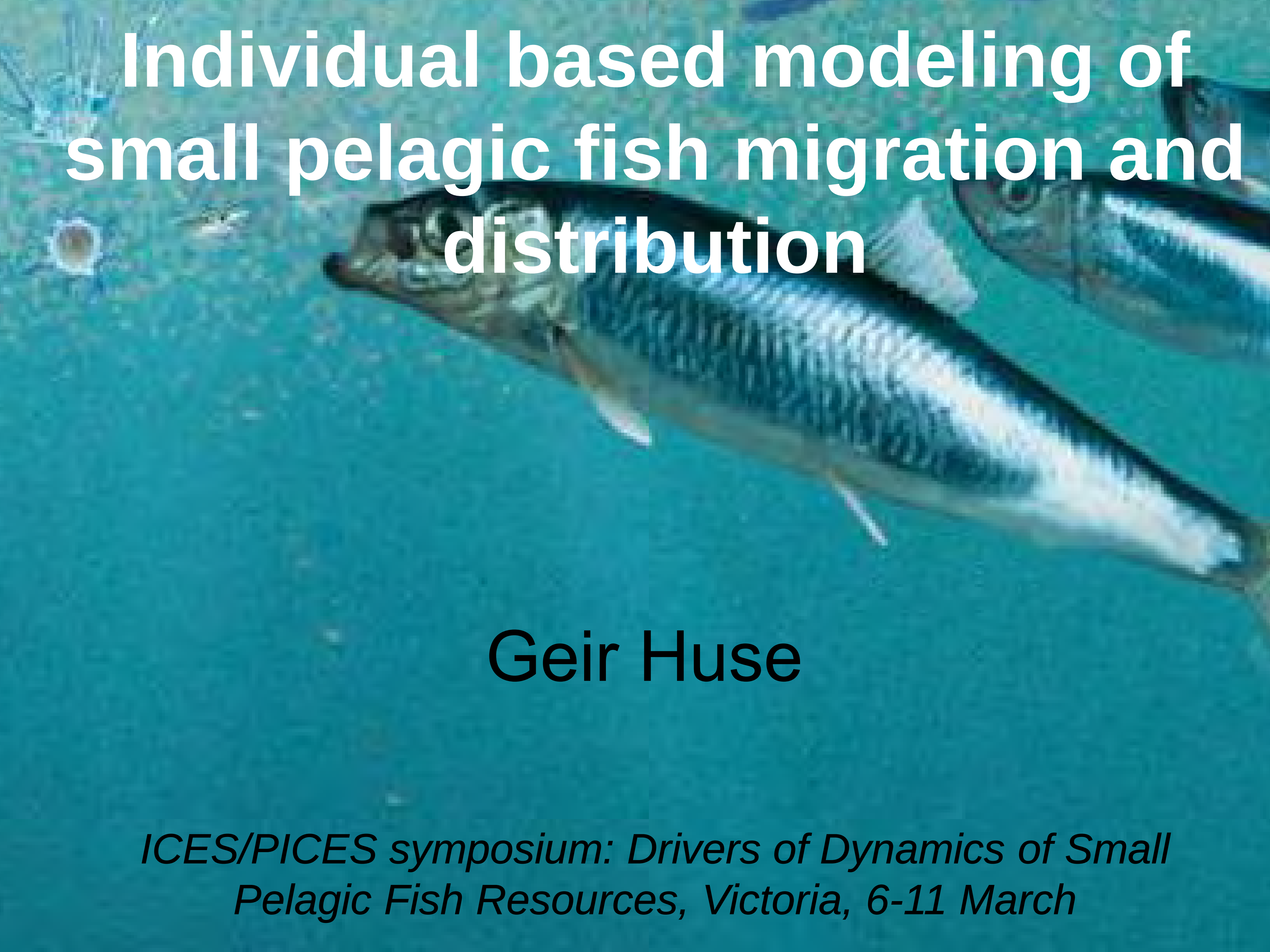


Individual based modeling of small pelagic fish migration and distribution

Geir Huse

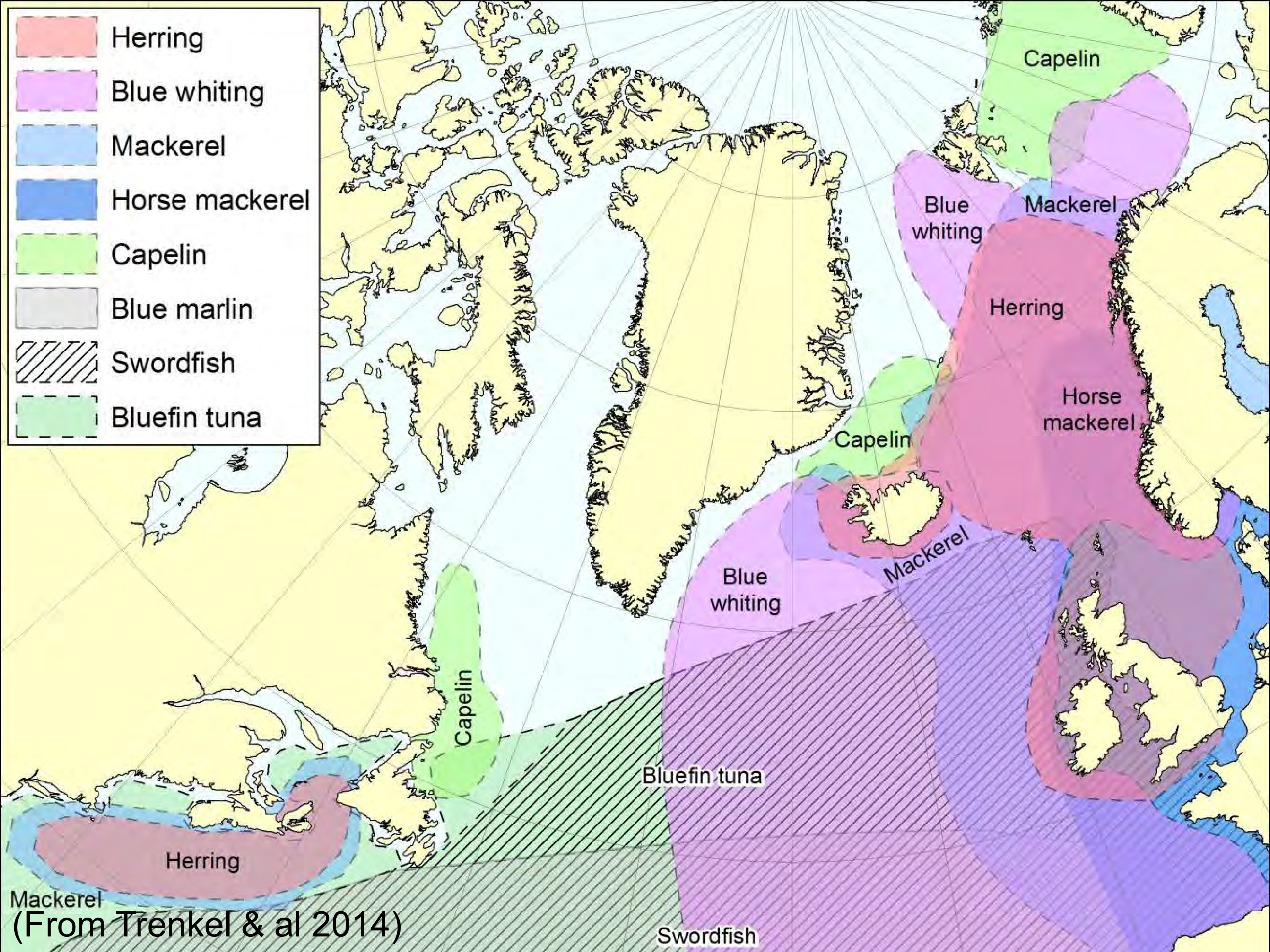
ICES/PICES symposium: Drivers of Dynamics of Small Pelagic Fish Resources, Victoria, 6-11 March

Outline

- WHY?
  - Motivation for modellling fish migration and distribution
- HOW?
  - Introduction to some key concepts
- WHAT?
  - Presenting four case studies
- WHERE?
  - Suggestions about where to go next

WHY?

- Improve understanding of fish distribution and migration and responses to the environment including climate change



(From Trenkel & al 2014)

WHY?

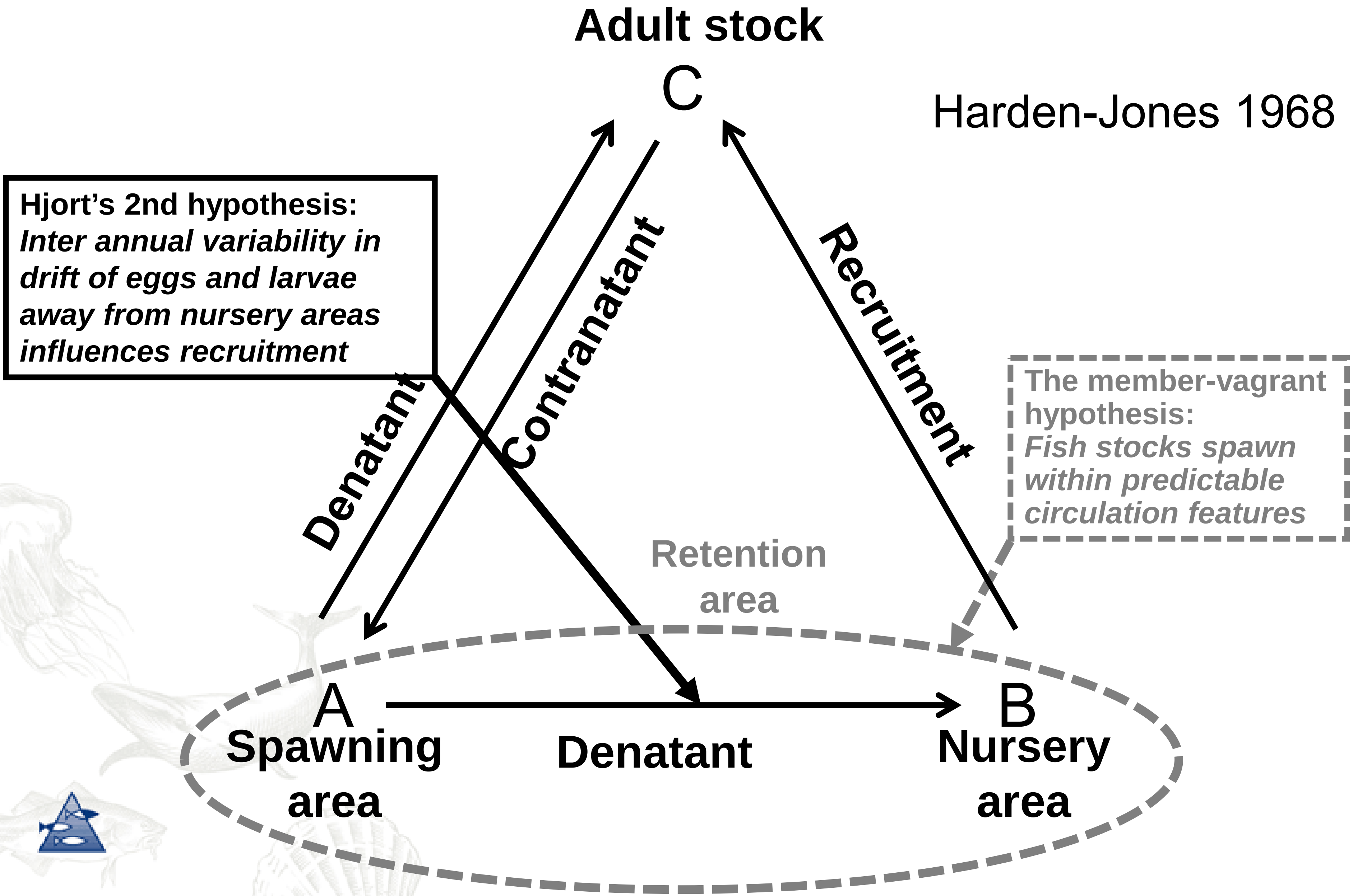
- Improve understanding of fish distribution and migration and responses to the environment including climate change
- Study species interactions, predator-prey dynamics
- Parameterisation of ecosystem models
- Plan surveys
- ..

HOW?

- Introducing some key concepts as basis for modelling migration and distribution
- Introduction to super-individual approach for simulating migration and distribution
- Assumptions & emergence

Key concepts in fish stock migration

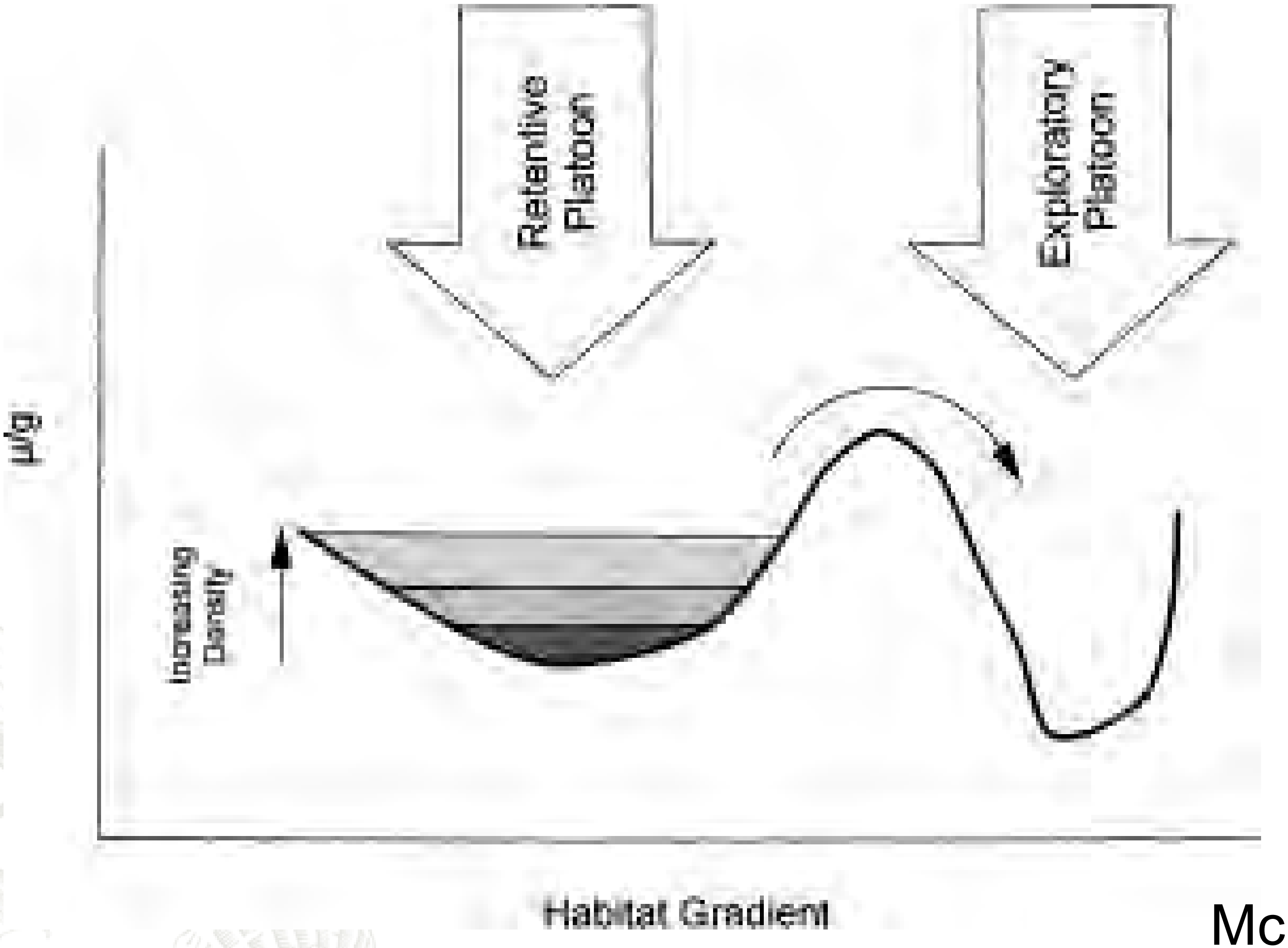
Harden-Jones 1968



Hjort's 2nd hypothesis:
Inter annual variability in drift of eggs and larvae away from nursery areas influences recruitment

