# Bank resolved prognoses of sandeel fishing potential in the North Sea

**Christensen, Asbjørn**

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Final survey report for the national project *Fiskeriudsigt for tobis i Nordsøen på bankeniveau* (2005-2007). This project has been financed under §24.33.02,§24.38.60.30 and §24.38.40.10, *Innovationsloven, forsøgsfiskeri* (50 %), (J. nr. 3305-06-00011) FIUF, and *pilot- og demonstrationsprojekter* (50 %), (J. nr. 3704-3-05-0145).

**Asbjørn Christensen**

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DTU-AQUA, Afdelingen for Havfiskeri
Danmarks tekniske Universitet
Charlottenlund Slot
2920 Charlottenlund Slot

## Preface

Over the past 20 years the art of computer based oceanographical modeling has advanced enormously, and today oceanographical modeling is performed routinely in many research institutions as a very cost efficient and reliable tool of probing and forecasting the state of the ocean, supplementary to expensive cruises and surveys. Oceanographical modeling itself can not stand alone, but is a useful, complementary approach to traditional biological methods for data collection and analysis. In the present project we combine state-of-art hydrodynamical modeling of the North Sea with available and new fisheries data and biological knowledge to demonstrate that generation of bank resolved prognoses of sandeel fishing potential is within reach, much similar to ubiquitous weather prognoses.

The core activities of the present project have been to setup infrastructure (computer programs, collaborations with institutions with the necessary competence, collecting and processing field data) needed to generate prognoses. This has been successful and first generation demonstration prognoses have been provided as end products of this projects.

Looking ahead, the tools developed in this project has significantly increased DTU-AQUAs strategic ability and response time to address important questions involving oceanographical influence on fish stocks, as well as improving DTU-AQUAs collaborative potential in future national and international research projects for improving the scientific basis for fisheries management. The aims and tools of the present project is already being pursued in other current and future projects, to improve DTU-AQUAs skill on prognosis generation. Further, we consider sandeel a spearhead species for methodological development, due to its relatively simple biology. Therefore the tools and know-how of this project is also being extended in other current and future projects considering other species (e.g. cod, herring and sprat) focused at a variety of other issues concerning spatial fisheries management (e.g. marine protected areas and climate impacts).

The project has been conducted based on financial support from the Ministry for Food, Agriculture and Fisheries and from the EU, within the FIUF programme.

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## Project main purpose:

The project has three main objectives: the first is to fill some gaps in the biological knowledge of North Sea sandeels and assess the sandeel stock levels and conditions through survey programmes financed in the present project. The second is to demonstrate that by combining state-of-art modelling with available biological knowledge, a fishing bank resolved prognosis framework can be established, which at sight can be incorporated in fishery management. The third main objective is to extend the collaboration with *Danmarks Firskeriforening* (DF) and thereby faciliate a sustainable sandeel fishery based on an increased level of fishery self regulation

## Project progress:

### Summary

The projektet has achieved all proposed targets, both with respect to survey and modelling activities.

In December 2005 and 2006, the planned dredge surveys were successfully undertaken and the collected material was analyzed. In sping 2006, larval collection was accomplished in collaboration with fishing vessels. The results has been presented to the fishery community as well as in scientific fora, most recently to ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK) i oktober 2007, which found the applied survey methodology in this project well founded and promising for the purpose of generating surveybased recruitment indices for North Sea sandeel stocks. However, it was also emphasized that a better spatial coverage was needed to generate reliable indices on recruitment and stock conditions in general, and a benchmark of the cost-efficiency of parallel national sandeel survey programmes, including the one covered by the present project, was desirable. Additionally, it should be investigated that survey based data collection gives a true biological picture of the stock abundance and codition.

The modelling activities are centered around two model frameworks. The first is a larval component that describes and analyses hydrodynamical transport of larvae, which is believed to be a bottleneck in the recruitment. The other is a population component, which synthezises the

hydrodynamical transport calculations with other available biological data and knowledge and gives as output a spatially resolved timeseries of the sandeel population dynamics in the North Sea. This population component is the implementation device for the prognosis tool in the present project.

The larval component is a flexible modelling package, which combined with a hydrographical data pipeline to DMI, facilitates a high resolution description of the water transport of fish eggs and larvae, with a minimal delay. The most important lessons learned are that North Sea water transport has strong spatial and interannual variability and that process-oriented recruitment prognoses must include realistic 3D hydrographical data to succeed.

