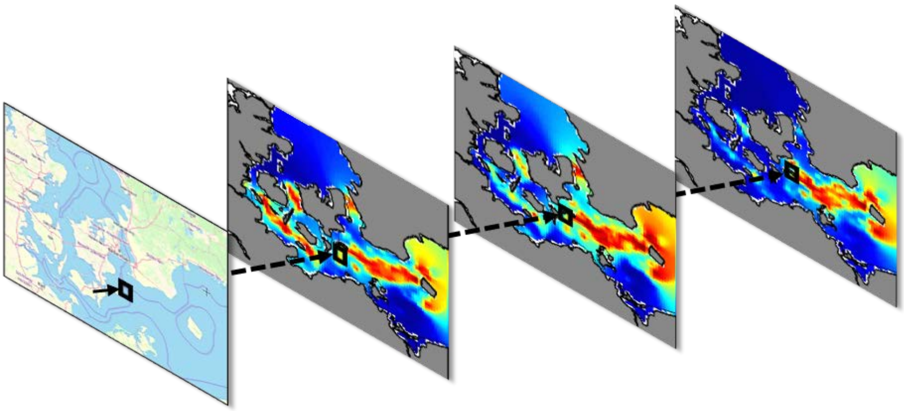

Figure 2.3.2: Schematic figure to illustrate the abundance extraction from the LGNB models correspondent to the same spatial coordinates as those from the DISPLACE´s fishing locations.

The above mentioned coupling consists of a real-time coupling, in the sense that DISPLACE can be informed with species abundance until the present time-frame. Nevertheless, because MSE approaches also seek to examine possible future scenarios, we adapt the coupling for a predictive mode. Since predictions are an inherent feature of statistical models, the LGNB model can also estimate and predict abundances for a future time step. Compared to simpler statistical models that do not consider spatial and temporal dependencies, the strength of the LGNB model is that the forward-predictions in both space and time can be done with much higher confidence, as the spatial and temporal correlation parameters are explicitly taken into account. Thus, for each considered stock and its respective size-group, four main model components had to be retrieved, namely: (1) the predicted abundances for each time-step, (2) the estimated spatial correlation parameter (summarized by two parameters, delta $\boldsymbol{\delta}$ and scale $\boldsymbol{\kappa}$), (3) the estimated temporal correlation parameter (rho $\boldsymbol{\rho}$), and (4) the precision matrix $\boldsymbol{Q}$ that corresponds to the inverse of the covariance matrix of the spatio-temporal random effect.

In order to use these components for the forward-predictions, a multivariate Gaussian random distribution function (hereby *rmvnorm* function) had to be developed (Appendix A). This is so, as the spatio-temporal correlation parameters in the LGNB model are assumed to be drawn from such a distribution and which is necessary to reconstruct the underlying latent field (also known by Gaussian Random Field in the spatial statistical literature). The function is essentially described by the mean of the predicted abundance field in time $\boldsymbol{t}$, and the precision $\boldsymbol{\psi}$ of the full space-time field. The calculation of the precision is described as:

$$\psi = Q\kappa\sqrt{1-\rho^2}$$
$$Q = Q_0 + \delta I$$

where Q is the sparse precision matrix that is related to the initial sparse matrix Q_0, I its diagonal matrix, and δ the spatial correlation delta parameter. Once applying the necessary LGNB model components into the *rmvnorm* function, a new abundance field is predicted for one time-step ahead, $\boldsymbol{t+1}$ (Fig. 2.3.3). If abundances are to be predicted for further time-steps, say $\boldsymbol{t+2}$, then the *rmvnorm* function needs to be applied for the abundances of the precedent time-step, $\boldsymbol{t+1}$, while keeping the other parameters constant.

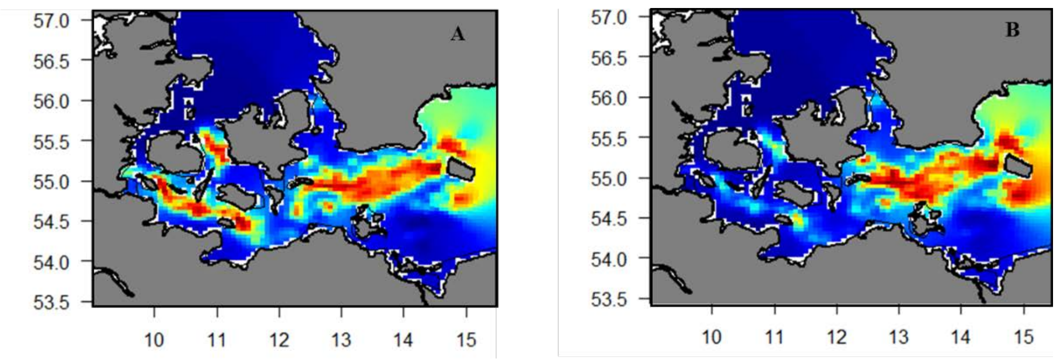

Figure 2.3.3: Example of the forward predictions for the Western Baltic Cod stock. While panel A shows the abundance field for the last time period (fourth quarter of 2016), panel B illustrates the abundance predicted for one time-step ahead (first quarter of 2017).

2.3.3 Challenges and future perspectives

The present project attended the aims of the third MSPTOOLS work package, except for full application of the developed methods into concrete case studies. The main reason for the latter was because many of the MSPTOOLS aims and tasks were strongly interrelated with respect time dependence on each other; thus, any delays experienced in one of those resulted in delays of the subsequent tasks. The model calibration and data compilation within the second MSPTOOLS work package, for example, went through severe delays especially what concerns the gathering of the different data sources that were necessary for the LGNB model. Furthermore, the development of the LGNB model revealed to be much more complicated than initially thought, as pooling commercial fisheries and scientific research survey data into an integrated model demanded several high-level and innovative statistical skills (referring to chapter 2.1 in the present report for a preview). Despite the severe challenges in work package two were overcome and the aims achieved, it should be noted that much more efforts and resources needed to be allocated into this than originally anticipated and, accordingly, the deliverables were delivered at a much later stage in the project time schedule than planned.