The member-vagrant hypothesis:
Fish stocks spawn within predictable circulation features

Key concept i fish stock distribution



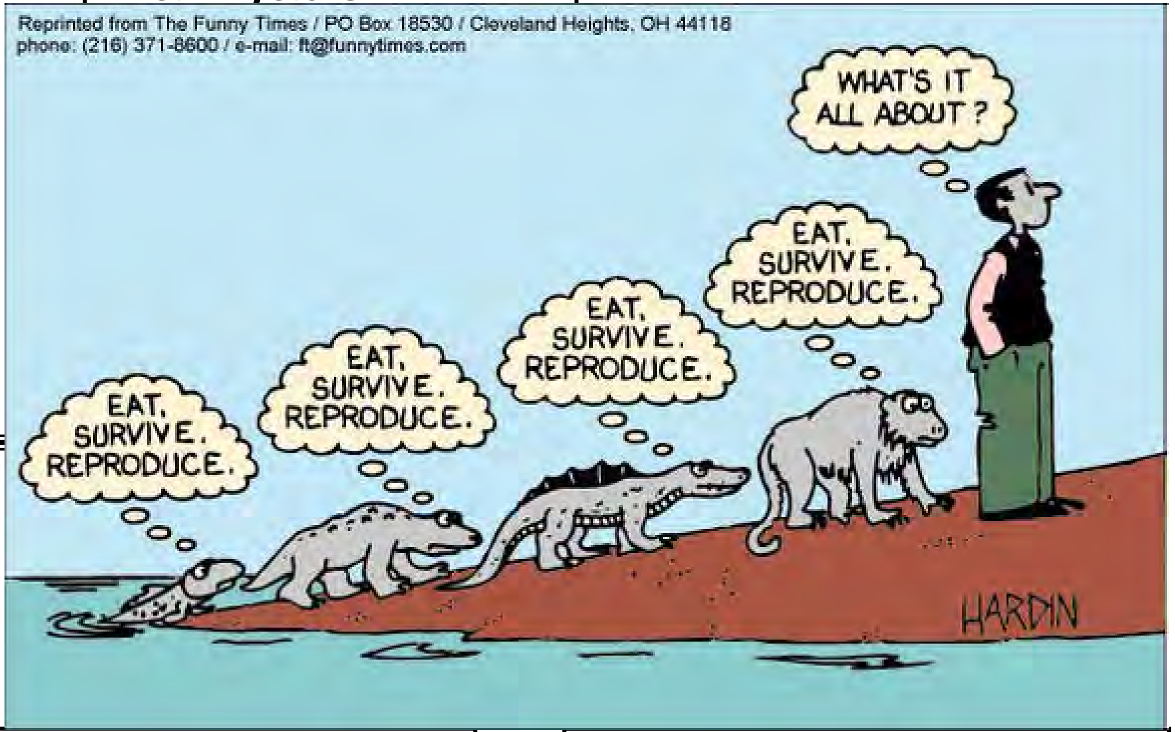
McCall 1990

Capabilities

Sensory
Navigation

Forcing factors

Currents, Smell, Salinity, Light Pressure, Sound, Oxygen, Temperature, Prey, Predators, Competition, Collectives



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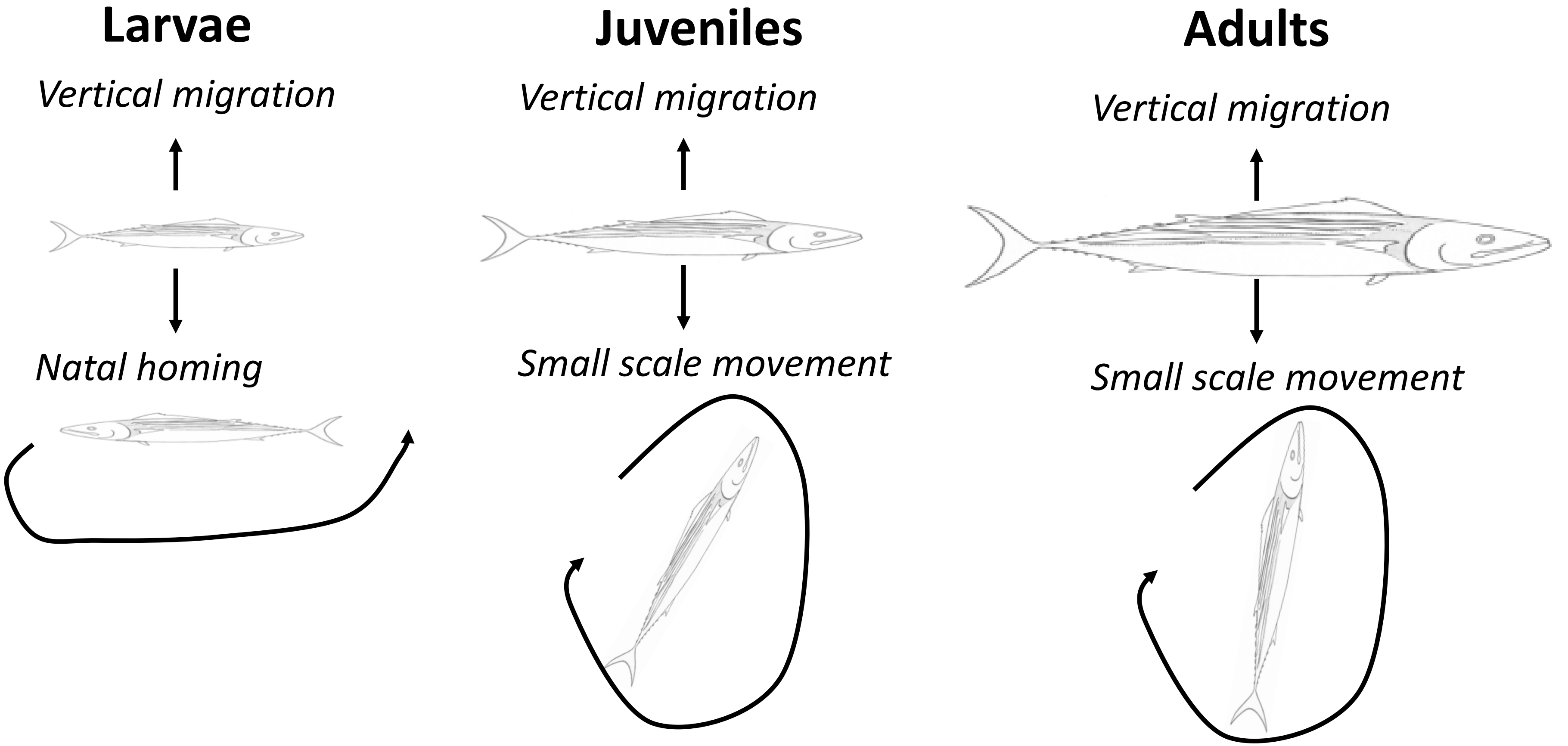
Evolution
Phenotypic plasticity
Individual learning
Social learning & tradition

Adaptation

Eat
Survive
Reproduce

Ultimate causes

Movement repertoire of fish in different life stages



Larvae

Vertical migration

Natal homing

Juveniles

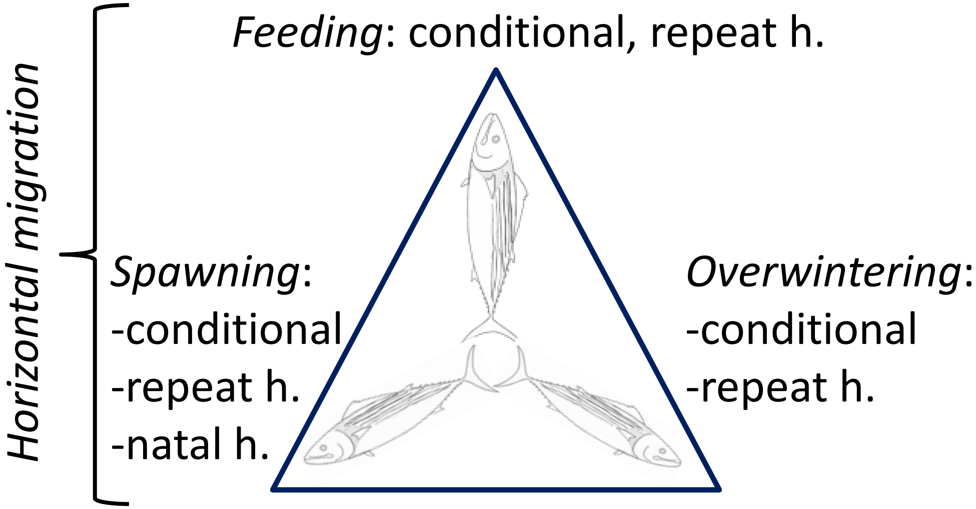
Vertical migration

Small scale movement

Adults

Vertical migration

Small scale movement



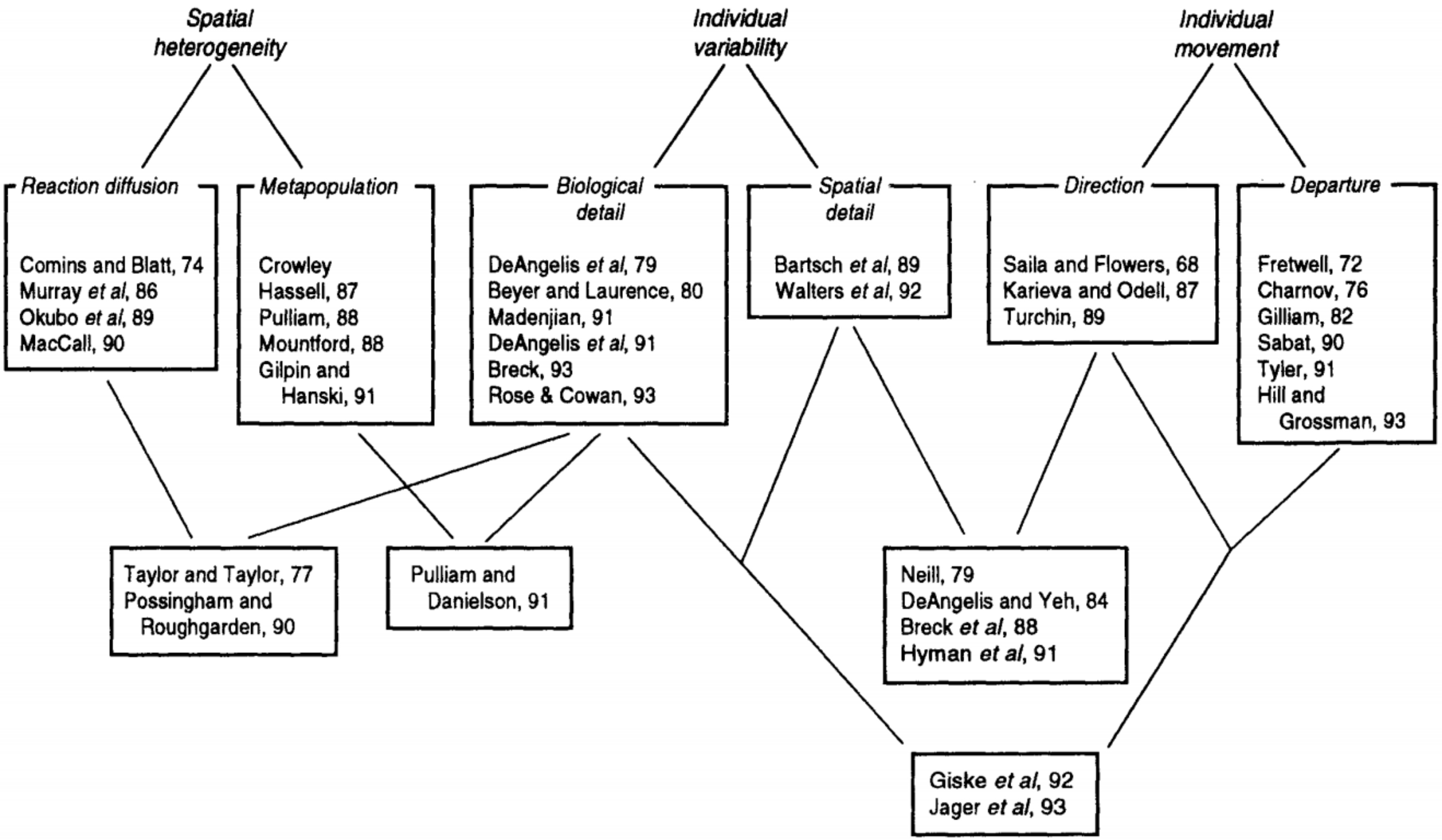
Horizontal migration

Feeding: conditional, repeat h.

Spawning:
-conditional
-repeat h.
-natal h.

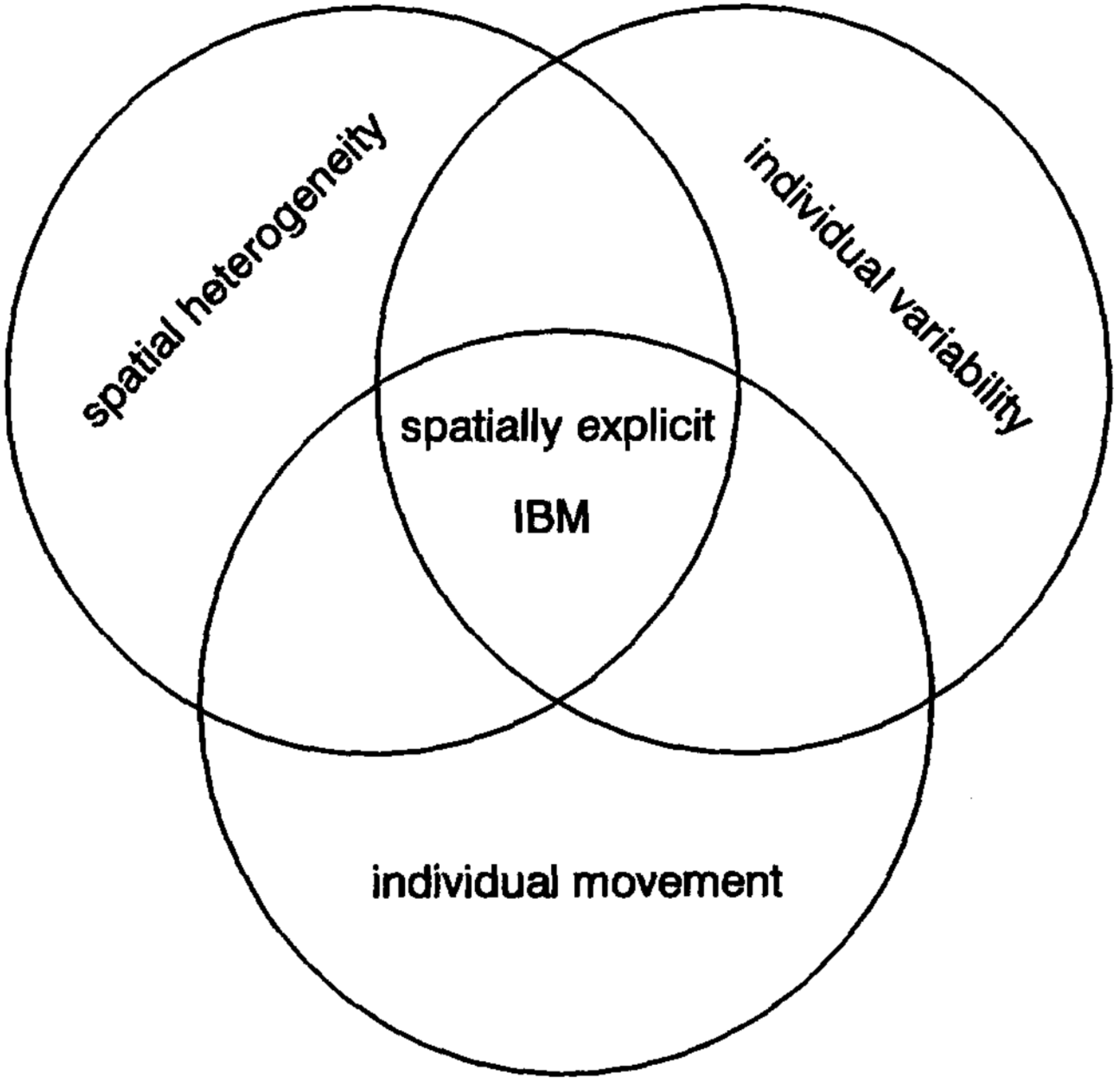
Overwintering:
-conditional
-repeat h.