The population component describes central elements of the larval and post-larval life cycle: growth, fishery, mortality and reproduction. A central conclusion here is that realistic stock-recruitment relations for prognoses, in addition to hydrographical data, needs a well-founded parameterization of demographic density effects (i.e. food competition and cannibalism for sandeels) and that memory effects in population dynamics are essential, i.e. the regional stock dynamics depends on the age structure of local as well as remote sub stocks.

## Discussion of project progress and results

### Evaluation of progress in relation to proposed milestone

The project has achieved the proposed milestones, considered over the entire project curriculum. Some milestones in the project are critically timed to the fishery season, and because the project proposal was approved rather late (approval Feb 2006) in relation to the project time line, certain milestone scheduled early in project phase 1, e.g. milestone 1b (scheduled Feb 2006), had to be postponed by one year. However, after necessary rescheduling, all milestone were achieved over the project curriculum. Below are comments to specific project milestones:

**Phase 1:**

- Milestone 1a: Collection and analysis of 0-group (winter 2005/06):

Cruise, using modified scallop dredge, was performed successfully in Dec 2005 followed by analysis of biological material in Spring 2006

- Milestone 1b: Development/demonstration of recruitment model to the fisheries:

  Due to delayed approval of project, demonstration to fisheries organizations was postponed to March 2007 (because very little interest was expected from the fishery community after start of the fishing season). The project was also presented directly in a digested form to the fishery community in the periodical *FF-nyt* (Sep. 2006).

- Milestone 1c: Generation of model recruitment indices:

  Both fishery and hydrographic recruitment indices have been generated in the project. The generated recruitment indices have been presented to many scientific/management workshops/working groups, e.g. WKIMS (Feb 2006), WGNSSK 2006/2007, and AGSAN (Nov 2007).

**Phase 2:**

- Milestone 2a: Integration of hydrographical data in models:

  This task has involved setting up the SLAM model, within the NSParticle framework; both these model components are presented in more detail in section G.

- Milestone 2b: Collection and analysis of larvae (spring 2006):

  This component was successfully accomplished in collaboration with two commercial vessels.

**Phase 3:**

- Milestone 3a: Collection and analysis of 0-group (winter 2006/07):

  Cruise, using modified scallop dredge, were performed successfully in Dec 2006, followed by analysis of biological material in spring 2007.

- Milestone 3b: Development/demonstration of prognosis framework:

The SPAM model framework (see section G) for generating sandeel stock prognoses has been presented in many regional and international fora, e.g DG-Fish seminar Jan 2007 and WGNSSK Feb 2007, Nordic Workshop on Marine Spatial Planning, June 2007, and European Symposium on Marine Protected Areas as a Tool for Fisheries Management and Ecosystem Conservation, Sept 2007. *Dansk fiskeriforening* (DF) was represented in the latter fora. The SPAM model was also presented directly to the fishery at a dedicated meeting in Esbjerg, Mar 2007.

- Milestone 3c: Final report

## Evaluation of the usefulness of the project results and their future perspectives

The project products are current at a demonstration level and over the next few years ensues a maturation and validation phase, where project products are incorporated into the management process.

During the course of the project, critical knowledge gaps have also been identified. Most critical is the need for improved zooplankton models with high spatial and temporal resolution, and currently this issue is being pursued in newly started and proposed projects.

Another important question crystallized during the project is if - and how - sand banks (sandeel habitats) should be aggregated into representative regions, because single sand banks (sandeel habitats) are not realistic units from a manament perspective. We will elaborate on this in section G below.

## Evaluation of the marketing potential of the project results and their contribution to the national economy

The project has developed tools that facilitates i) better economical planning potential of the fishery and postprocessing industry, as well as ii) an optimal harvest strategy determination by scenario simulations, that can be used to manage the fishery to increase yields and minimize the risk of overfishing. The software products developed in the present project are research tools

with a small anticipated business volume, so that commercialization and customer support are not expected to produce an attractive revenue.

## Evaluation of new competences etc. achieved in the host institution

This project is part of a strategic initiative of DFU to strengthen the modelling competence of the institution to increase the level of insight obtained from collected biological data and to bridge disciplines.

The two modelling frameworks in the present project, especially the transport software package, are generic modelling infrastructure components allowing DFU to address a wider range of problems, like climate effects and design of marine protected areas, as well as management related questions in general.

The platforms partially financed in the present project has been a leverage for several new national projects (ModRec, TORTN and SUNFISH) and EU projects (RECLAIM, MEECE and MyOcean) which are at the approval stage or already ongoing. It is also anticipated that the computational platforms partially financed in the present project are extended to other species and areas of Danish economical interest.