Regarding particularly the LGNB model coupling to DISPLACE, two main challenges were found. The first was in regards to the size of the LGNB model outputs and which hampered some of the coupling R-script routines. Spatio-temporal statistical models are naturally computationally demanding and keeping their correlation matrices to forecast abundances greatly increases the output file size, especially if the model is applied on a very fine spatial and temporal resolution as it was the case here. For instance, the LGNB model had a spatial and temporal resolution of 5 km and quarterly time-steps, respectively, and was then applied for each stock and size-group along a 12-year time series (2005-2016), yielding an output of roughly 3 GB for each considered case. The second major challenge was related to the forward abundance predictions. Although statistical models have the advantage of predicting events, their predictive ability decreases the further in the future one goes. This is also true for the proposed LGNB model, where even medium to long term predictions (say 5-10 year-time) are masked by high uncertainties. In this sense, it is usually advised to stay within save prediction limits and which are usually set to 1-2 years ahead the considered time-frame.

The LGNB-DISPLACE coupling constituted only a first-level coupling since currently only the LGNB model informs DISPLACE. An ultimate ambition, however, would be to have a full-feedback dynamic (cyclic) coupling, such that the fishery depleted abundance fields from DISPLACE would be used as an input in the LGNB model, and together with recent dataset, have the abundance fields accordingly updated. This kind of dynamic coupling will possibly imply in substituting DISPLACE´s *harvest function* by the LGNB model itself, and could result in a more automatized, faster and efficient coupling routine. However, it should be stressed that the full integration might also require to further adapt the LGNB model structure in order to account for the fishing mortality that is imposed by the DISPLACE vessel simulation. This would ultimately allow to perform concrete validation checks, where the DISPLACE simulations could be contrasted to real case studies, and hence its predictive quality evaluated. While further improvements in the coupling routine is aimed, a manuscript for this first-step coupling is made, where the results from the non-coupled and coupled DISPLACE versions are contrasted and compared for publication in a scientific peer reviewed journal.

2.4 Results from project contributions to the ICES Working Group on Spatial Fisheries Data (ICES WGSFD 2018)

By Marie-Christine Rufener

2.4.1 Introduction, Background and State-of-the-Art

A more comprehensive understanding between marine ecosystems and fisheries can be achieved through spatially-indexed fisheries data, *i.e.*, data including the geolocations of the fishing hauls. They typically allow to describe the spatial and temporal dynamics of the different fishing activities, and potentially their ecological footprint therein. As these data can provide several types of indicators defined in both the Marine Strategy Framework (MSFD) and Common Fisheries Policy (CFP), the analysis and use of this kind of data has faced an increased demand from the European Union (EU) member states to support some of their maritime policies.

The most commonly used data for such purposes are the Vessel Monitoring by Satellite (VMS) and logbook data. While VMS data provides information mainly on the spatial location, heading and vessel speed for all vessels above 12m at a 1-2h poll rate, the logbook data supplies information on the fishing operation and vessel-related aspects, such as gear type, amount of landings, engine power and vessel size (Hintzen *et al*., 2012). By coupling these datasets, the description of the fishing impact on marine habitats can be considerably improved due to its refined spatial and temporal resolution.

Within this context, the ICES Working Group on Spatial Fisheries Data (ICES, 2018: ICES WGSFD, https://www.ices.dk/community/groups/Pages/WGSFD.aspx) was formally formed in 2013 with the main purpose of achieving not solely reliable estimates on the spatial distribution on of fishing effort, as well as for developing robust methods that can provide a set of different indices related to fishing intensity, seabed pressure, among many other indicators. The ICES WGSFD-2018 (ICES, 2018) was part of the annual meeting of a three-year cycle (second cycle started in 2016), on which the participants discussed previous Terms of Reference (ToRs) that included the product delivery to OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic). Moreover, all participants worked on remaining ToRs and established new reference terms to be included for third 3-year ICES-WGSFD cycle to be started in 2019.

In the latter case, the discussion on new ToRs included, among many others, the description of fisheries spatial conflicts in regards to the displacement of their fishing activities along different time-scales in both past and future scenarios, where the main conflict-drivers will also be identified. The inclusion of this particular ToR was mainly motivated by the existing bio-economic modelling platform DISPLACE (Bastardie *et al*., 2014; www.displace-project.org), also extensively used within the MSPTOOLS project, since it can simulate individual fishing vessels as a function of individual incentives and resource availability and hence shed insights on possible spatial fishery conflicts.

As MSPTOOLS established a set of robust and reliable frameworks to be used for an integrated evaluation of spatial management strategies, the participation on the ICES WGSFD-2018 seemed therefore productive for the working group, as well as an appropriate place to disseminate further some of its work tasks, also because they could likely be used by the working group within the upcoming 3-year cycle. For example, preliminary results related to the development of a robust statistical model (hereby termed as LGNB; Rufener *et al.,* 2019a) that can compare and integrate simultaneously scientific survey and commercial fisheries data on a very fine spatio-temporal resolution was presented, and highlighted that its use can provide more precise abundance estimates of fisheries-target species. Moreover, first insights to the attempt of coupling the LGNB model to the DISPLACE framework was shown. Extra emphasis was given on the aspect that the coupled set-up will contribute for a better understanding of fish and fleet dynamics, and consequently provide a more effective decision-supporting tool to evaluate systematically the trade-offs among the ecological-socio-economic system.