Classifying spatial fish models

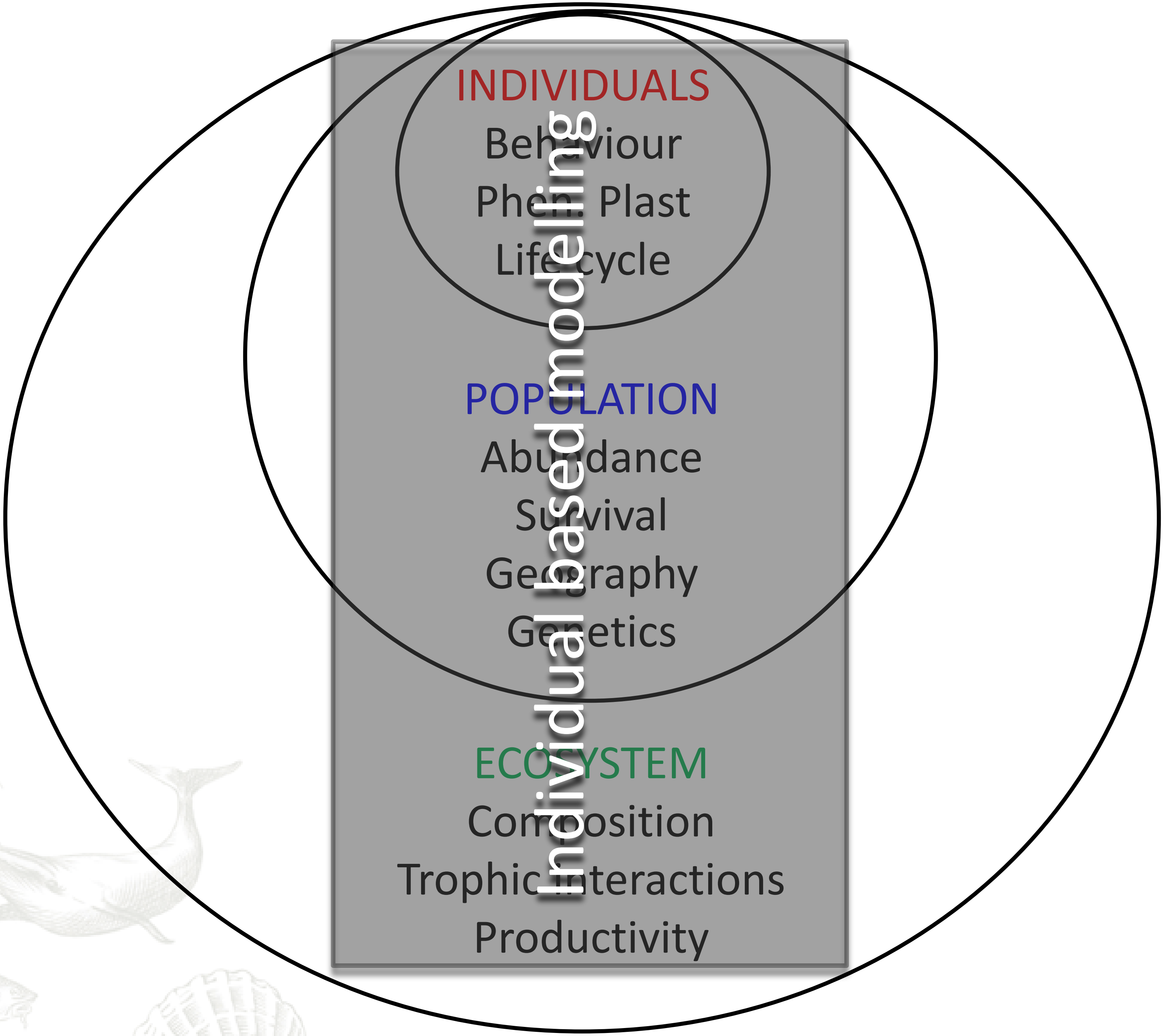


From Tyler & Rose 1994

Classifying spatial fish models



From Tyler & Rose 1994



INDIVIDUALS

Behaviour

Phen. Plast

Life cycle

POPULATION

Abundance

Survival

Geography

Genetics

ECOSYSTEM

Composition

Trophic interactions

Productivity

Individual based modelling

Spesifying individuals in IBMs:

Attribute vector A_i: (Chambers 1993)
Contains all the "book keeping" characters of an individual such as weight, age, length, position

$\mathbf{A_i} = (\alpha 1_i, \alpha 2_i, \alpha 3_i, \ldots, \alpha m_i, x_i, y_i, z_i, t)$

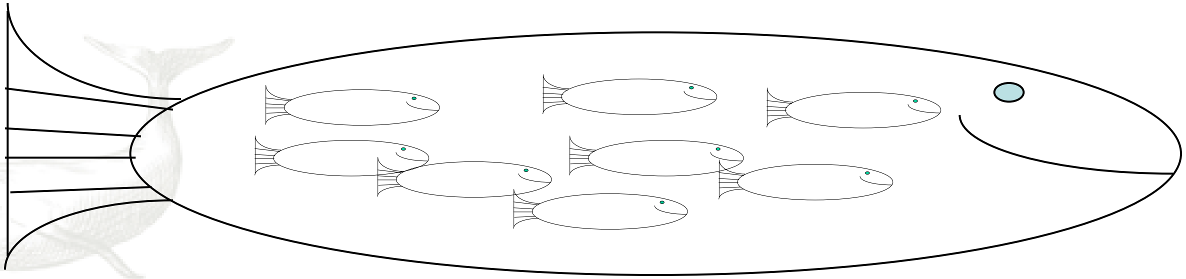
Strategy vector S_i:
Contains adaptive characters – may be fixed rules or traits for optimization by evolution or learning

$\mathbf{S_i} = (b1_i, b2_i, b3_i, \ldots, bm_i)$

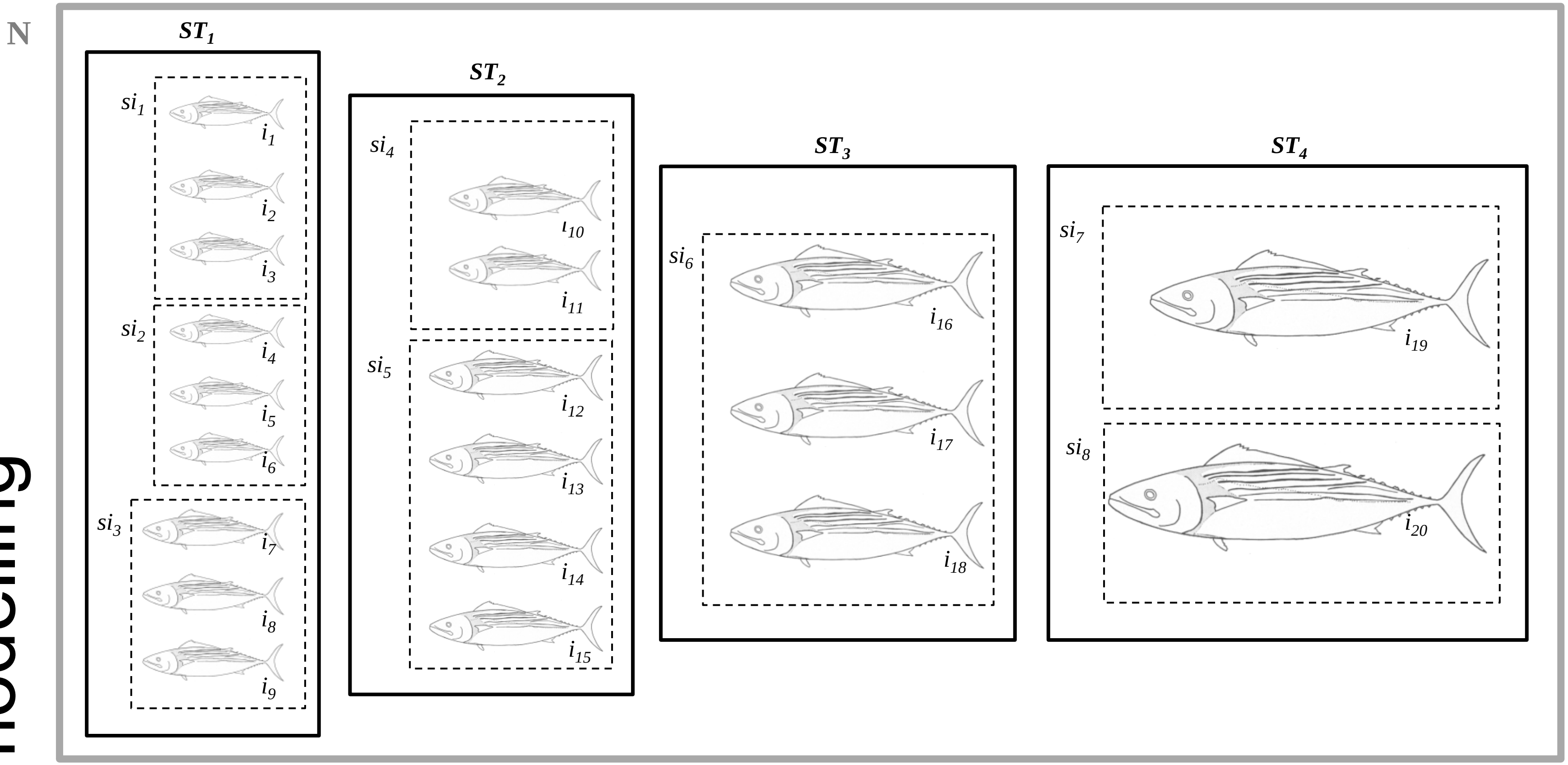
Representation of fish populations: Super individuals (*Scheffer et al. 1995*)

A super individual represents many identical individuals and in this case the number of such identical siblings ($\boldsymbol{n_s}$) thus becomes an attribute of the super individual:

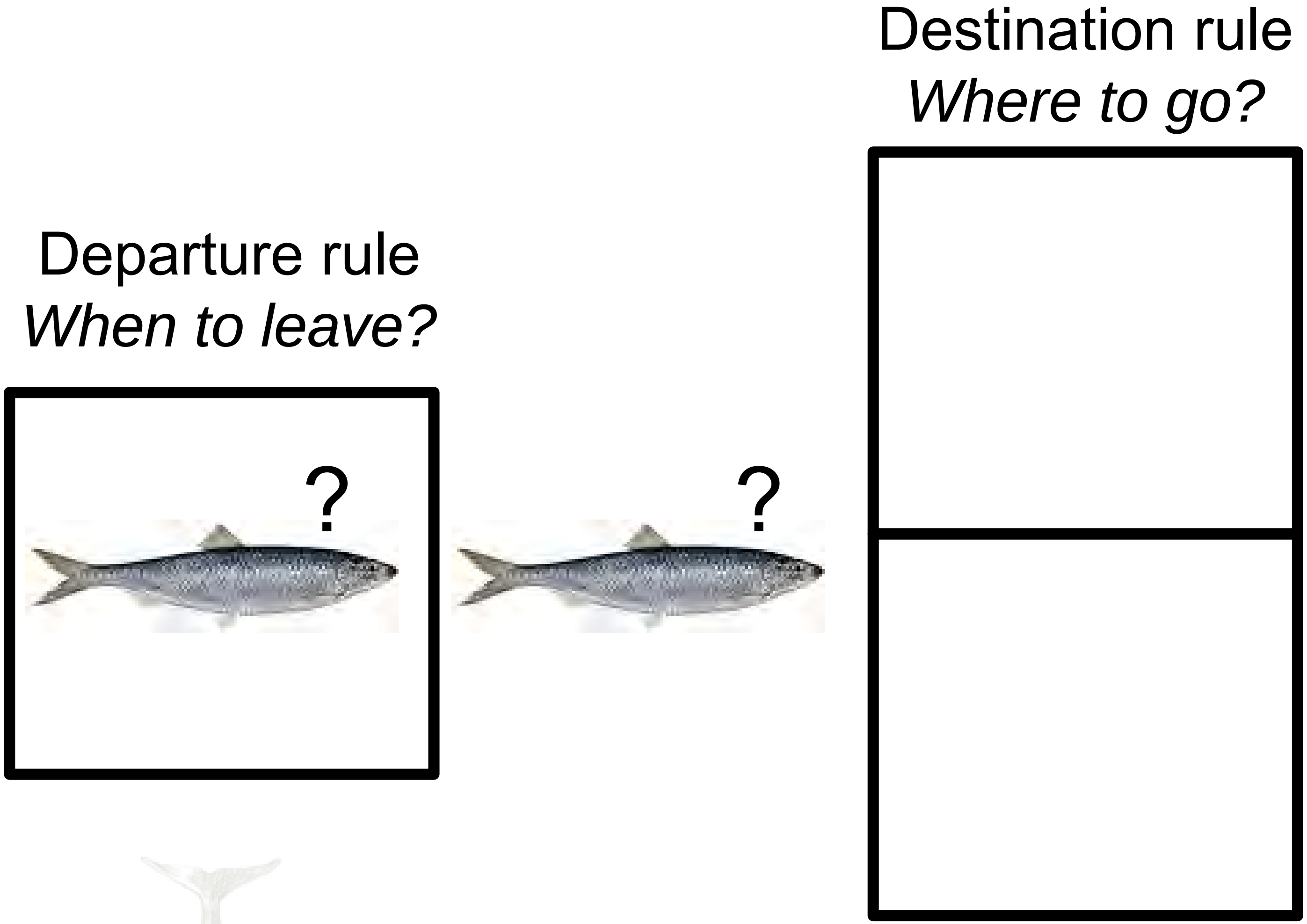
$$\mathbf{A_s} = (\alpha 1_s, \alpha 2_s, \alpha 3_s, \ldots, \alpha m_s, x_s, y_s, z_s, \boldsymbol{n_s}, t)$$



Structuring of population modelling



Movement rules



Destination rule

Where to go?

Departure rule

When to leave?

Two approaches for migration modelling:

- Pattern matching – fitting observations
- Process based – fitness max., rules etc.

Movement rules

Departure rule
When to leave?