## Evaluation of the deployment of project results in relation to governmental body alertness

In addition to improving DFUs ability to provide management advice on sandeel related questions, the modelling infrastructure developed in the present project is relatively generic by design, and may therefore significantly decrease the response time of DFU to address new questions and hypotheses involving hydrographical influence on fish stocks in general.

## List of publications etc which are direct derivatives of the project

## Papers in international, peer-reviewed journals

- Computing larval transport indices and sandeel subpopulation structure:
  Asbjørn Christensen, Henrik Jensen, Henrik Mosegaard, Mike St. John[2], and Corinna Schrum

*Sandeel (Ammodytes marinus) larval transport patterns in North Sea from an individual-based hydrodynamic egg and larval model*
Accepted in Canadian Journaal of Fisheries and Aquatic Sciences, 2008

- Spatially explicit sandeel population model (in the paper used for marine protected area simulation):

  Asbjørn Christensen, Henrik Jensen, and Henrik Mosegaard
  *Spatially resolved fish population analysis for designing of MPAs: influence on neighboring habitats.*
  Submitted to ICES Journal of Marine Science, 2008

- Larval hydrodynamical backtracking and growth model parameterization and validation:

  Christensen, A., Ute Daewel, U., Jensen, H., Henrik Mosegaard, H., St. John, M., and Schrum, C. 2007.
  *Hydrodynamic backtracking of fish larvae by individual-based modelling.*
  Mar. Ecol. Prog. Ser. **347** *(2007): 221-232*

## Patents

No patents have been applied for.

## Presentations at congresses, symposia etc

- Workshop on Indices of Meso-scale Structures, IFREMER, Nantes, France, 22-24 February 2006.

  Asbjørn Christensen (oral presentation): *Meso-scale larval transport indices in the North Sea*

- Workshop on advancements in modelling physical-biological interactions in fish early-life history: recommended practices and future directions, 3-5 April 2006, Nantes, France:

  Asbjørn Christensen (oral presentation): *Hydrographic simulation of Sandeel larvae dynamics in the North Sea*

- Kickoff meeting in EU project RECLAIM, Dec 18 2006, University of Wageningen, Netherlands:

  Asbjørn Christensen (oral presentation): *Sandeels: a sensitive ecosystem probe in the North Sea*

- Seminar on "Marine Protected Areas", Review of knowledge - evaluation of MPAs effects. 17 January 2007, DG FISH/A, EU, Brussels.

  Henrik Mosegaard (oral presentation): *Sand eels*.

- AGSAN (ICES Ad Hoc Group on Sandeel), Feb 28 2007, Copenhagen, Denmark:

  Asbjørn Christensen (oral presentation): *Sandeel Population Analysis Model: Integrating from processes to populations*

- Nordic Workshop on Marine Spatial Planning, 6-8 June 2007, Copenhagen, Denmark:

  Asbjørn Christensen (oral presentation): *Toward area-based management of Sandeel in the North Sea*

- European Symposium on Marine Protected Areas as a Tool for Fisheries Management and Ecosystem Conservation, 25-28 Sept 2007, Murcia, Spain:

  Asbjørn Christensen (oral presentation): *Spatially resolved fish population analysis for designing of MPAs*

## Esoteric papers

Jensen H. og Brogaard P. 2006. Indsamling af tobisyngel p kommercielle fiskefartjer. Direktoratet for FdevareErhverv Projekt no. 04/54. Slutrapport. December 2006.

## Other outreach, e.g. meeting contributions, open-house arrangements etc

Presentation of progresses in present project on development of sandeel stock prognoses tools for Danmarks Fiskeriforening, Mar 20 2007, Hotel Britannia, Esbjerg, Denmark:

Asbjørn Christensen (oral presentation): *Nyt fra forskningsfronten om tobis.*

*The presentation was well received, stimulated questions from the audience and gave inspiration for the work remaining in the present project*

- Marine Ecological Modelling Center seminar, May 19 2006:
  Asbjørn Christensen (oral presentation): *Hydrographic simulation of Sandeel larvae dynamics in the North Sea*

  Kickoff meeting for the national project Modelling Recruitment (Havforskningsprogrammet) May 16, 2007:
  Asbjørn Christensen (oral presentation): *Proposal for a common particle tracking framework.*

**Planned publications and papers**.

- Sensitivity of larval transport on tidal phase and other parameters.
- Detailed presentation of general SPAM framework.
- Generic model of larval transport structure in the North Sea.
- Optimal definition of sandeel habitats in the North Sea.