Lastly, besides disseminating the MSPTOOLS projects, additional contributions from both MSPTOOLS and ECOAST projects were made to the ICES WGSFD-2018. This involved mainly the ToR "*J*", where it was aimed to quantify and explain the spatio-temporal variability of fishing fleets across ICES areas (ICES, 2018). To do so, a basic spatio-temporal statistical model was developed and which is described in more details below.

2.4.2 Quantifying the spatio- and temporal variability of fishing fleets – a case study for the otter trawl fisheries in the North Sea

The proposed model belongs to the class of Hierarchical Bayesian Spatial Model (HBSM). In such a framework it was assumed that the fishing effort (thereafter calculated as the number of hours that a vessel spent at sea fishing) at nearby locations (s) and time intervals (t) are more similar than those more far apart; thus, spatial and temporal dependency are explicitly modelled as the fishing effort (i) is indexed by a space-time dimension. It also allows to include a set of covariates that might drive the spatial and temporal variability of fishing effort. Among the covariates that could affect the fishing effort, the following were discussed to be relevant for the addressed context: distance to coast, bottom positioning index, natural disturbance rate, type of sediment, bottom temperature, bottom salinity, primary productivity and oil price.

The overall structure of the HBSM is similar to a Generalized Linear Model (GLM), where the relationship between the response variable Y_i and a set of covariates X_i is described through a linear predictor η_i. The linear predictor is, in turn, linked to the mean of the response $E(Y_i) = \mu_i$ by means of a link function $(\cdot)$, such that $g(\mu_i) = \eta_i$. As such, the general model structure can be summarized by:

$$\eta_{s,t} = \beta_0 + \sum_{m=1}^{M} \beta_m X_m(s,t) + \xi(s,t)$$

where β_0 is an intercept vector; β_m a design matrix quantifying the fixed effect of the considered covariates X_m, and ξ represents the spatio-temporal structured random effect.The $\xi(s,t)$ term was considered as a Gaussian Random Field (GRF), which reduces to a multivariate Gaussian distribution (MG) with mean zero and covariance matrix $\mathbf{\Sigma}$ when evaluated at a finite set of locations:

$$\xi(s,t) \sim MG(0, \Sigma)$$

The covariance matrix was considered as separable random field process, where its variance is decomposed into a spatial covariance (following a Matérn distribution) and temporal covariance (following an Autoregressive process of order 1 – AR1).

Since the model was built under a Bayesian perspective, all parameters are treated as random variables where their estimations are achieved through marginal posterior distributions. To do so, the Integrated Nested Laplace Approximation (INLA) methodology and respective R-package is used (www.inla.org) to both build the model and estimate its parameters. No prior knowledge on the covariates existed, and therefore default non-informative priors for all fixed-effect parameters were assigned as recommended by Held *et al.* (2010). To predict the fishing effort across the North Sea, the study area under concern was divided into a triangular mesh (Fig. 2.4.1). The construction of the mesh is an important step and deserves careful consideration, as it will be used to project the predicted values. Hence, it is paramount that the triangles have relatively regular shapes and sizes (Lindgren *et al*., 2011). Furthermore, since the variance becomes twice as larger at the border when compared to the main domain, the mesh should be extended beyond the study area to overcome the boundary effect issue (Lindgren & Rue, 2015; Krainski *et al.*, 2017).

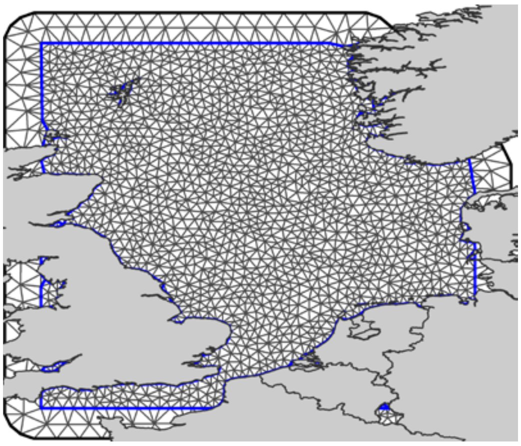

Figure 2.4.1: Triangular mesh created for the North Sea.

2.4.3 Conclusions and future perspectives

Although the MSPTOOOLS contributions were well and positively received by the ICES WGSFD-2018 participants, the proposed NBCP model could not yet been applied by the working group as further improvements had to be done and because it also required a set of different data sources that were not all available by the time of the meeting. Similarly, the coupled LGNB-DISCPLACE set-up could not be used since it was still under development. However, this work is ongoing, and the ICES working group showed high interest towards both proposed frameworks and which could potentially be used to address their future ToRs, including the ToR mentioned in the first section. As both frameworks were considerably improved by the time of their first presentation at the meeting, it is noteworthy that if indeed used by the working group, a proper introduction on how to apply them and relate to different case-studies will have to be provided. Therefore, it is likely that collaboration will be made and disseminate even more the outcomes of the MSPTOOLS projects in the near future.

2.5 Results from a pilot project coupling fisheries and research survey information for spatial fisheries management evaluation: Opening of the Norway pout box: will it change the ecological impacts of the North Sea Norway pout fishery?

By J. Rasmus Nielsen, Matthieu Bigné, Thomas Thøgersen and Francois Bastardie

In an initial pilot study under the MSPTOOLS project we combine fishery-independent research survey information on catch rates as well as commercial fishery catch and effort information from the targeted Danish Norway pout fishery in integrated analyses with very high spatial resolution to evaluate spatial fisheries management measures in form of a specific fishing closure. Specifically, we look at species composition, species-specific distribution, and density patterns according to fish size in the different areas covering the northern North Sea including the Norway pout box fishing closure area and the surrounding region. On this basis, the pilot study showed that, by coupling and integration of commercial fishery and research survey information, we were able to provide new knowledge about the environmental impacts of the Norway pout fishery and the ability of the Norway pout box fishing closure to limit bycatch levels of other species and their juvenile stages along different types of benthic habitats.