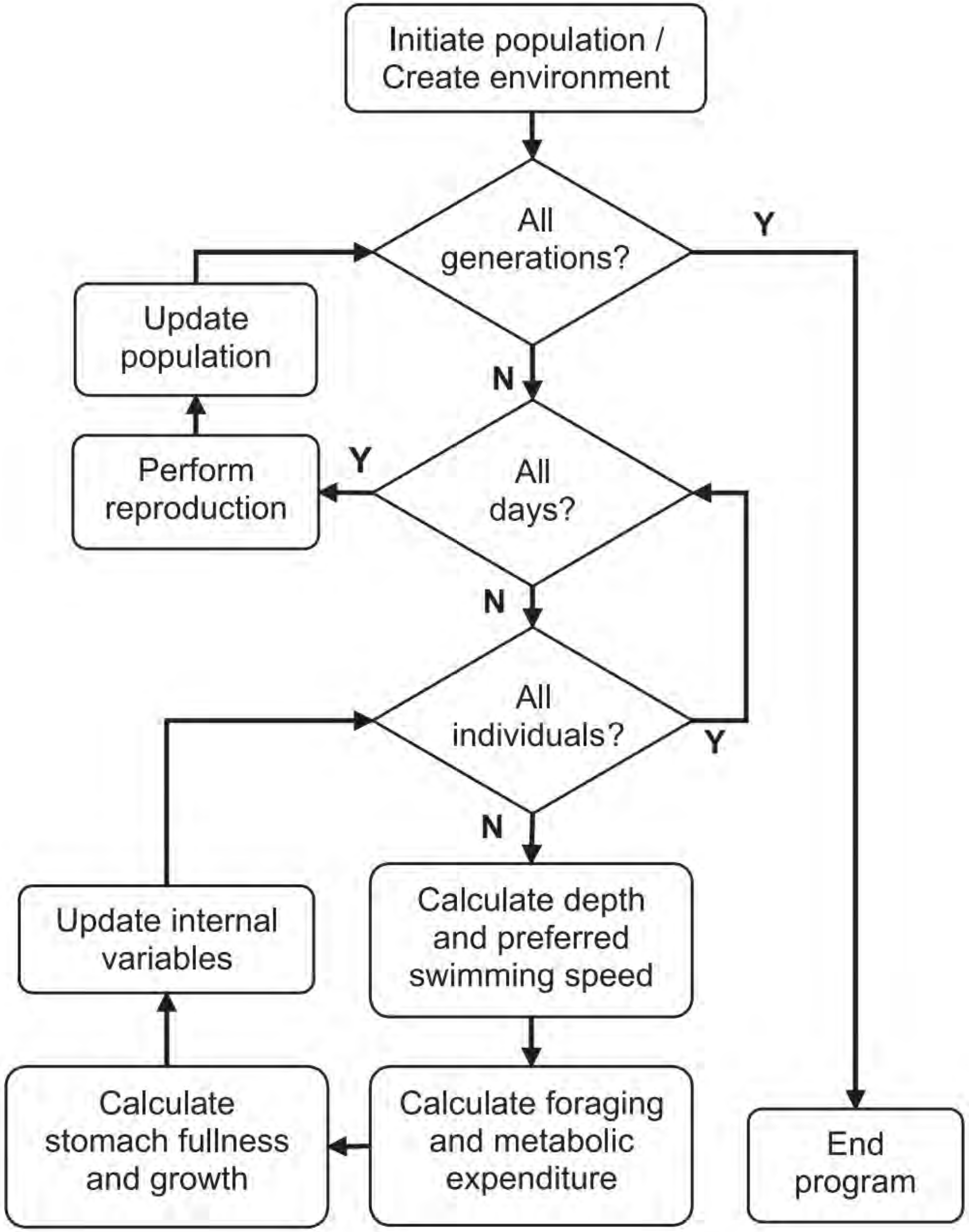
- **Life history rules**
  - Minimize μ/g
  - Marginal value theorem
  - Unified Foraging Theory
  - Growth < T
  - Mortality > T
  - ..

Destination rule
Where to go?

- **Life history rules**
  - Minimize μ/g
  - Unified Foraging Theory
- **Ethological rules**
  - Taxis
  - Kinesis
- **Environmental "rules"**
  - Borders for movement
- **Pattern matching**
  - Using observations to "tune" movement

- **Integrated approaches**
  - SDP
  - ANNs & Gas
  - Predictive & reactive

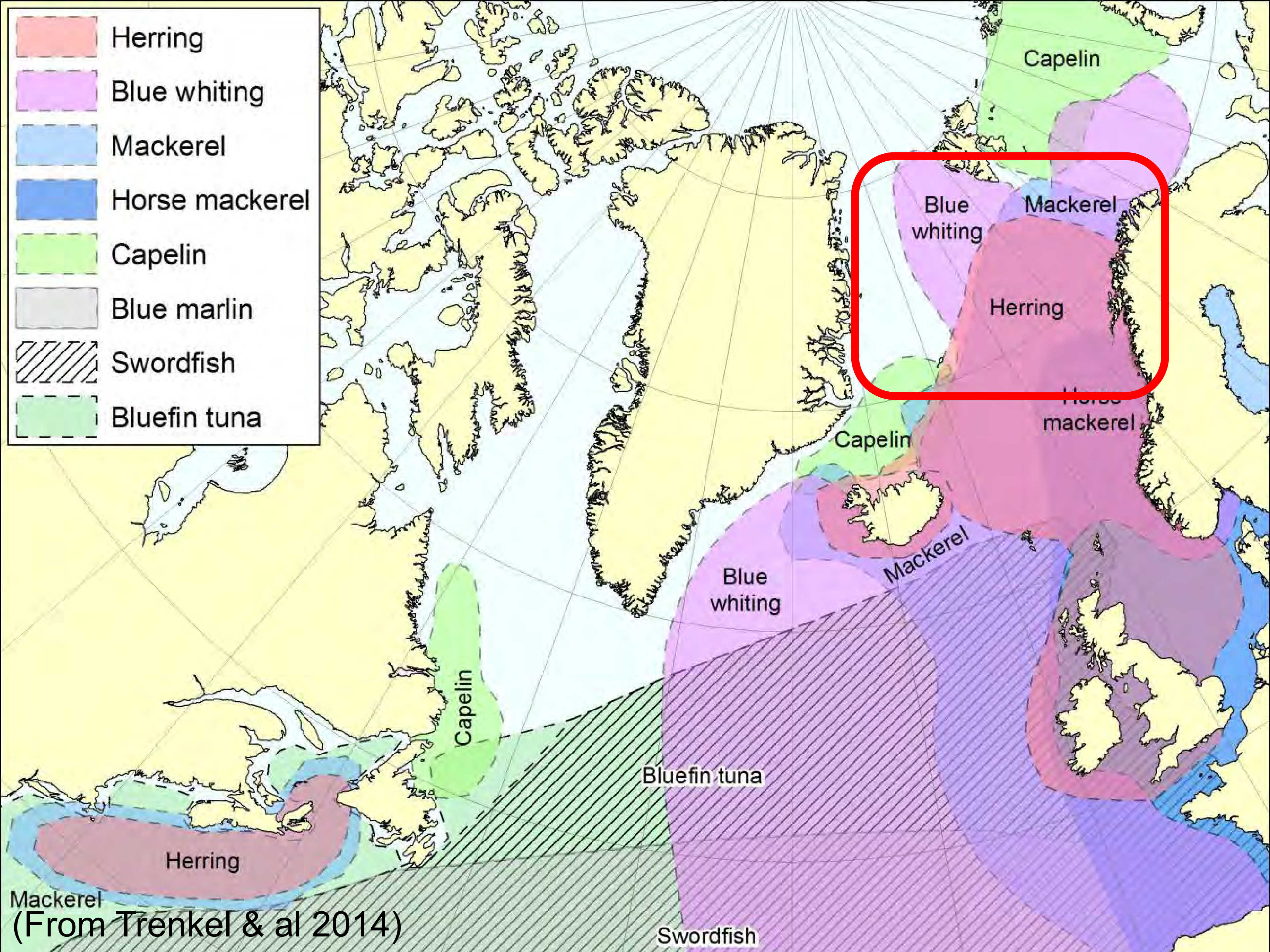
IBM Flowchart



WHAT?

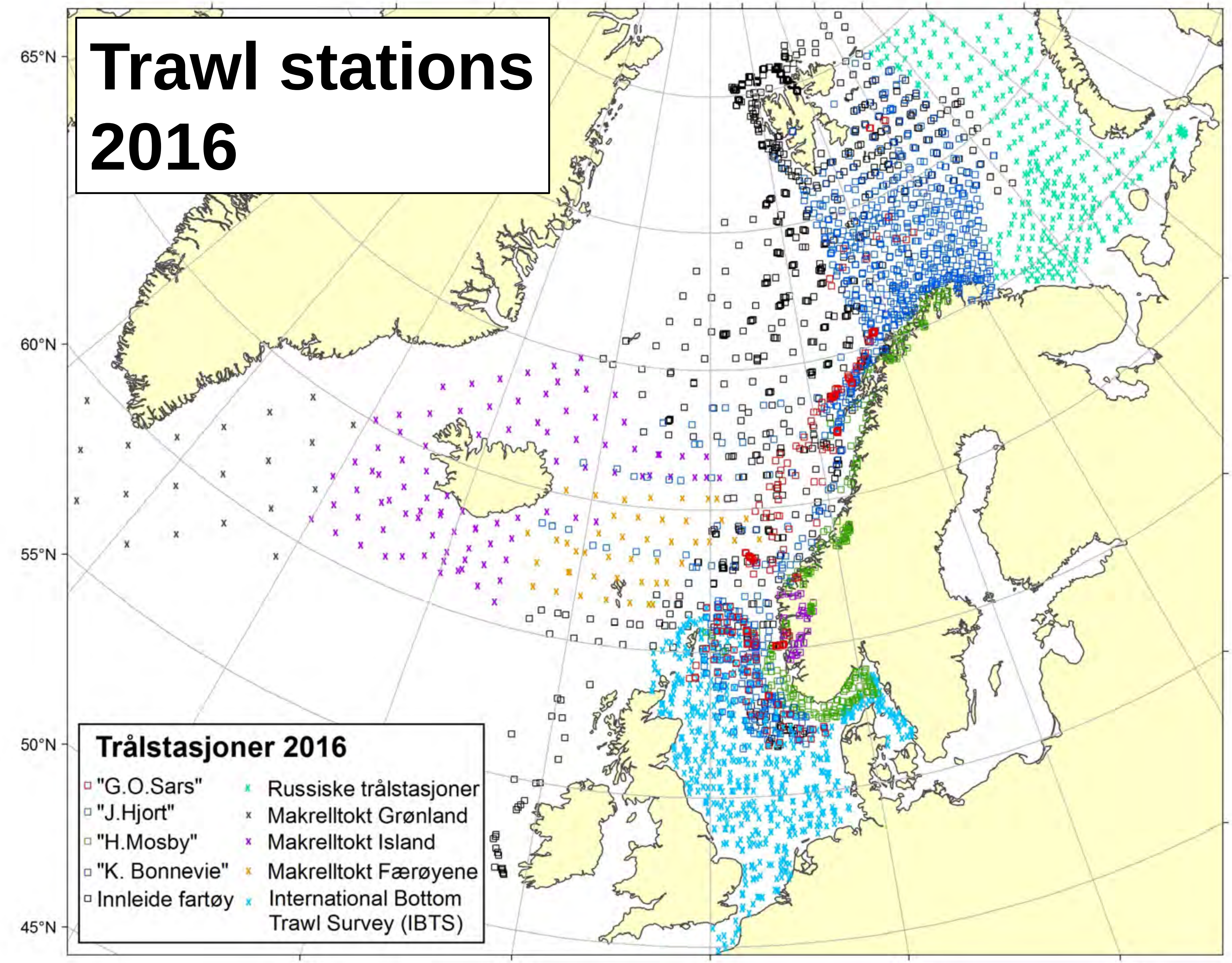
Four case studies:

1. The migrations of the pelagic complex in the Norwegian Sea
2. Cod-capelin interactions in the Barents Sea
3. An analysis of capelin responses to climate change
4. Using migration models to test monitoring surveys

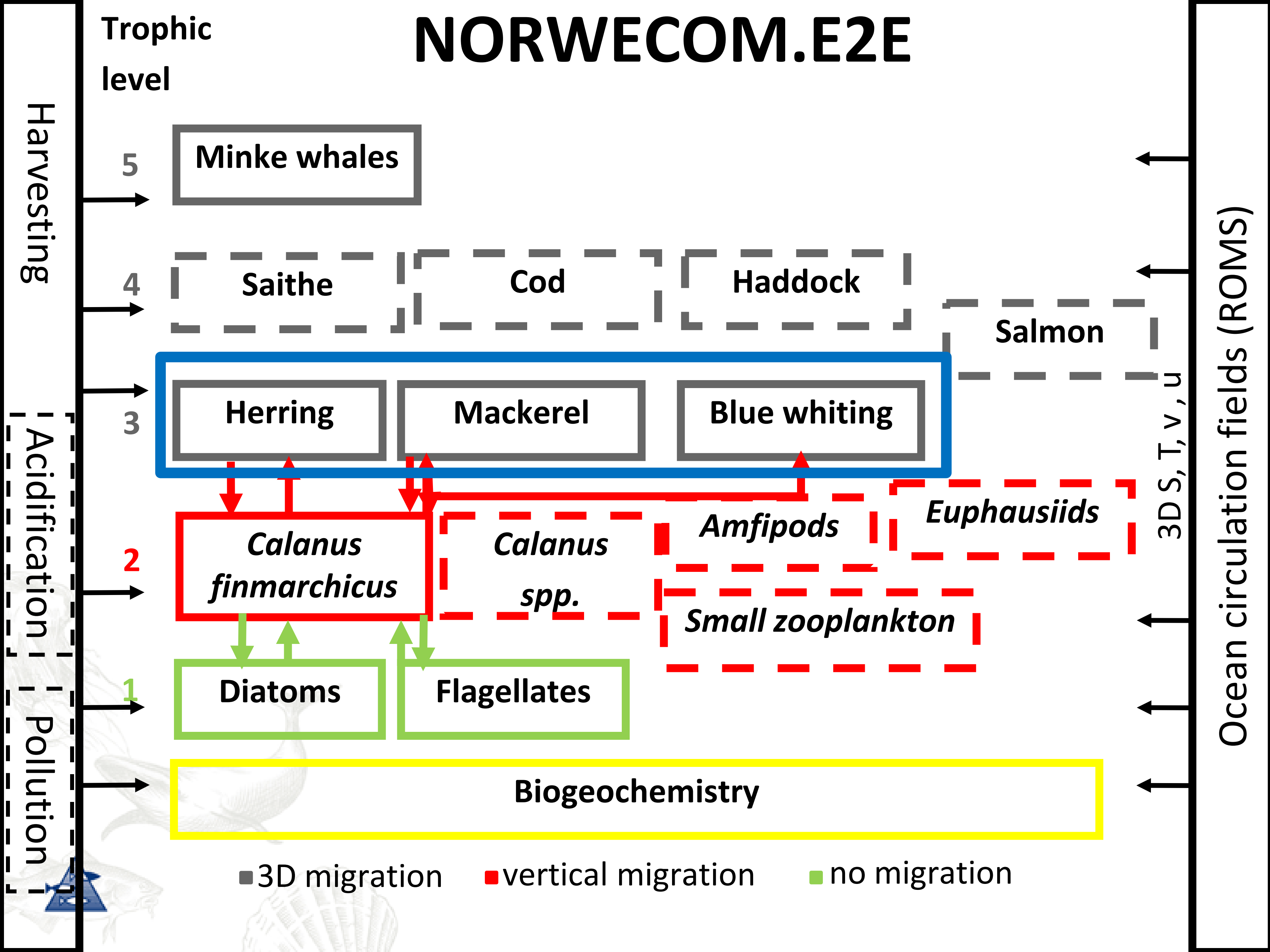


(From Trenkel & al 2014)