**Summary of scientist educational activities (phd. og post doc.), including guest researchers and deployment**

NA

**Summary of associated master and bachelor level students**

Research assistent: Mikael van Deurs:
*A pilot-study: Evaluating the possibility that Atlantic herring (Clupea harengus L.) exerts a negative effect on lesser sandeel (Ammodytes marinus) in the North Sea, using IBTS- and TBM-data.*
DFU-report **165-06**, Danish Institute of Fisheries Research, HFI, 2006.

Master student: Elsi Kauppinen, University of Joensuu, Finland.
Supervisors: Henrik Mosegaard, DFU and Ismo Holopainen, University of Joensuu
Subject: Comparison of coupled biological production and hydrographic drift models of sandeel larval dispersion/retention with observed patterns of size/age distribution and abundance

Master student: Marco Gauger, IHB, University of Hamburg, Germany.
Supervisors: Henrik Mosegaard, DFU and Prof. Michael St. John
Subject: "Otoliths as indicators of good and poor conditions for sandeel 0-group recruitment in the North Sea".

## Summary of national and international collaborations with universities and private companies

The present project is a precursor of the Marine Ecological Modelling Center (MEMC) established between DFU, DMI and DMU. These institutions brings together complementary competences on ecological modelling, in an initiative to make Denmark a strong regional player in oceanographic modelling, with obvious long term benefits for the fishery related research and the fishery itself. Via current and future EU financed projects (PROTECT, RECLAIM, MEECE and MyOcean) the activities in the present project have also buildt and strengthened contacts to research groups in other marine laboratories in the North Sea region, e.g. IHB (Germany), FRS and PML (UK) and IMR (Norway).

## Elaboration of project progress and results

In this section we will presents some aspects of the project products which are not traditionally included in peer-reviewed journals, which awaits future publication or which relates to the development process *per se*. For a detailed presentation and discussion, we refer to the research papers and the reports produced by the activities mentioned above.

## Larval tranport generic simulation framework

One of the model components developed in the present project is a generic larval transport simulation framework, NSParticle. The framework couples state-of-art extensive 3D hydrographical databases (70+ GB data) and biological modules within a simulation environment, which allows testing biological hypotheses. The biological module for sandeel is called SLAM (Sandeel Larval Advection Model), and the hydrographical databases currently available is provided through collaborations with DMI (hourly, 5nm resolution, 2002-2006) and IHB, University of Hamburg (daily, 5nm resolution, 1970-2004). The larval transport program NSParticle is implemented in a modern object-oriented programming style in Fortran 90, so that it is easily adapted and extended to new cases (by adding new biological modules). The package adds up to 7000+ lines of computer code. The software design is illustrated below in Figure 1