The small-mesh Norway pout (*Trisopterus esmarkii*) fishery intensified in the northern North Sea during the 1970s. Concerns about juvenile gadoid bycatch led to the "Norway pout box" closure along the Scottish coast in 1977. To assess the justification of the box today and the potential current impacts of opening the box, we evaluated the closure effects on selected fish stocks by analysing high-resolution research survey and commercial fishery data. The species- and size-specific distribution patterns in relation to environmental influencing factors are analysed for Norway pout and important bycatch species inside and outside the box. Relative distribution of benthic habitats was compared between inside–outside areas according to fish occurrence and fishery spatial footprint. No area differences in fish size composition were observed. However, species abundance depends significantly on benthic habitat and depth whose area distribution is not homogenous. The current fishery is mainly in deeper, muddy seabeds. Haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) density is higher in shallow and sandy habitats, with a relatively larger area coverage inside the box. If a box opening implies relatively more fishery in those habitats, then increased bycatch can be expected. Consequently, closure of certain benthic habitats may instead be better management, opening new fishing opportunities without risk.

This pilot study led to publication of a scientific paper under the MSPTOOLS project in a high ranking international scientific peer reviewed journal, and we refer to the detailed results of the project published herein: Bigné, M.*, Nielsen, J.R.*,[1], and Bastardie, F. 2019. Opening of the Norway pout box: will it change the ecological impacts of the North Sea Norway pout fishery? ICES Journal of Marine Science 76 (1): 136-152, http://dx.doi.org/10.1093/icesjms/fsy121 (*Authorship equal. [1]Corresponding author). The results from the development, investigations and application of this pilot study method of coupling commercial fishery and research survey data for making management strategy evaluation of a spatial management measure exemplified by the fishing closure (MPA) of the Norway pout box are also directly relevant to and integrated into the stock assessment and management advice under the ICES WGNSSK Assessment Working Group for this stock with high importance for Danish fishery.

2.6 Model Developments and Applications into the ICES Scientific and Management Advice Working Groups

By J. Rasmus Nielsen, Marie-Christine Rufener, Kasper Kristensen and Francois Bastardie

2.6.1 Implementation of Models into the ICES Advice and Scientific Network

The MSPTOOLS work has very much been targeted towards model application and implementation of the methodological developments made under the project through the ICES management advisory system and community, as well as the ICES scientific community and network. The project has as such contributed significantly to a row of ICES methodological development working groups such ICES WGSFD, ICES WGFBIT, ICES WKTRADE2 and ICES WGECON, as well as provided contributions to major ICES assessment working groups such the ICES WGNSSK with published pilot studies. Under those ICES working groups, the method developments under the MSPTOOLS project have been directly presented, evaluated and discussed among other through direct project (financed) participation in those working groups. This has also included provision of specific recommendations regarding future data calls, methodological further developments and directions, application to management advice, as well as management strategies in general under ICES according to important stocks, habitats and fisheries (among other for Danish fishery).

The contributions to different ICES working groups are summarised in the overview table below (Table 2.6.1). This table presents the working group, the years of the contributions to respective working groups and working group reports associated hereto, the type of working group, and the type of the MSPTOOLS contribution, as well as the role and level of the MSPTOOLS contribution hereto including MSPTOOLS participants involved in the work. Besides of the overview of the contributions provided in this table, the details of the input, method developments, and evaluations in relation to the MSPTOOLS project are reported in the respective ICES working group reports for each working group and year. Here the MSPTOOLS contributions as well as the participation of the MSPTOOLS project scientists appear in general in accordance with the overview tables, and all those working group reports for the specific working groups and years are available from the ICES web site and home page: *http://www.ices.dk/community/groups/Pages/default.aspx.* The reports are available from this web site link for each of the respective working groups, years and stocks listed in the Table 2.6.1.

Table 2.6.1. Overview of the MSPTOOLS model developments and preparation for implementation in ICES working groups and the ICES management advisory framework.

ICES Working Group	Years	Type of working group	Type of work (and stocks if relevant)	MSPTOOLS Role; Participants
ICES WGSFD	2018	Methodological Development & Test Applications	Development of methods, model development and evaluation: Quantify and explain the spatio-temporal variability of fishing fleets across ICES areas. To do so, a basic spatio-temporal statistical model was developed and which is described in details above and in the ICES WGSFD 2018 Report. Development of methods for MSE & Advisory Rules.	Major, essential; M.-C. Rufener (DTU Aqua)

ICES WGFBIT	2018	Methodological Development & Test Applications	Presentation and evaluation of progress with model development, implementation and application exemplified through selected Baltic Sea demersal fisheries conducted with hauled gears (with high importance for Danish fishery). The model development, test application and presentation in this context has focused on harmonizing the ICES (WGFBIT & WKTRADE2) and HELCOM (ACTION) procedures for evaluating fishing pressures and stock, fisheries and benthic impacts, i.e. on harmonizing and standardizing the latter with the first.	Major, essential; Francois Bastardie, Jeppe Olsen (DTU Aqua)
ICES WKTRADE2	2019	Methodological Development & Test Applications	Presentation and evaluation of progress with model development, implementation and application exemplified through selected Baltic Sea demersal fisheries conducted with hauled gears (with high importance for Danish fishery). The model development, test application and presentation in this context has focused on harmonizing the ICES (WGFBIT & WKTRADE2) and HELCOM (ACTION) procedures for evaluating fishing pressures and stock, fisheries and benthic impacts, i.e. on harmonizing and standardizing the latter with the first.	Major, essential; Francois Bastardie (DTU Aqua)
ICES WGNSSK	2017, 2018	Application of pilot investigations relevant for stock assessment and management advice	Development, investigations and application of a pilot study method of coupling commercial fishery and research survey data for making management strategy evaluation of a spatial management measures exemplified by the fishing closure of the Norway pout box and MPA with direct impact on the assessment and management advice for the Norway pout stock (with high importance for Danish fishery);	Medium, important; J.R. Nielsen, Matthieu Bigné, Francois Bastardie, Thomas Thøgersen, Jeppe Olsen (DTU Aqua)
ICES WGECON	2018; 2019	Methodological Development & Test Applications	Presentation and evaluation of progress with model development, implementation and application among other associated to ICES WKTRADE2 and ICES WGFBIT.	Medium, important; J.R. Nielsen, Francois Bastardie (DTU Aqua)