Trawl stations 2016

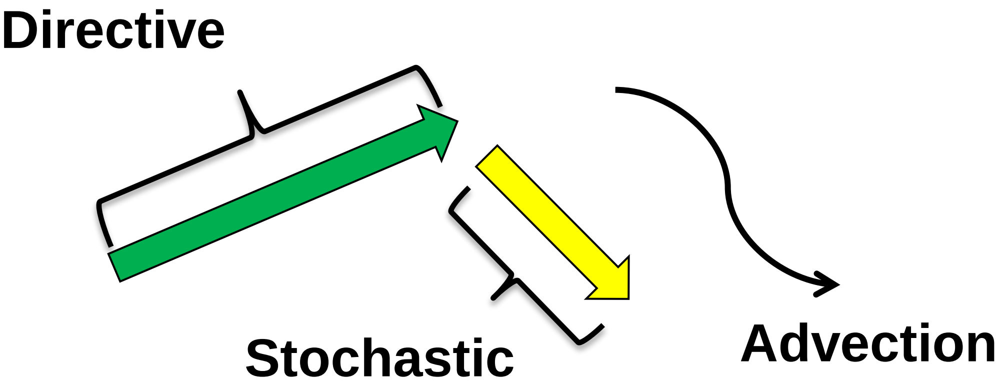


NORWECOM.E2E



Migration model

Individual movement – own decision and currents

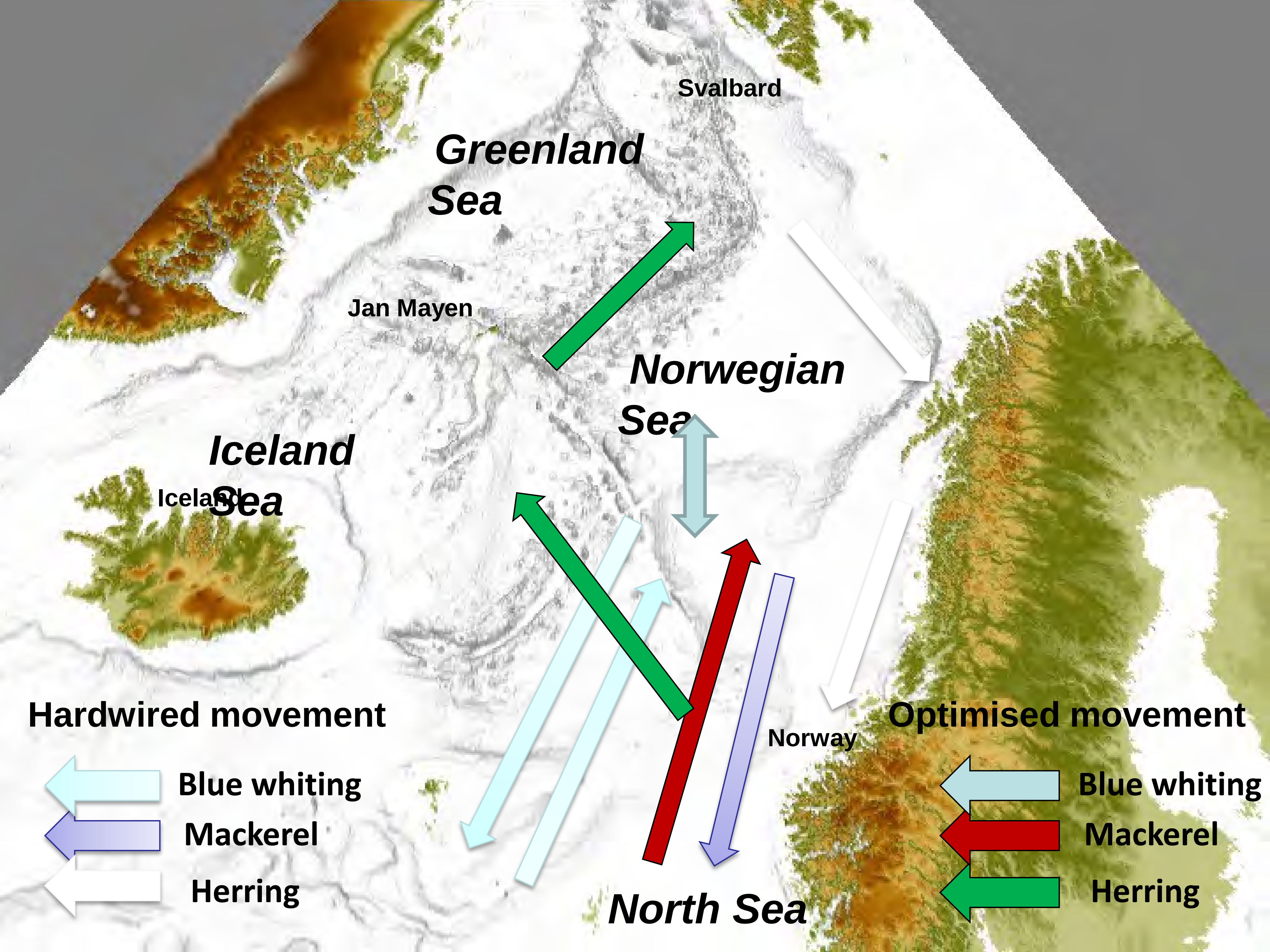


Directive

Stochastic

Advection

- The fish cannot migrate into water masses colder than 2 (her and bw) or 8° C (mac).
- The simulations are a combination of modelling fish movement and hardwired movement.



Hardwired movement

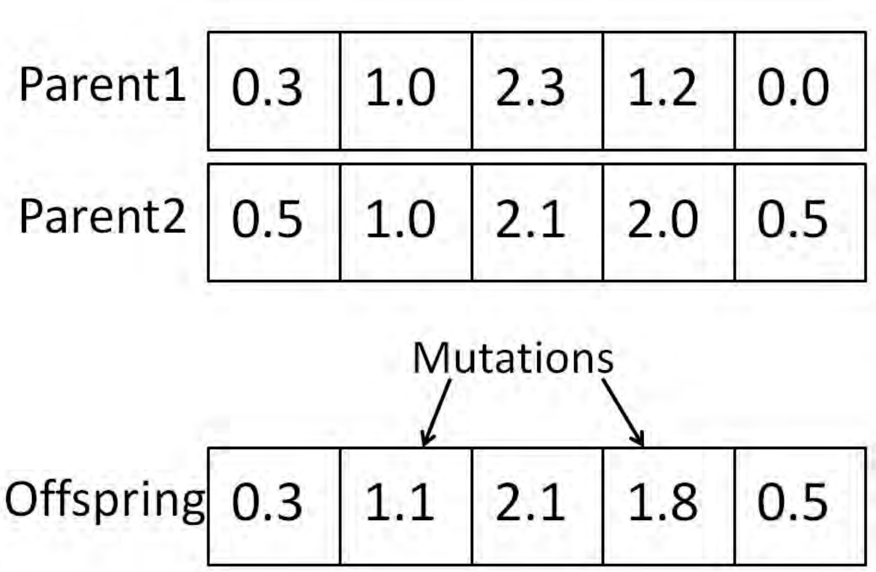
- Blue whiting
- Mackerel
- Herring

Optimised movement

- Blue whiting
- Mackerel
- Herring

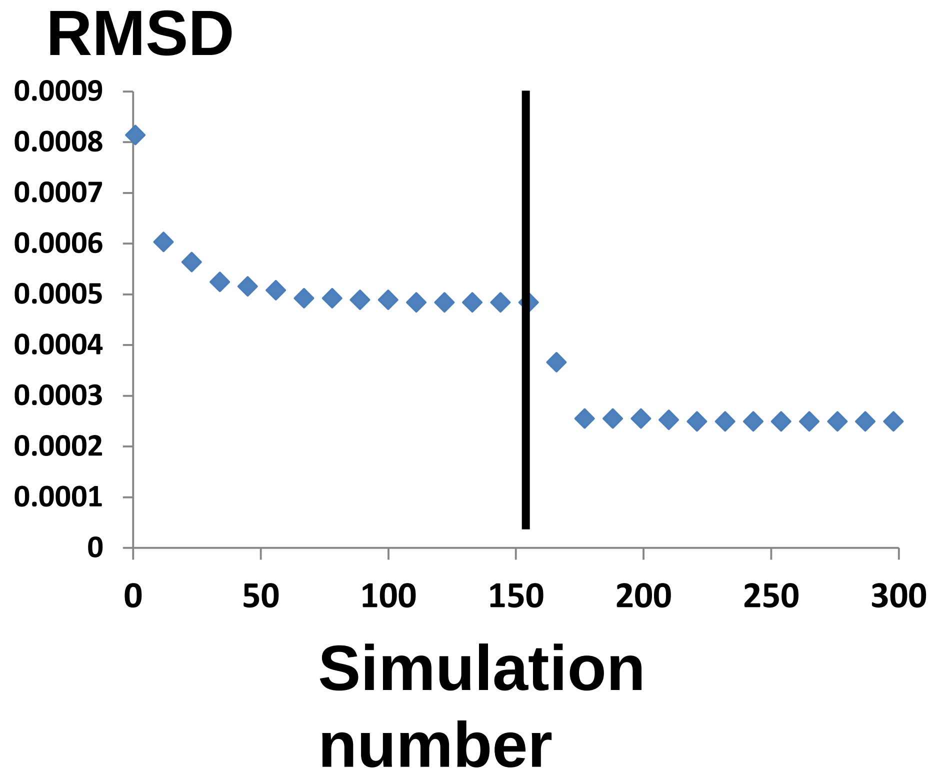
Optimize migrations parameters

- Migration speed, direction and randomness
- Survey observations
- Genetic Algorithm (GA)
- 10 simulations, keep 2, 30 generations

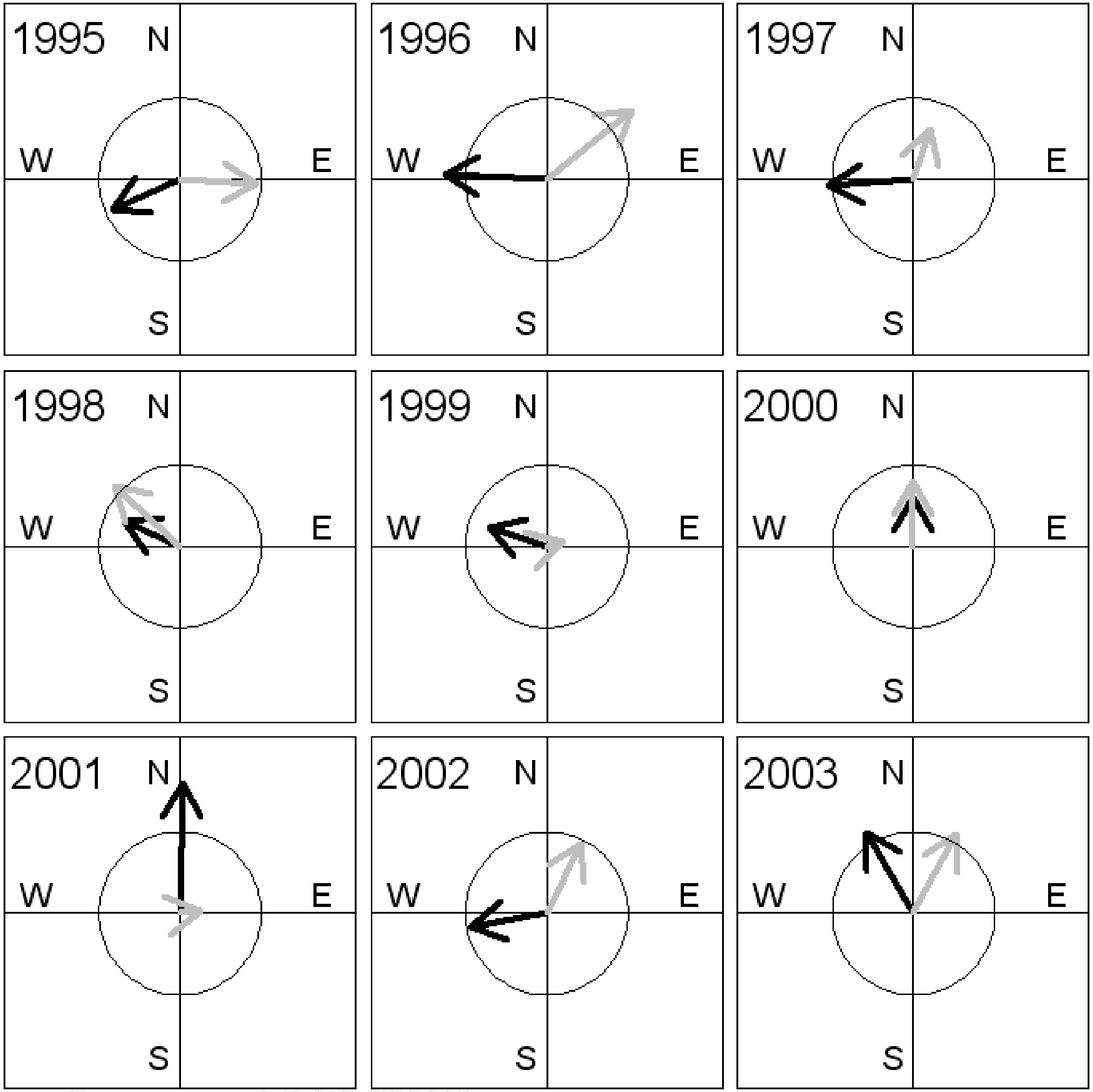


Parent1	0.3	1.0	2.3	1.2	0.0
Parent2	0.5	1.0	2.1	2.0	0.5
Offspring	0.3	1.1	2.1	1.8	0.5