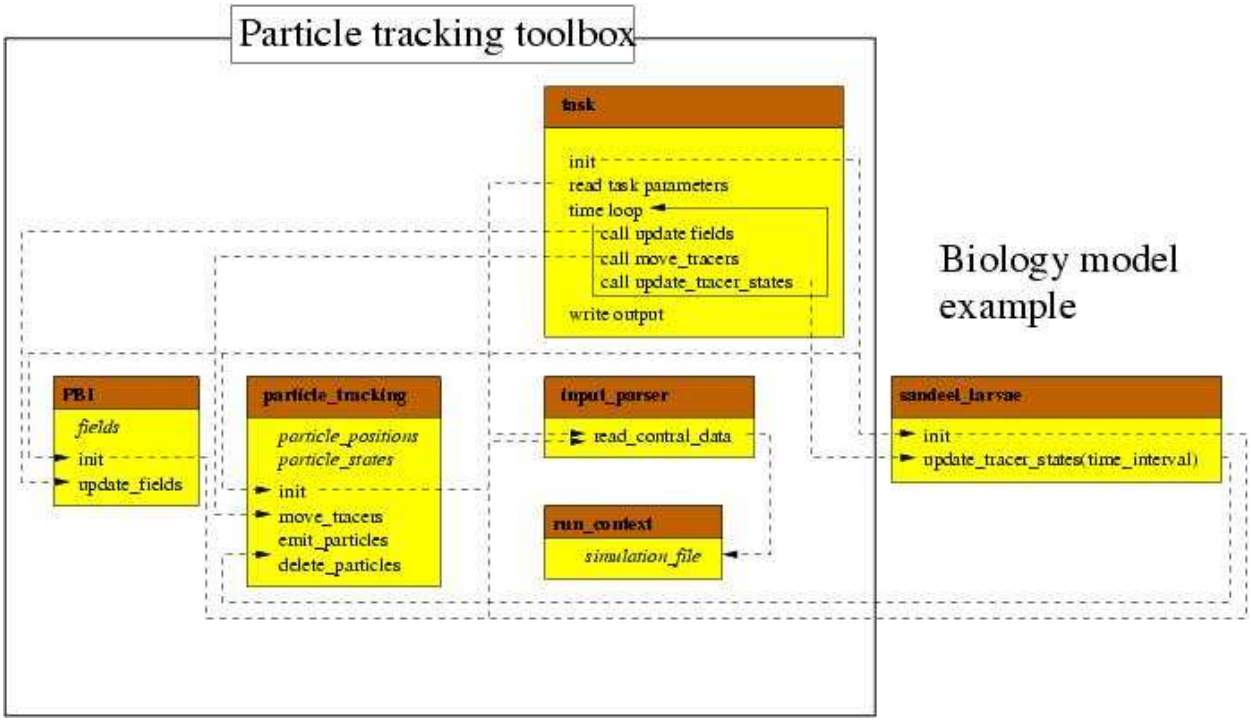


**Figure 1 Software design scheme of the generic NSParticle simulation framework**

Using the NSParticle framework with the SLAM biological module for sandeel larvae, many fishery relevant quantities can be computed. In Figure 2 (left) we as example show the larval transport survival

chance, depending on its hatch site (we have scanned all registered sandeel habitats) and in Figure 2(right) we show the fishing sensitivity. Sensitive banks are characterized by being mostly self recruiting, whereas insensitive banks are characterized by recruitment from other areas (so that the bank will replenish, if it is fished up).

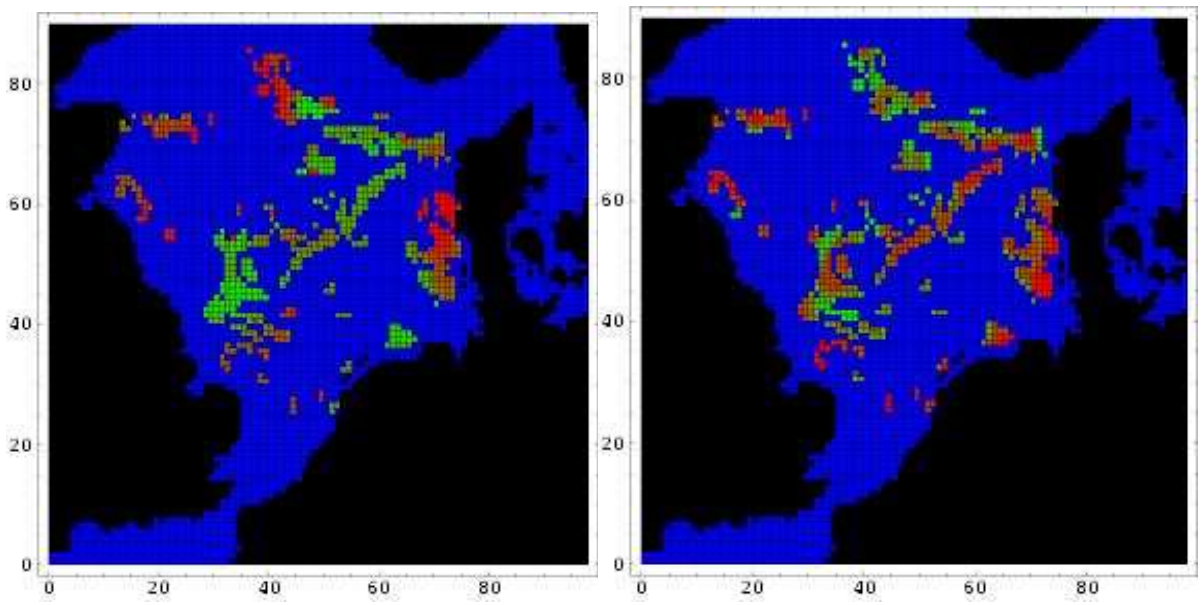


**Figure 2 (left). Larval transport survival in 2006, color coded by hatch bank. Red: larvae coming from banks in these areas have low transport survival chance, opposed to green: high survival chance.**

**Right: bank fishing sensitivity in 2006. Red: sensitive banks (dominated by large self recruitment). Green: less sensitive recruitment comes from other areas to a larger extend)**

## Sandeel stock simulation framework

The population component developed in the present project is a called SPAM (Sandeel Population Analysis Model) and is a framework integrating the output from transport calculations from NSParticle above, with survey data, fishery data and other available biological knowledge. It is a process-oriented approach striving for a minimum number of parameters, also setup according to modern object-oriented design principles in the language Python, allowing for long term development and maturation of the software package. The highlights of the models are

- Direct coupling to first principles hydrodynamics and other relevant physical and biological fields that controls conditions for early life-stages.
- Spatial explicit dynamics, with arbitrary resolution and habitat aggregation.
- Focus on demographic effects on stock abundance/growth (which have been shown to play in important role for North Sea sandeels). Demographic effects faciliate stock self regulation, and for sandeels the mechanism is food competition and cannibalism.