2.6.2 Implementation of Models in Cooperation with Sister Research Projects

Furthermore, the implementation of the models has been affiliated further through MSPTOOLS contributions to other EU projects covering the EU-COFASP ECOAST and EU-HELCOM ACTION projects. These contributions are described in the dissemination overview Table 3.1 below under the Dissemination chapter. This has involved direct cooperation between those projects and several contributions from the MSPTOOLS project to those projects with input to methodological reviews and improved methods. As such, the MSPTOOLS project has also been further implemented and disseminated through the international expert networks working under these international research projects, as well as implementation of the model developments under MSPTOOLS in the work conducted under those research projects.

3. Dissemination of Results and Future Perspectives

By J. Rasmus Nielsen, Marie-Christine Rufener, Kasper Kristensen, Francois Bastardie, Hanne M. Jacobsen, Anna Rindorf, and Karin Stubgaard

The MSPTOOLS dissemination has very importantly included the above method development and initial application of improved methods under the ICES working groups and the ICES scientific and management advisory framework as described under chapter 2. As such, the results and methodological developments achieved under MSPTOOLS have been communicated and implemented among other through project participation in ICES working groups. The project dissemination through other research projects is also described under chapter 2 above as well as in the dissemination overview table given below (Table 3.1). This table list the major dissemination activities conducted under the MSPTOOLS project summarising the type of activity, work and contribution as well as the role and level of the MSPTOOLS contribution.

The methodological developments carried out within the scope of the MSPTOOLS encompass the development and testing of advanced methods. The methodological work is summarised in several ICES working group reports and four scientific manuscripts, whereof one is published, one in review, and two written and in very advanced preparation (see descriptions and summaries below in this chapter 3 on project dissemination). The developments of methods and models in MSPTOOLS have to high extent been produced and achieved under a PhD project partly financed by and conducted under MSPTOOLS (approximately 1 year) and partly under the EU-COFASP ECOAST project (approximately 1 year) and also financed under an internal DTU Aqua PhD project (approximately 1 year).

Very specific and significant dissemination on methodological improvements and developments includes the production of the following four scientific manuscripts targeted at high ranking international scientific peer reviewed journals directly produced under MSPTOOLS:

- Bigné, M., Nielsen, J.R., and Bastardie, F. 2019. Opening of the Norway pout box: will it change the ecological impacts of the North Sea Norway pout fishery? *ICES Journal of Marine Science 76 (1): 136-152.* http://dx.doi.org/10.1093/icesjms/fsy121.
- Rufener, M.C., Kristensen, K., Nielsen, J. R., Bastardie, F. 2019a. Bridging the gap between commercial fisheries and scientific survey data to model the spatio-temporal dynamics of harvested marine species. *Manuscript in Review in Journal of Applied Ecology.*
- Rufener, M.C., Pascoe, S., Nielsen, J. R., Bastardie. F. (In Prep.1). Cost-effectiveness of the Danish fishery-dependent and -independent sampling programs. *Manuscript in Advanced Preparation and to be submitted to Conservation Biology.*
- Rufener, M.C., Nielsen, J.R., Kristensen, K. and Bastardie, F. (In Prep. 2). Improving the evaluation of fisheries management strategies by an advanced coupling of species spatio-temporal dynamics to fishing agents. *Manuscript in Advanced Preparation.*

The published manuscripts are publicly available and the draft manuscripts are summarised in the sub-chapters under the project results chapter 2 above, and can be provided by contact to the authors.

Furthermore, methodological results produced under MSPTOOLS were also disseminated in form of an oral presentation with an abstract presented to the international scientific community at the International Society for Ecological Modelling Global Conference (ISEM) October 2019, Salzburg, Austria. The work and submission of this symposium contribution was completed under the MSPTOOLS by May 2019:

- Rufener, M.C., Kristensen, K., Nielsen, J.R., Bastardie, F. 2019b. Pooling fishery-dependent and –independent data to model species spatio-temporal dynamics: a framework for data boosting and multiple bias correction. *Oral Presentation held at the International Society for Ecological Modelling Global Conference (ISEM) 2019, Salzburg, Austria. https://www.elsevier.com/events/conferences/international-society-for-ecological-modelling-global-conference, accessed in November, 2019*

Concerning additional project contributions to the methodological developments under ICES, special emphasis should be put on the contributions to the ICES WGFSD (ICES, 2018) and the ICES WKTRADE2 (Bastardie *et al.,* 2019) and there is referred to the specific working group reports here. For the WKTRADE2 there has been focus on implementing models and developing methods that evaluates benthic impacts of fisheries and trade-off scenarios between the impact on seafloor habitats and provisions of catch/value (Bastardie *et al.,* 2019).