Mutations



Herring migration vectors



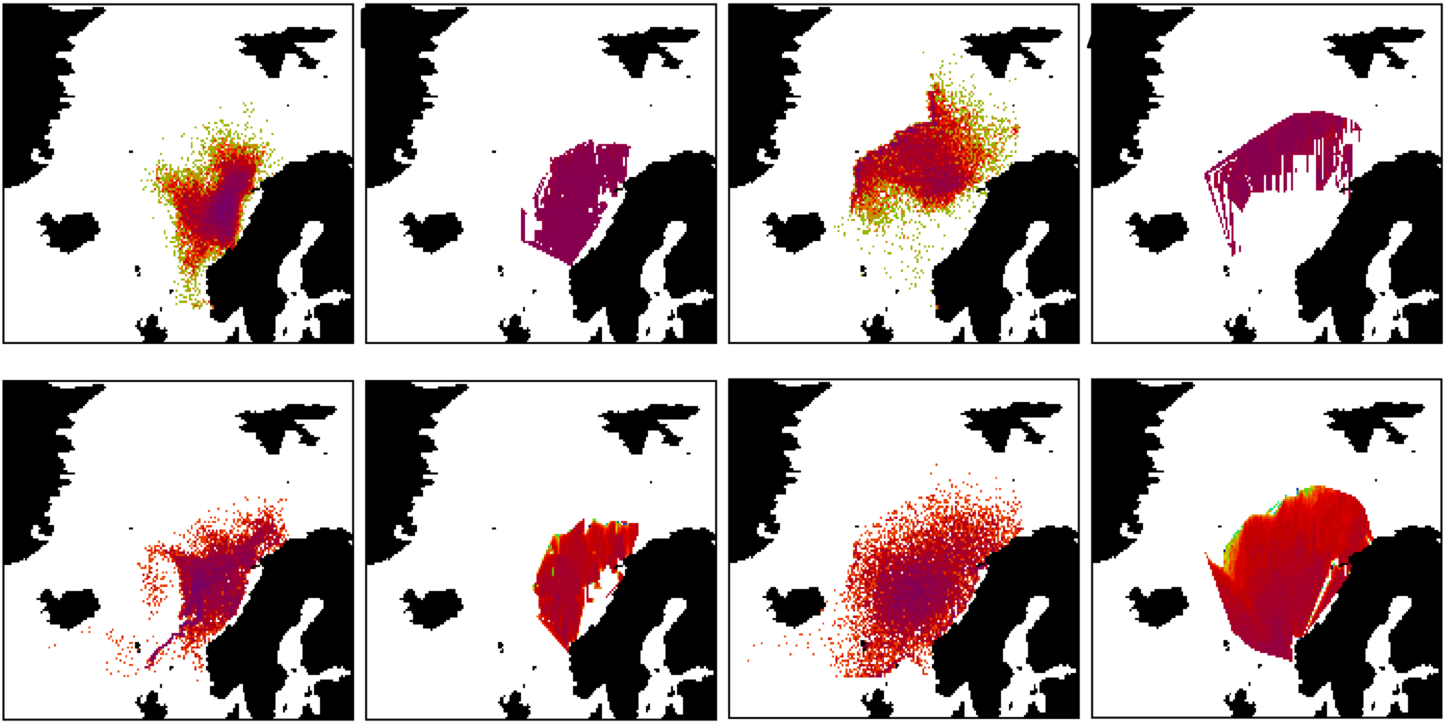
Black arrows
Early summer

Gray arrows
Late summer

Predictions **Observations** **Predictions** **Observations**

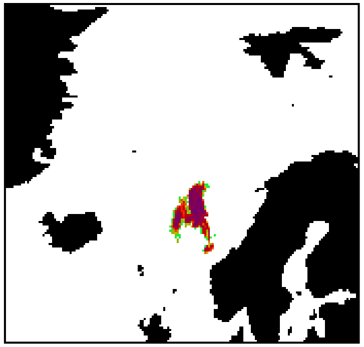
Herring

Blue whiting

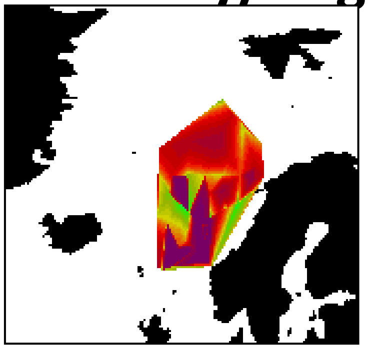


Mackerel

Predictions July



Obs. July/Aug



Obs. July

Simulated seasonal migrations of pelagic fish

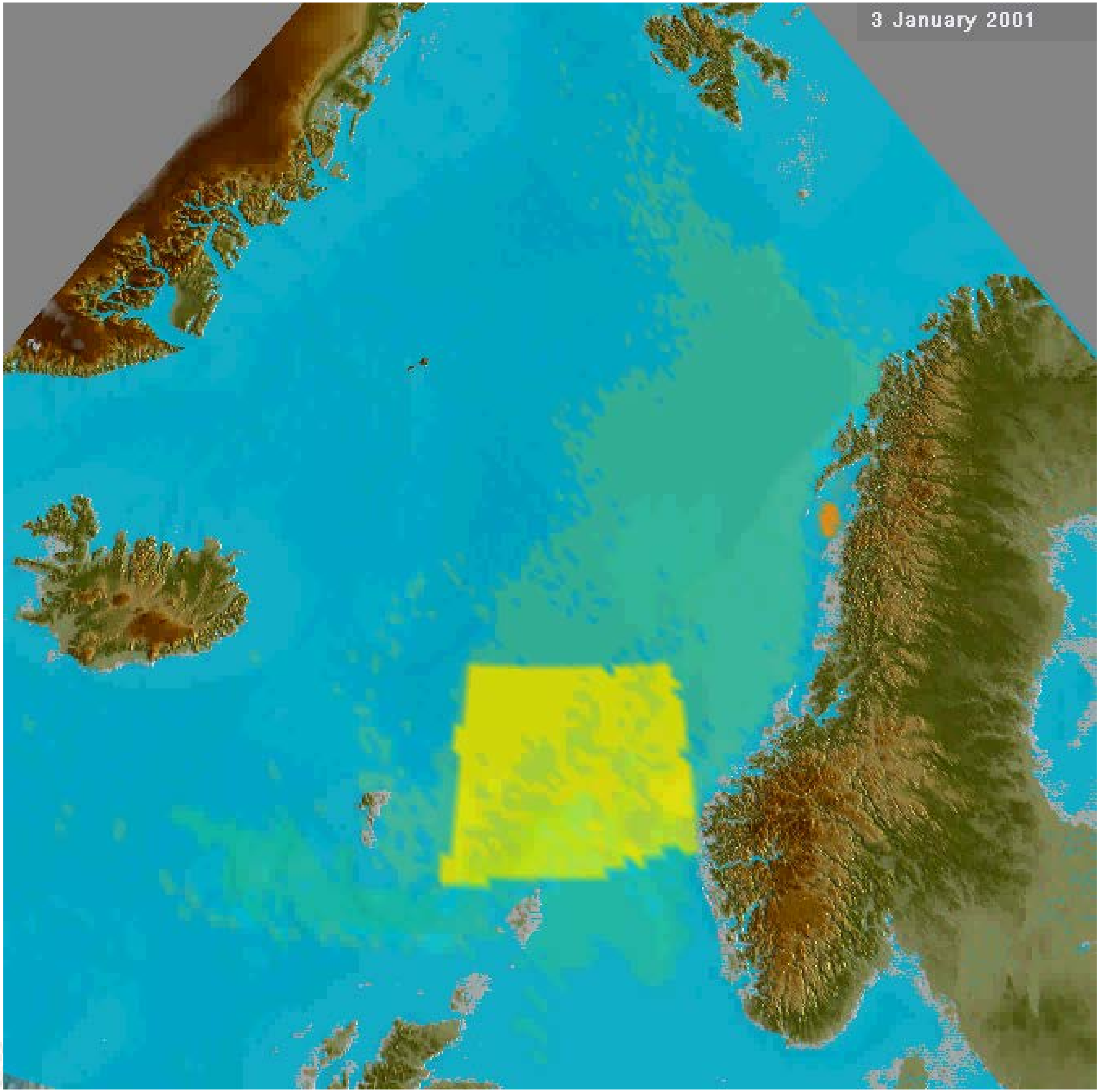
🟧 

🟨 

🟩 

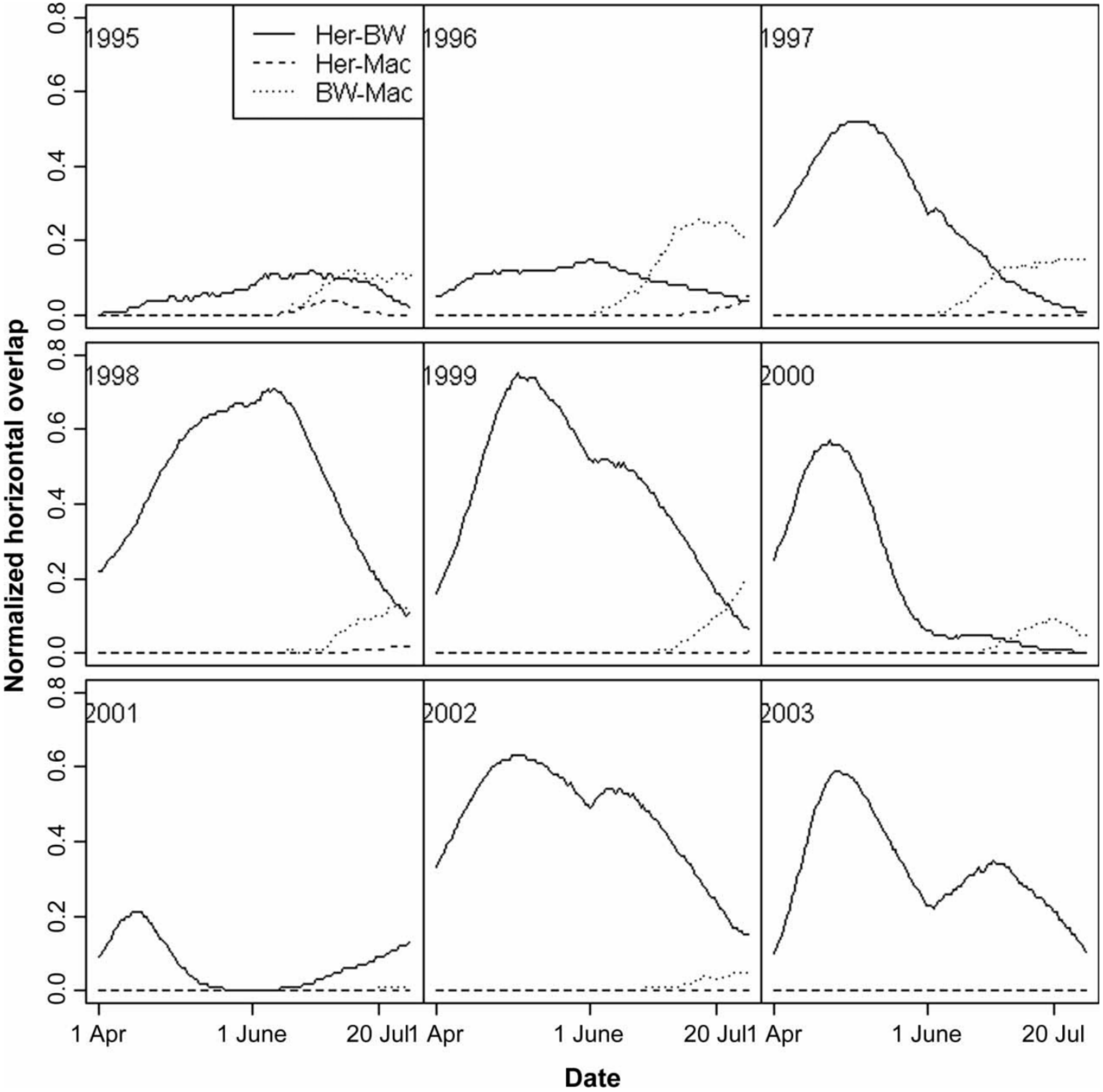
🟦 Overlap between two species

🟥 Overlap between three species

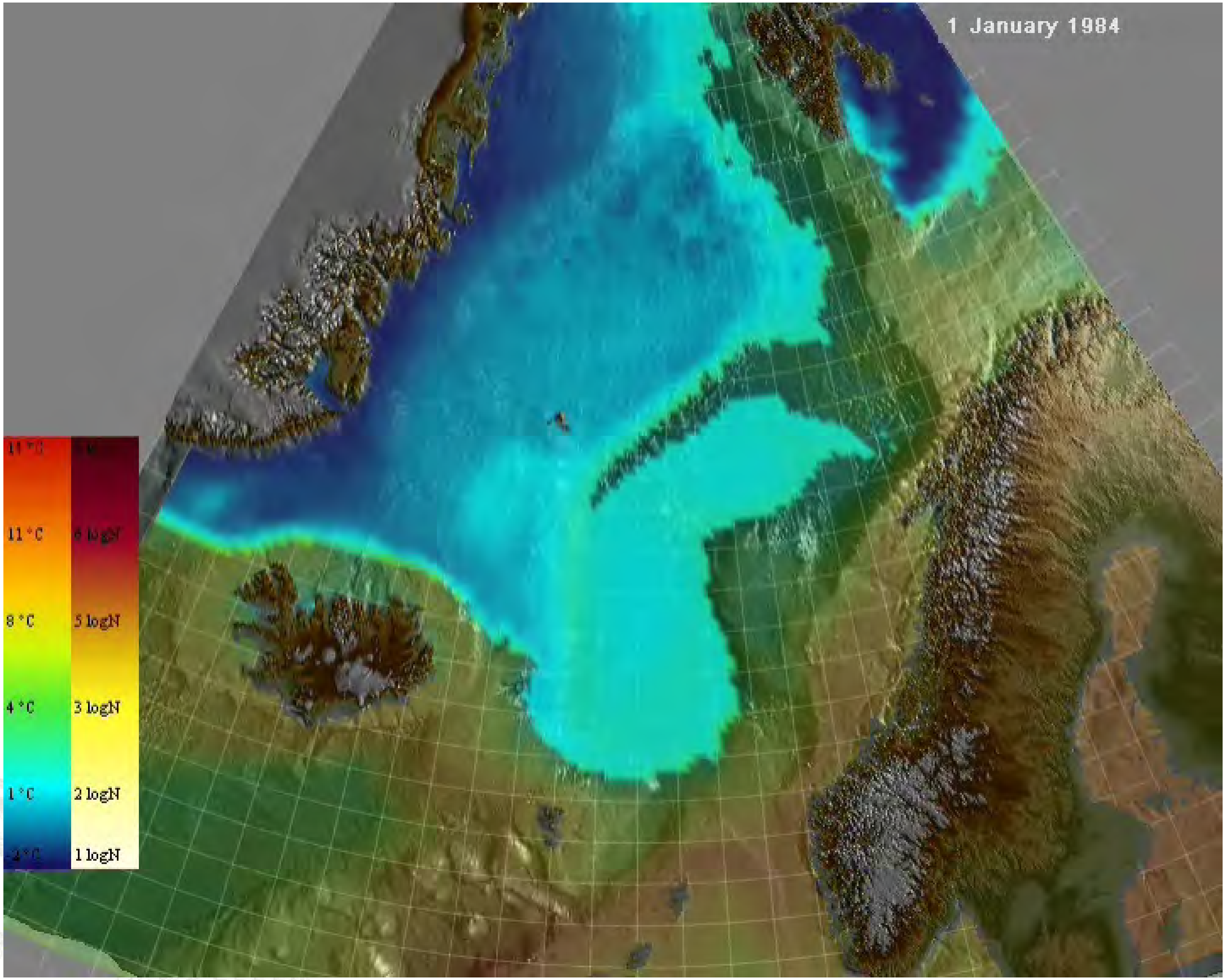


(Utne & al. 2012)

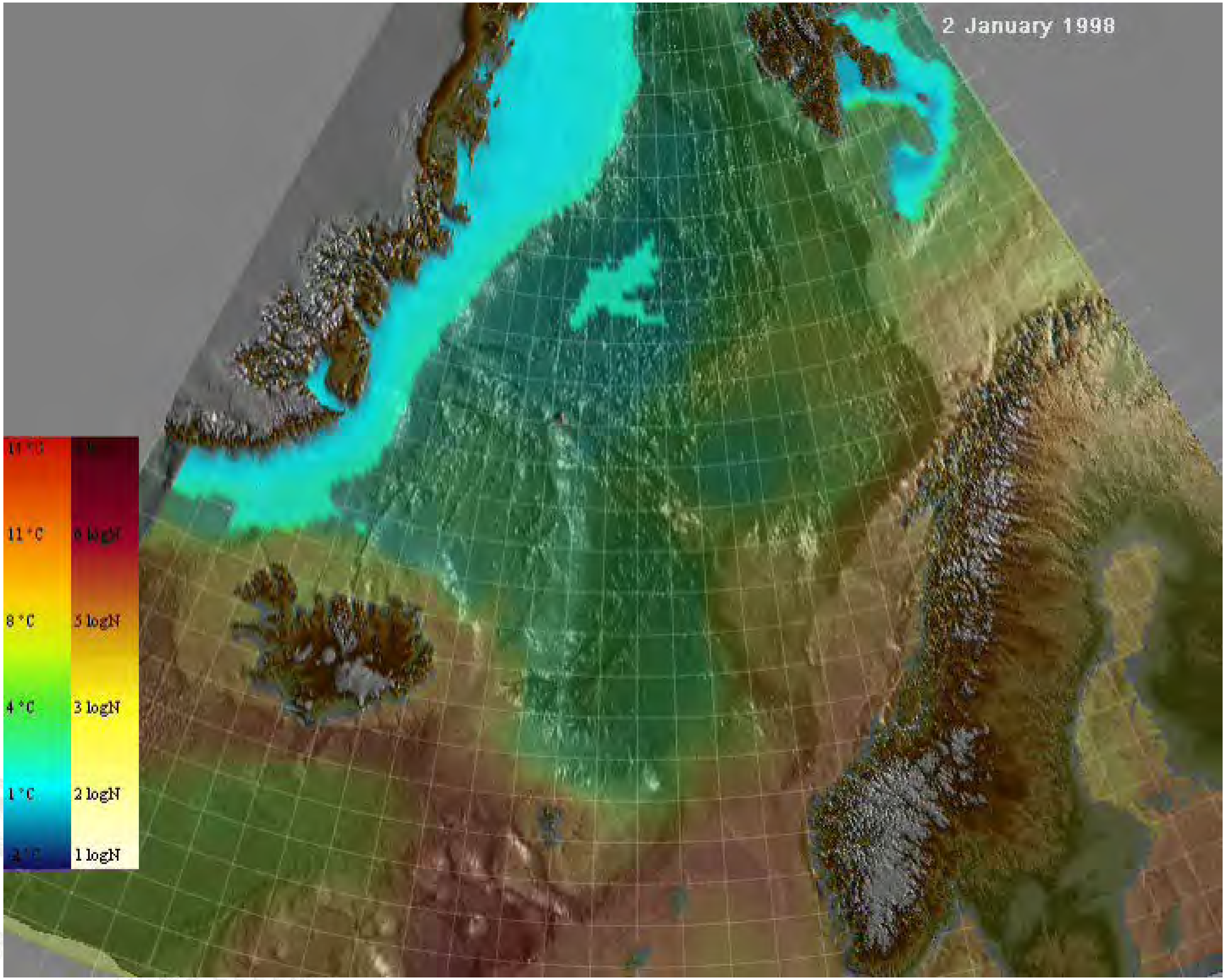
Horizontal overlap between herring, blue whiting and mackerel