Outputs from the models are time series of bank/age resolved biomass, growth, fishery yield, and recruitment. The model setup is sketched below in Figure 3 below.

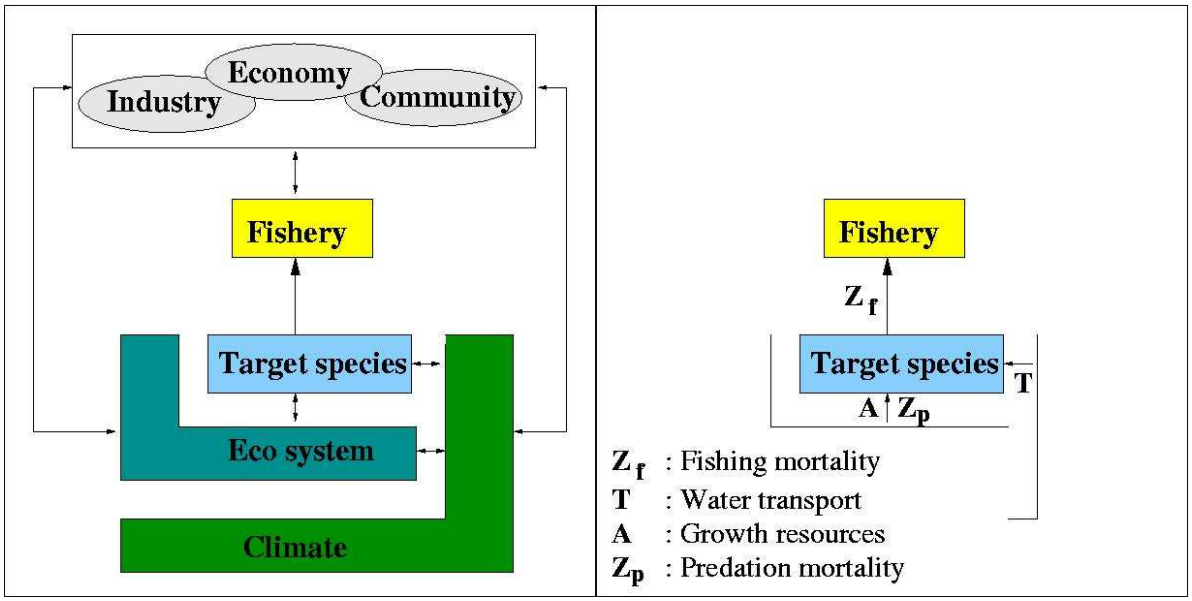


**Figure 3 Left: sketch of the target species (sandeel) with its relation to the ocean, ecosystem and fishery. Right: influence of ocean, ecosystem and fishery are aggregated into 4 drivers: Fishing mortality ($Z_f$), hydrodynamical transport (T), growth potential (A) and predation mortality ($Z_p$)**

The SPAM model is able to run with different levels of dataassimilation, from strongly forcing with survey/fishery data and coarse biological models, toward full life-cycle modelling, with advanced biological models. The target is selfcontained full life-cycle simulations, as knowledge gaps on the biological side get filled. However, in the present project, the focus is on strong forcing by survey/fishery data for prognosis generation, as there has been identified important knowledge gaps in the biological basis. An example of a stock prognosis is provided in Figure 4 below.