The dissemination overview Table 3.1 describes three project workshops held in cooperation between the EMFF MSPTOOLS and EMFF ManDaLiS projects. One of the workshops was international and was held in association with and just after an International Conference Special Session: IIFET Conference, Seattle, USA, July 2018, (IIFET 2018 International Institute of Fisheries Economics and Trade, *https://www.xcdsystem.com/iifet/website/*). This Special Open Session was directly arranged by the MSPTOOLS and ManDaLiS Projects with invitation of stakeholders and including stakeholder perspectives. Besides initiative taking, planning, arranging, organizing, coordinating, announcing, leading and carrying through this special session directly under the MSPTOOLS and ManDaLiS Projects the projects produced the session abstract and a full scientific publication reporting of the outcomes of the session (Nielsen *et al*., 2018):

- Nielsen, J.R., Pallisgaard, B., Andersen, M., Dickey-Collas, M., Pascoe, S., Holland, D., Thébaud, O., Curtis, H., Thunberg, E., Mildenberger, T., Rufener, M.C., Nowlis, J., Yuniarta, S., and Bastardie, F. 2018. Challenges in implementing stock assessment, economic fishery analysis, and risk assessment for sustainable management strategies of data poor stocks. Paper presented at the Nineteenth Biennial Conference of the International Institute of Fisheries Economics & Trade (IIFET): Adapting to a Changing World: Challenges and Opportunities. Seattle, WA, USA. Compiled by A.L. Shriver. International Institute of Fisheries Economics & Trade, Corvallis, Oregon, USA, 2019. *http://oregonstate.edu/dept/IIFET/publications.html*, *https://ir.library.oregonstate.edu/concern/-conference_-proceedings_or_journals/k643b6739? locale=en.*

Under the IIFET 2018 Special Session “Tools for Stock Assessment, Economic Fishery Analysis, and Risk Assessment for Sustainable Management Strategies of Data Poor Stocks in Mixed, Small Scale and Indigenous Fisheries” conducted under the MSPTOOLS and ManDaLiS projects a number of stakeholder presentations addressed the current status, challenges, needs and future perspectives for implementation of management and ecological / economic assessment of data poor fish stocks and fisheries in management advice. This covered methods, simulation models and management strategy evaluation (MSE) tools to conduct assessment, provide abundance estimates and to evaluate economic efficiency and risks in exploiting data poor stocks caught in mixed, small scale, and indigenous fisheries. Particular focus was on accessibility of models and their development to ensure widespread and open access availability, user-friendly model operation, and efficient widespread adoption and implementation of those by scientists, stakeholders, and managers. Additional focus was on the data requirements for those models. Finally, the aim of the session was to discuss the best possible way to link economic assessments, risk assessment and MSE with biological (ecological) assessment and evaluation of stock status according to sustainable harvest levels in those data limited situations and systems to provide robust abundance estimates, assessments and management advice – and maybe even integrated ecological-economic advice?

State of the art

In ICES there is an ongoing extensive advisory and scientific strategic initiative with respect to development and implementation of assessment and abundance estimation methods for data limited and data poor stocks that involves integrating the stocks into TAC (Total Allowable Catch) advice according to the MSY (Maximum Sustainable Yield) and PA (Precautionary Approach) principles.

Such a focus is important because most fish and shellfish stocks in the world are in a data poor or a data limited condition/situation, and those stocks are to a much higher extent over-exploited and poorly managed than data rich stocks which most often are well managed. This is especially needed and urgent in a mixed, small scale and indigenous fisheries management context, in order to achieve the objectives of an ecosystem-based approach to fisheries management set out in UNCLOS (UNCLOS III 1982: United Nations Convention on the Law of the Sea) and its follow up in the Johannesburg 2002 Declaration. Among others ICES, PICES (North Pacific Marine Science Organization), NAFO (North West Atlantic Fisheries Organization), and FAO (Food and Agriculture Organization of the United Nations) have major focus on this situation and try to improve the advisory methods and provide necessary knowledge and expertise to meet this situation.

Under ICES, there have recently been reviewed and evaluated a large number of methods and models to enable assessment and abundance estimation of data limited and data poor stocks and associated fisheries dynamics, management strategy evaluation (MSE), and fisheries advice. It has also involved development of advanced stochastic stock assessment models to provide MSY and PA advice. Here focus is especially on stocks acting as choke species in mixed fisheries as well as stocks in small scale and indigenous fisheries. Also methods and models using time series of fishery research survey and/or fishery information, either independently or on integrated basis, have been developed to assess fish and fishery resource abundances and variability herein on an area specific and seasonal basis which can also be used for data limited stocks.

Further needed progress and evaluation

There is a growing need for economic methods, simulation models and MSE tools to be developed and implemented on top of the biological evaluation enabling economic assessment and establishment of indicators of economic sustainability of fisheries that exploit data poor and data limited stocks. This involves development and implementation of robust methods to evaluate efficiency, risks, sensitivity and robustness of different management strategies for mixed, small scale and indigenous fisheries where data poor and data limited stocks are caught, either as intended or un-intended by-catch or as target species. The medium to long-term economic profitability is part of incentive for improving fisheries management, economic efficiency and ecological sustainability in the exploitation and management of those stocks. To enable sustainable development of data poor stocks this should be the targeted goal. To achieve this, the management needs to consider economic efficiency in the fishery accounting for fishermen behavior and overall incentives for exploitation.

Consequently, it is urgently necessary and important to review, investigate and discuss appropriate economic principles, methods, simulation models and MSE tools to evaluate economic viability and conduct risk assessment and robustness checks of different management strategies and harvest control rules for those stocks and fisheries. Also, it is relevant to identify, review and evaluate performance of those methods and their data needs according to their ability to provide efficient economic input to tactical and strategic management advice in data poor or limited stock situations. This is an important step toward achieving sustainable management and avoiding choke-species issues in high-value mixed fisheries as well as to ensure sustainability of small scale and indigenous fisheries.

In context of the above, the aim of the special open session and the paper produced on background of this (Nielsen *et al.,* 2018 to which we refer for further descriptions and details) was to present state-of-the-art developments within a set of new methods, simulation models and MSE tools and on this basis to obtain stakeholder feed-back on the developments and future perspectives and needs. This was achieved by presentations and feed-back commenting from invited stakeholder representatives from fishing industry, fisheries management, fisheries advice (ICES), and fisheries biological and economic science who presented their perspectives and views on the above challenges.