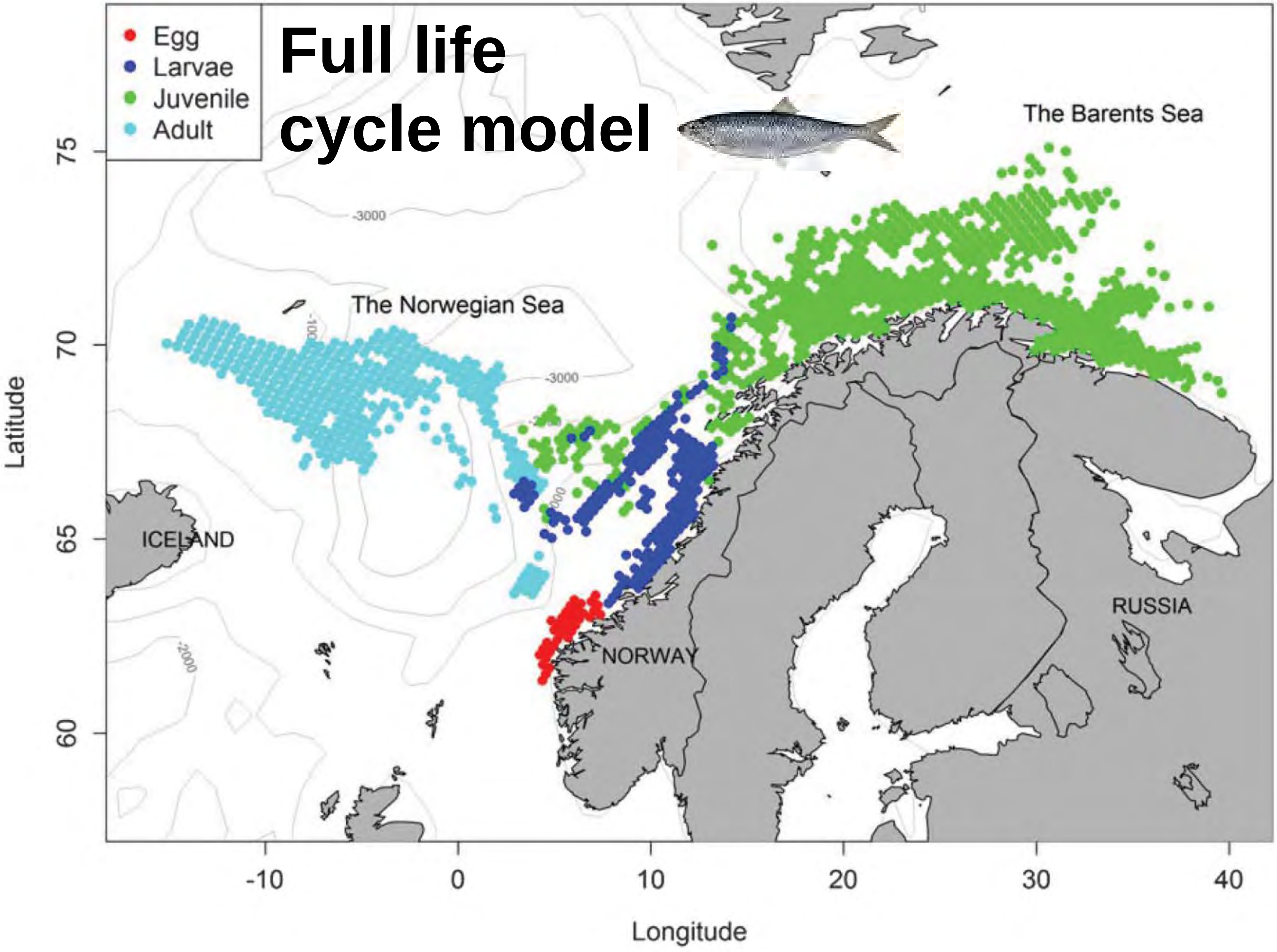
Herring migrations - cold climate

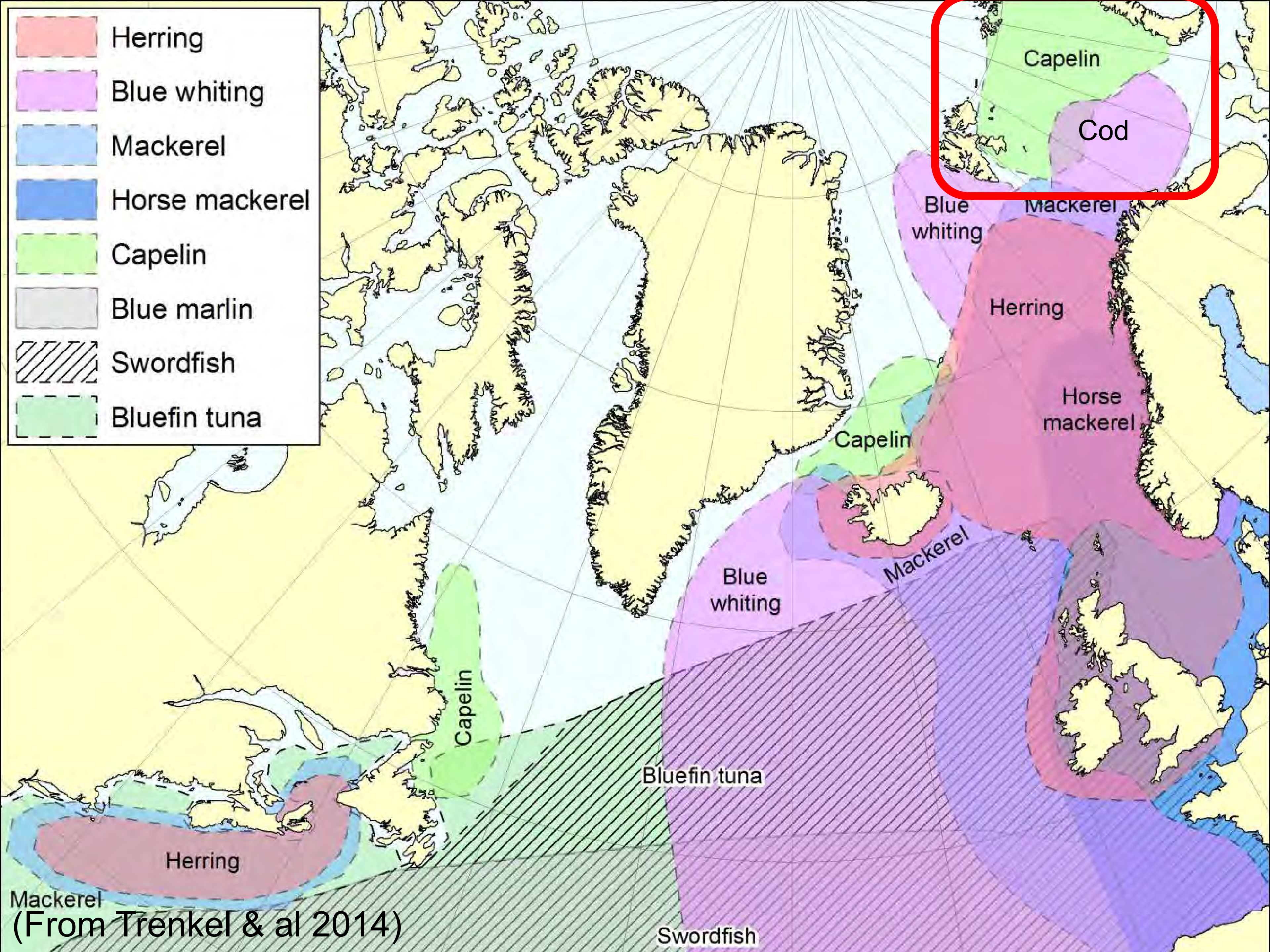


Herring migrations – warm climate



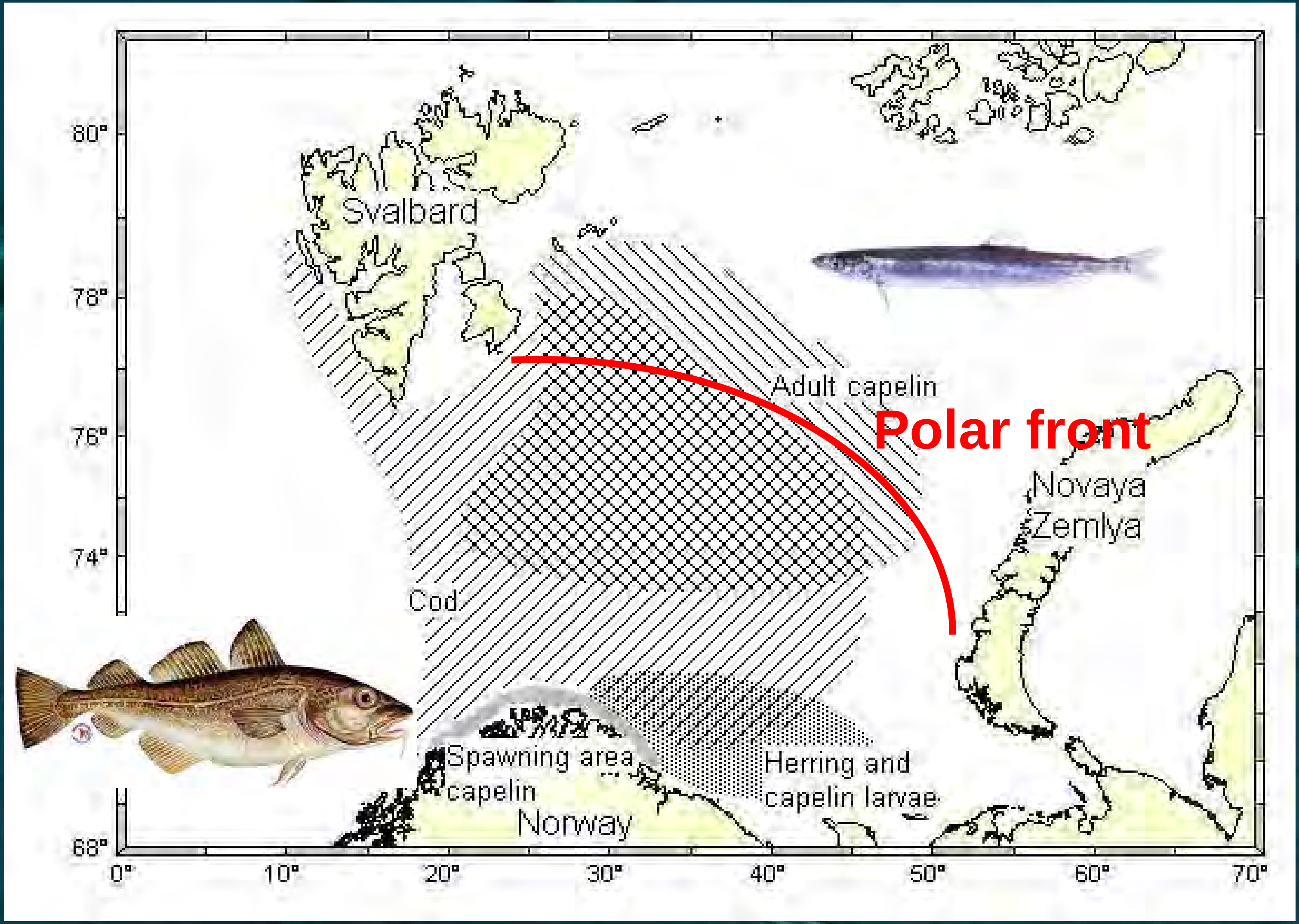
Full life cycle model





(From Trenkel & al 2014)

The impact of movement rules in modelling of cod-capelin interactions

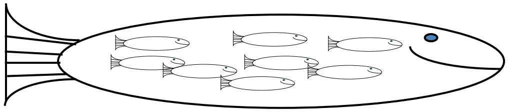


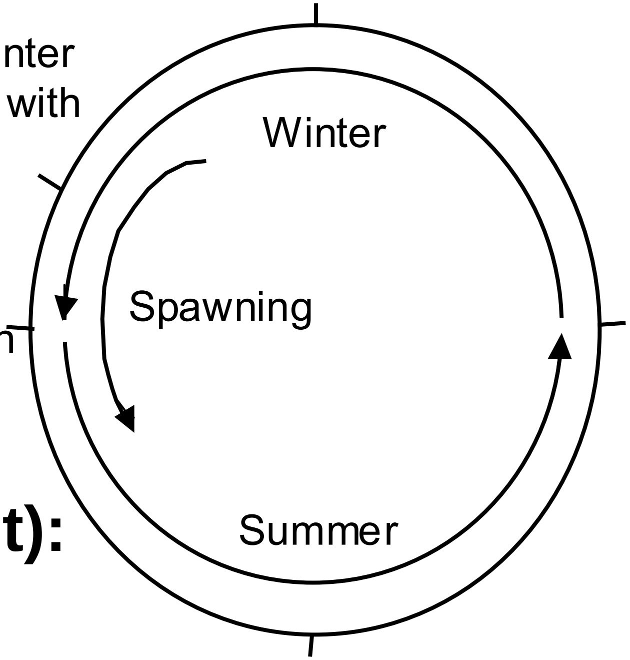
Huse & Fiksen 2010

The model

- 2D model - Domain: 90x100 squares, 20 km length
- Temperature fields for the Barents Sea generated by linear interpolation of measurements in fall and winter
- Currents from an ocean circulation model
- Zooplankton fields generated from temperature and seasonal components
- Encounter based cod-capelin interactions
- Bioenergetics growth models
- Study period 1990-1996