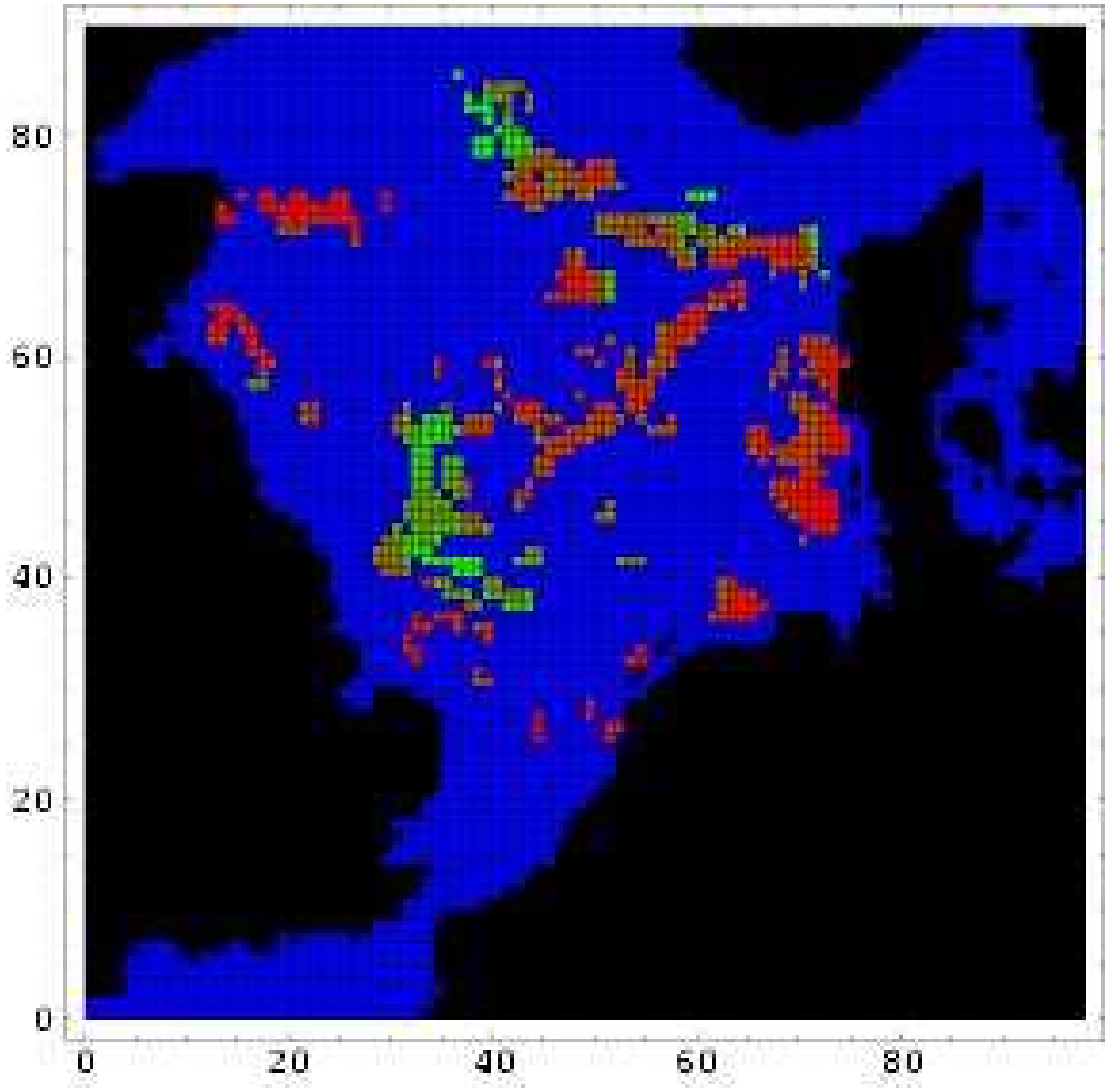


**Figure 4: Prognosis of relative abundance of fishable 1+ group sandeels for 2007 season. Green is high local stock abundance, red means lower local stock abundance**

Figure 4 displays a SPAM prognosis run for the fishing season 2007. The spin-up period was 2003-2006 and generated from realistic hydrodynamic hindcasts (2003-2006), with SSB estimates (2003-2006) assimilated in the spin-up phase. SSB estimates were generated from the log book database with ICES rectangle spatial resolution.

One of the most prominent knowledge gaps identified in relation to the present project is the lack of zooplankton distributions with sufficient spatial and temporal coverage. Currently, the most promising direction to fill this gap is zooplankton models based on primitive equations, socalled NPZD models. DFU has entered the MEMC cooperation mentioned above, with the objective of obtaining state-of-the-art NPZD model output for biological simulations. In the original project description it was proposed to use continuous plankton recorder time series for this purpose, but closer inspection revealed that these time series are not able to provide sufficient spatial and temporal coverage. In the present setup, the model uses a zooplankton proxy variable, a local carrying capacity that can be specified. In practice, the local carrying capacity is included in the parameter estimation process at calibration time or estimated from spatially resolved fishery data, but in the future it is intended that NPZD model output should be integrated on equal footing with the hydrographical data.