The paper gives summaries of the set of new methods and tools initially presented at the session as well as summaries of the follow-up and feedback presentations and discussions provided by the stakeholders. On this basis, the paper draws some general conclusions on developments, challenges and future needs in relation to data poor stock assessment and management strategy evaluation in an ecological and economic perspective. The details of the stakeholder perspectives and feedback is given in Nielsen *et al.* (2018) produced under the MSPTOOLS and ManDaLiS projects which we refer directly to here.

Table 3.1: Overview of the MSPTOOLS Dissemination activities besides dissemination in ICES.

Type of Activity	Years	Type of Work and Contribution	MSPTOOLS Role (Level of Involvement) & Participants
DTU PhD Project on integrating commercial fisheries and scientific survey data: advances and new tools to model the fish and fishery dynamics.	2017-2019 (2020)	Co-financed PhD project between MSPTOOLS (1 year), EU-COFASP ECOAST (1 year) and a DTU Aqua internal PhD project (1 year) on further development of statistical models for coupling of commercial fishery and research survey data to describe fish stock distribution and abundance surfaces, as well as further development of a bio-economic fisheries model, in order to link the two models. The work has also involvede valuation of economic efficiency of sampling commercial fisheries data and research survey data in relation to abundance estimation. Including a PhD External Research Stay for M.C. Rufener at CSIRO Oceans and Atmosphere Flagship, EcoSciences, Precinct, Brisbane, Australia with economic model development and application, as well as presentation of project results and discussion on methodological developments including feedback on those from an internationally highly recognized research group within the relevant scientific field and modelling topics.	Major, essential; M.-C. Rufener, DTU Aqua (PhD student), F. Bastardie, DTU Aqua (main supervisor), J.R. Nielsen & K. Kristensen, DTU Aqua (co-supervisors);
International Conference Special Session: IIFET Conference, Seattle, USA, July 2018 (with invitation of stakeholders). IIFET: International Institute of Fisheries Economics and Trade, *https://www.xcdsystem.com/iifet/website/* IIFET Open Session & Stakeholder Perspectives.	2018	Special Session arranged by the MSPTOOLS and ManDaLiS Projects: “Challenges in implementing stock assessment, economic fishery analysis, and risk assessment for sustainable management strategies of data poor stocks.” IIFET, Seattle, USA, 18/7-2018 (09-12 hours). Initiative taking, planning, arranging, organizing, coordinating and carrying through this special session directly under the MSPTOOLS and ManDaLiS Projects. Including Session announcement, Session Abstract, Session Lead, and producing a Session scientific publication (Nielsen *et al*., 2018).	Major, essential; J.R. Nielsen, M.-C. Rufener, T. Mildenberger, F. Bastardie (DTU Aqua)
Stakeholder Workshops (MSPTOOLS & ManDaLiS)	2017-2019	Project Stakeholder Workshop I: DTU Aqua, Charlottenlund, DK, 17/03-2017 (9-15 hours) with participation of Danish Stakeholders (totally 26 participants); Project Stakeholder Workshop II: University of Washington (IIFET Conference Site), USA,	Major, essential; National and International Stakeholders & DTU Aqua Scientists (involved in the

		18/7-2018 (13-18 hours) with participation of international stakeholders (8 participants); Project Stakeholder Workshop III: DTU Aqua, Lyngby, DK, 13/8-2019 (12-17 hours) with participation of national and international stakeholders (totally 16 participants).	MSPTOOLS & ManDaLiS projects)
Project Cooperation with the EU-COFASP ECOAST project on developing methodologies for testing fishing closures and minimizing fishing impacts according to different benthic habitats also considered in a broader Maritime Spatial Planning context.	2016-2019	The cooperation involved development of a flexible and robust abundance predictive statistical model (LGNB) where the LGNB integrates both commercial fisheries and scientific survey data while accounting for spatio-temporal correlation and differences in fishing catchability and effort. Furthermore, the cooperation involved integration of the LGNB model into the bio-economic DISPLACE fisheries model by coupling or linking of the models, where DISPLACE is built upon a set of interrelated functions that links the fishing vessels dynamics to the population dynamics of commercial important fish species.	Major, essential; M.-C. Rufener, F. Bastardie, J.R. Nielsen, K. Kristensen (DTU Aqua)
ICES Annual Science Conference (ICES ASC), Fort Lauderdale, USA, Sept. 2018 & ICES WGECON 2018, Cph, DK June 2018 & ICES WGECON 2019, Paris, FR, June 2019.		Presentation and discussion of the project developments and project implementation and model involvement in ICES management advice and science to the ICES SCICOM (ICES Science Committee) meeting during the ICES ASC 2018 involving also the broader ICES Scientific Community.	Major, essential; J. R. Nielsen; M.C. Rufener
Project Cooperation with EU-HELCOM ACTION Project: Actions to evaluate and identify effective measures to reach GES (Good Environmental Status) in the Baltic Sea marine region	2018-2019	Presentation and evaluation of progress with model development, implementation and application exemplified through selected Baltic Sea demersal fisheries conducted with hauled gears (with high importance for Danish fishery). The model development, test application and presentation in this context has focused on harmonizing the ICES (WGFBIT & WKTRADE2) and HELCOM (ACTION) procedures for evaluating fishing pressures and stock, fisheries and benthic impacts, i.e. on harmonizing and standardizing the latter with the first. This is with special focus on evaluating scenarios of fishing pressures and displacement of fishing effort in certain selected benthic habitat areas and Baltic national economic zones according to spatial fishing closure management measures and in relation to impacts on environmental status for selected benthic communities/habitats and fish stocks.	Medium; F. Bastardie, J.R. Nielsen, M.-C. Rufener (DTU Aqua)
Project Cooperation with EU H2020 MEESO Project on mesopelagic stocks	2019	Guidelines on perspectives in and possibilities for model application of the developed statistical distribution and abundance to two selected NE Atlantic mesopelagic fish species / stocks.	Low; J.R. Nielsen, M.-C. Rufener, F. Bastardie (DTU Aqua)