Another issue that needs further attention is the nature of the stock self regulation mechanisms in play for North Sea sandeels, i.e. quantify the influence of food and habitat competition within the sandeel stock on the stock abundance fluctuations observed recently, as well as the potential effect of cannibalism. In the present context relatively generic functional relations has been applied, parameterized from observed stock variability.

## Optimal habitat aggregation.

Sandeel habitats in the North Sea are constituted by numerous adjacent, elongated sand banks, formed by tidal currents. These primary habitats are not optimal from a stock assessment perspective for three reasons: first they are not well suited as management units (too many, too small) and secondly, it is unrealistic (too expensive) to assess biological heterogeneity at this fine scale and thirdly adult sandeel migration may become a factor at a very fine scale, and needs to be accounted for, if the very high spatial resolution should have any justification. Therefore, some level of primary habitat aggregation is needed for management purposes. The highest horizontal resolution in our setup is 5 nm, dictated by the hydrodynamic setup (this resolution corresponds to Figure 2). Initial analyses of larval transport patterns were performed on the *s5* major regional aggregation level (Figure 5) featuring five major sand bank systems (W,D,C,SE and NE) as displayed in Figure 5.

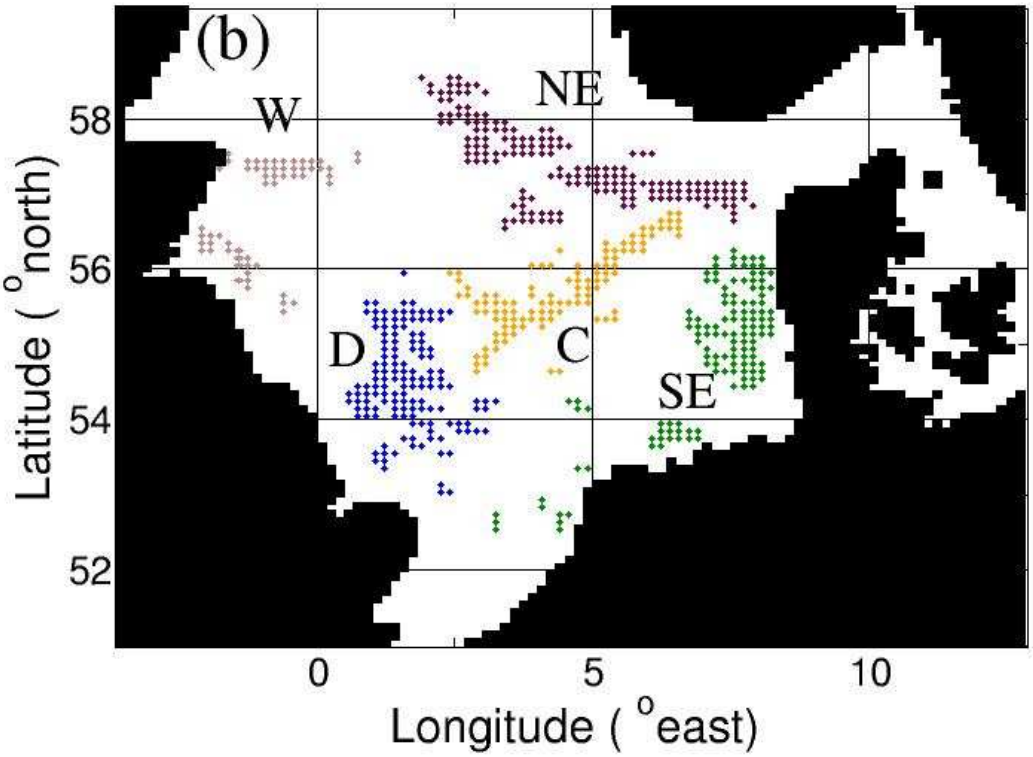


**Figure 5 The s5 major coarse regional division of sandeel habitats.**

We have also run our setup on ICES square spatial resolution level, which is highly convenient when assimilating fishery and ICES survey data, which is recorded with this resolution. Transport distance scaling analysis indicates that an optimal habitat definition for North Sea sandeels is likely around 10 bank systems, a figure which is also feasible from a management perspective. A division in 10 habitat regions is also realistic from the perspective of addressing biological heterogeneity between habitat areas.

This estimate of approximately 10 essential sandeel habitat regions in the North Sea is also consistent with survey information that indicates the major area division *s5* in Figure 5 is too coarse as management units, since significant spatial heterogenity in stock abundance is observed within some *s5* regions in Figure 5.