Additional future perspectives and needs raised by the stakeholders during the MSPTOOLS and ManDaLiS workshops included repeated and consistent suggestions for continuation of the development and implementation of the models developed under the projects. Further, feedback and recommendations from the stakeholder workshops was that certainty of the model outcomes should be further explored in cases where commercial fishery and survey data were not integrated and included in the models following the remark that the results should always be considered in a real world perspective where there may be some uncertainty in only using catch data because trends herein can often be explained by political reasons. Further stakeholder feedback was that there are wide perspectives in the tool in relation to describing fish movements (distribution and migration besides density and abundance) with high spatial resolution and certainty, and that the framework so far applied to cod, sprat, herring and plaice in the W. Baltic & Kattegat should be supplemented with new case studies in future studies. That included suggestions for use of the tool for describing changes in fish stock distribution patterns in the North Sea in relation to Northwards shift in distribution for many fish stocks. This involves applying the models on the North Sea stocks, fisheries and benthic habitats taking into consideration changes in distribution also due to the physical environment, i.e. by integration of environmental information and parameters as co-variates in the models. Further suggested application could be evaluation of impacts of eutrophication and oxygen depletion areas on fish distribution and fishing possibilities for example in the Baltic Sea by coupling the models to bio-geo-chemical model output. Other suggestions covered investigation of the mixed fishery of herring and sprat in the W. Baltic Sea and Kattegat with high spatial and temporal resolution data and models as well as investigating the mixed fishery of herring and sprat in the North Sea with the model framework. A stakeholder comment was that the tool could support spatial explicit management of cod in Kattegat and W. Baltic Sea, and could make advanced comparison of survey data and fisheries data in this context.

Finally, the stakeholders found the tool important for better use of ministerial databases, and this use should be expanded to respond to MSP projects and requests, as well as for coupling to economic institute data bases focusing on individual vessel activities. In general, the tool was considered very useful for evaluating impacts of spatial regulations.

In accordance with several of the above stakeholder perspectives there has directly in relation to the MSPTOOLS project been produced a follow up research project proposal and application (NORDFO) submitted to the EMFF project call in spring 2019. This project proposal has had a positive evaluation and is for the time being placed as number one at the waiting list for funding under the EMFF in 2019 for which final decision is pending. The NORDFO project proposes the below future topics to be covered.

North Sea Resource Distribution & Fishery opportunities (NORDFO):

- Follow-up on EMFF MSPTOOLS to document ways to increase fishing opportunities in the crowded and changing North Sea;
- Integrate knowledge & dynamics of key factors determining and regulating the distribution of many important fish stocks to the Danish fleet;
- Evaluate the social, economic & environmental implications in changing the fisheries economic incomes;

- Consolidate the CFP with further supportive information for sustainable & profitable fisheries;
- Consolidate relevance for spatial management in a EU CFP, MSFD and MSPD context.

WP1 – High resolution integration of fisheries & research survey data
Task 1.1: Data collection of the North Sea fish & fisheries data
Task 1.2: Application of the LGNB framework to combined fisheries & survey data
Task 1.3: Maps production and time series analysis of fish abundance fields and change in fish assemblages

WP2 – High resolution correlations to marine environmental factors
Task 2.1: Data collation of the North Sea environmental data
Task 2.2: Expanding the LGNB framework to include environmental data
Task 2.3: Predicting historical fish abundance field under influence of environment

WP3 - Applied management evaluation framework with implementation in the North Sea
Task 3.1: Conditioning LGNB-DISPLACE platform to North Sea
Task 3.2: Designing the fish & fisheries baseline scenario
Task 3.3: Evaluating the suite of CFP, MSFD and MSPD-related scenarios

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Enclosed A Program and R code to simulate and predict abundances for a future time-step in the model development

A.1. Appendix A

```
#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# Multivariate normal distribution simulation function
#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# @ mu = mean of the abundance field (given by the model output)
# @ prec = precision of the spatio-temporal covariance matrix (given by
the model output)
# @ n.sims = number of simulations (given by the user)

rmvnorm_prec <- function(mu, prec, n.sims) {
  z <- matrix(rnorm(length(mu) * n.sims), ncol=n.sims)
  L <- Cholesky(prec, super=TRUE)
  z <- solve(L, z, system = "Lt") ## z = Lt^-1 %*% z
  z <- solve(L, z, system = "Pt") ## z = Pt    %*% z
  z <- as.matrix(z)
  mu + z
}


#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# Predicting abundances one time-step ahead
#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
dyn.load(dynlib("model")) # Load the C++ file of the LGNB model
load("cod_S5.RData") # Load the model results

obj <- res$obj # Retrieve obj from model
obj$fn(res$fit$par) # Evaluate again the obj function
lpb <- obj$env$last.par.best # Get spatio-temporal parameters
r <- obj$env$random # Get latent (random) variables
h <- obj$env$spHess(lpb, random=TRUE) # Get Hessian matrix
time_corr <- lpb["time_corr"] # Get time correlation

phi <- time_corr/sqrt(1.0+time_corr*time_corr) # phi (time correlation
param.)
delta <- exp(lpb["logdelta"]) # Get delta (spatial correlation param.)
scale <- exp(lpb ["logscale"]) # Get scale (spatial correlation param)
Q <- obj$env$data$Q0+delta*obj$env$data$I # Get Precision matrix

Xt1 <- rmvnorm_prec(mu = Xt, prec = scale*sqrt(1-phi^2)*Q, n.sims = 1)
# Predict abundance current abundance (Xt) in time t+1 (Xt1).
```

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