Model structure





January1

March1:
comparing winter
observations with
predictions

Winter

April 1:
changefromwinter
to summermigration
direction

Spawning

Summer

July 1

September 30:
comparing
observations with
predictions

40 000 super-individuals

From survey observations

Age, weight, length, N, X,Y

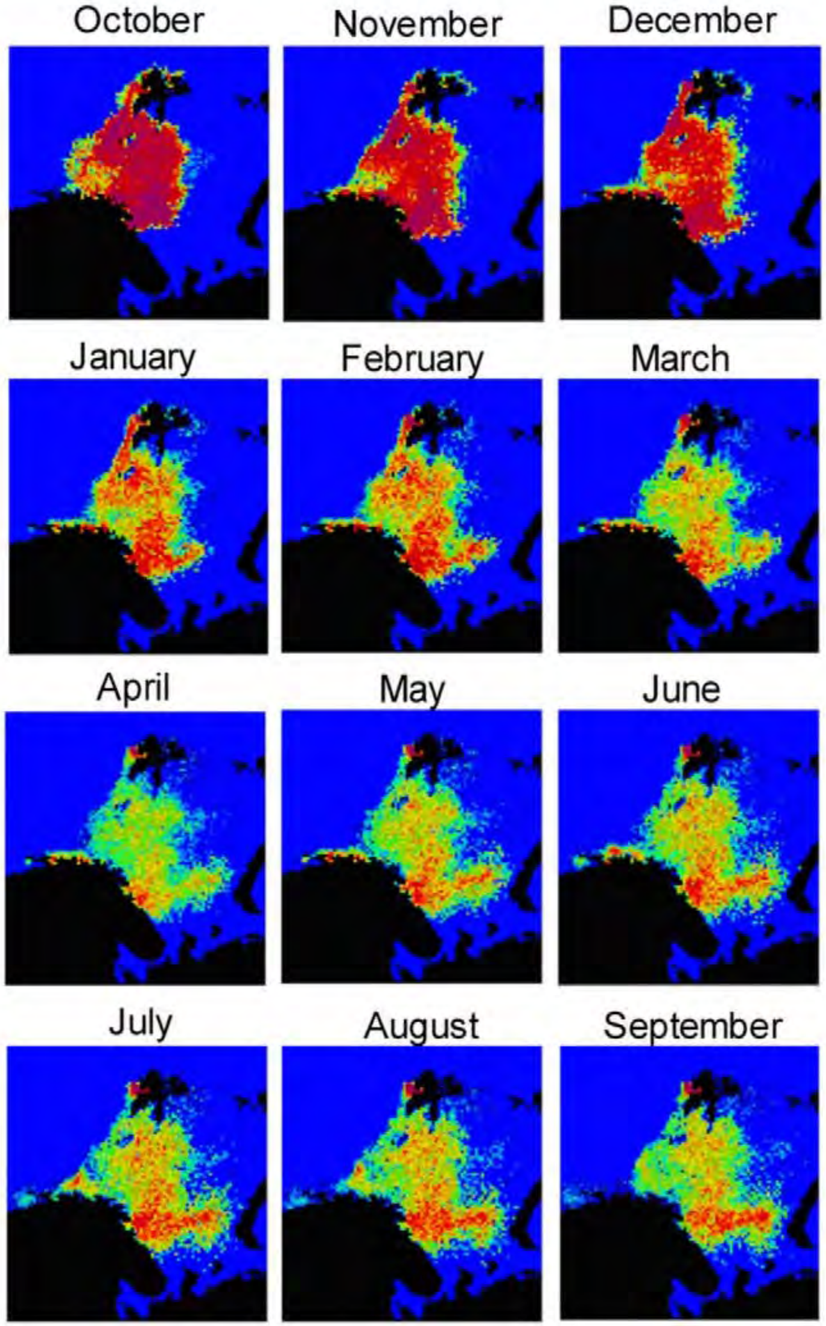
October1: initiation

Movement (best fit): geographical directions + random factor

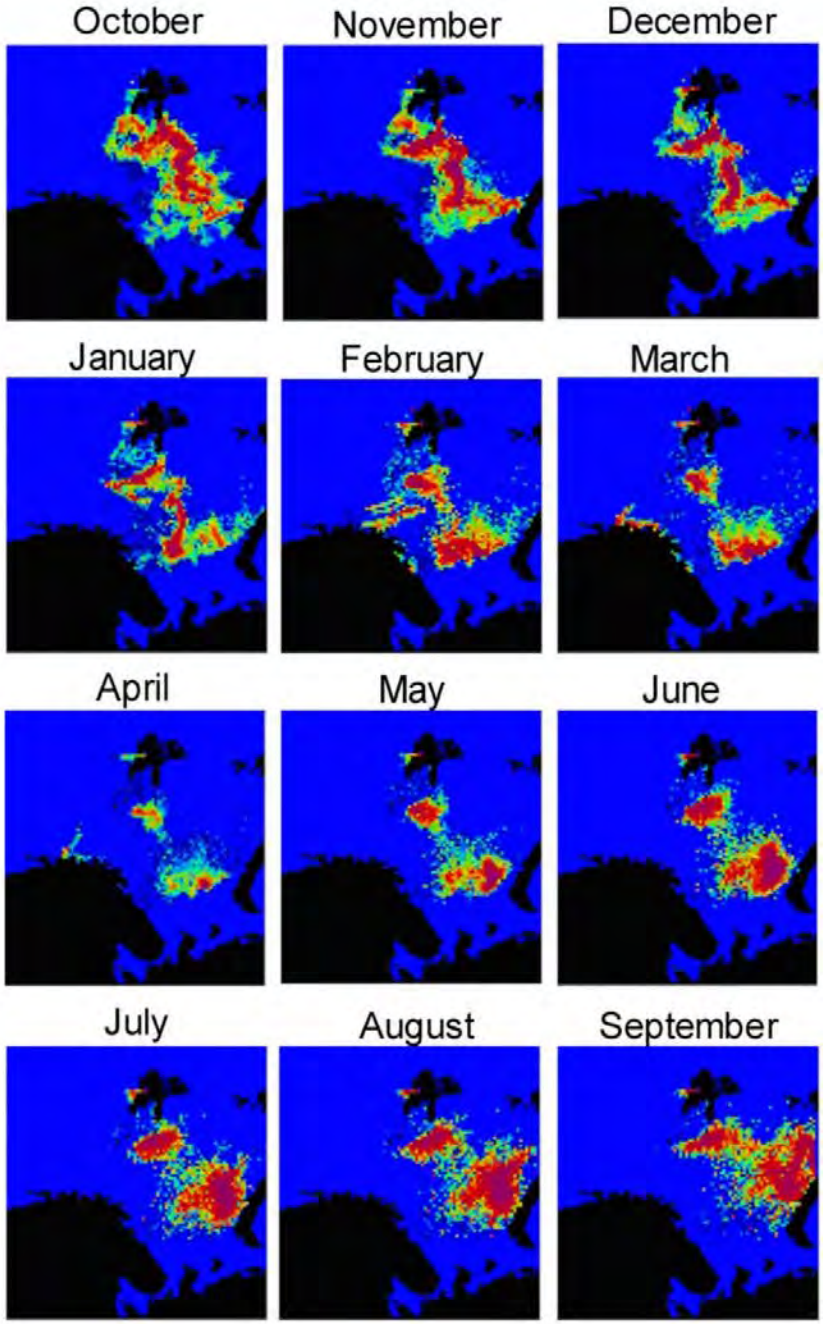
Spatial distribution was validated using root mean square (RMS):

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{i\max}\sum_{j=1}^{j\max}(P_{ij}-O_{ij})^2}$$

Cod


October
November
December
January
February
March
April
May
June
July
August
September

Capelin


October
November
December
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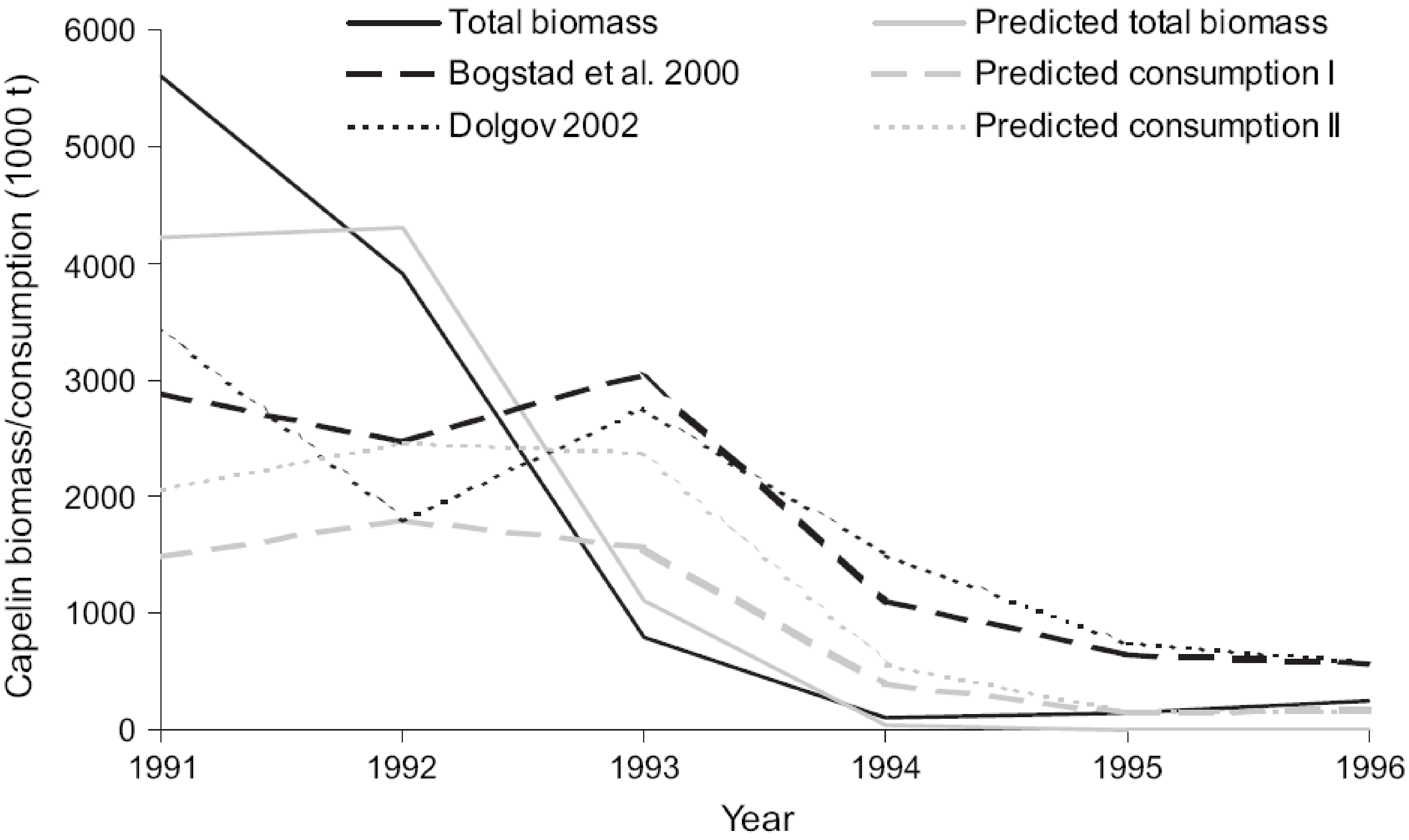
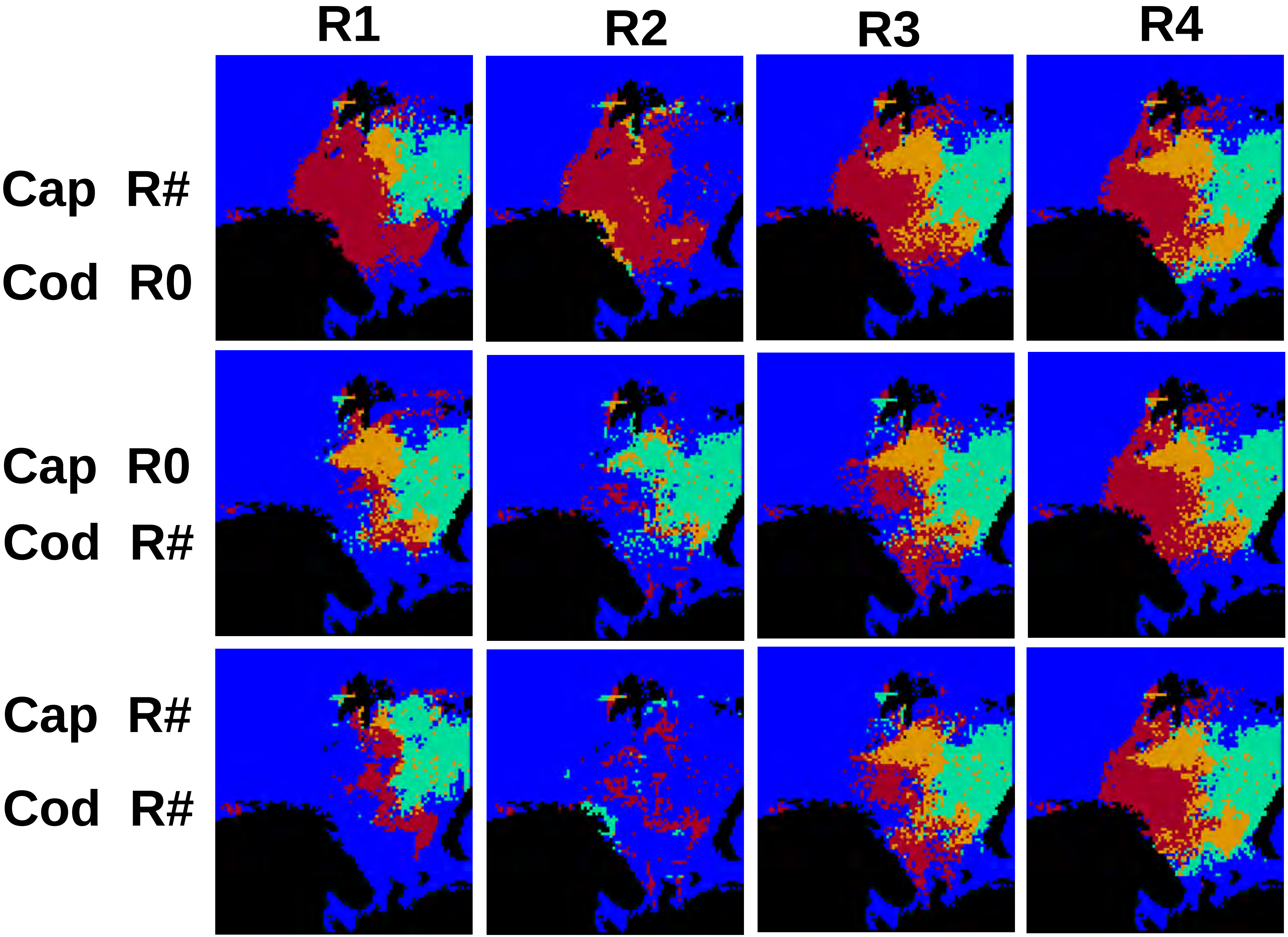
June
July
August
September

Biomass and consumption



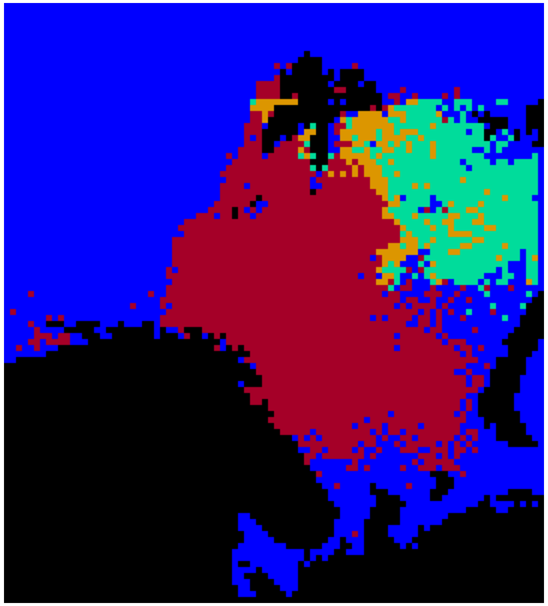
Movement rules

Rule #	
0	Default - from observations (*Huse et al. 2004*)
1_{cap}	Move towards northeast if $B_{cod} > T_{cod}$ else use 0
1_{cod}	Move towards northeast if $B_{cap} = 0$ else use 0
2	Move towards "fittest" square in neighbourhood
3	Same as 2 if ΔFitness > FitnessT else 0
4	Stay if Fitness > average Fitness else 0

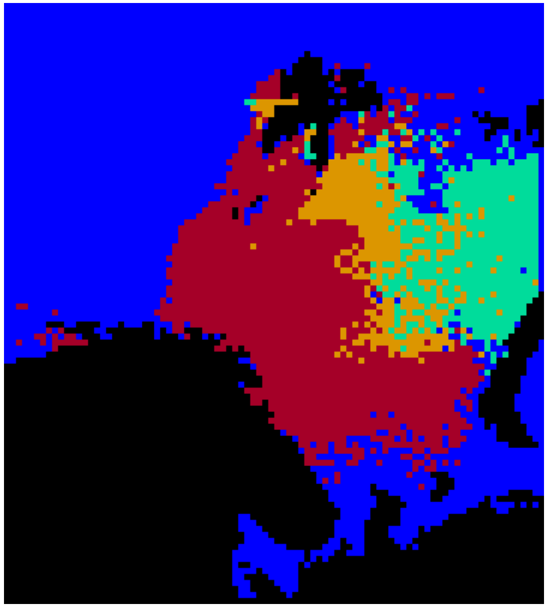

R1
R2
R3
R4
Cap R#
Cod R0
Cap R0
Cod R#
Cap R#
Cod R#

Modifying threshold for capelin risk acceptance

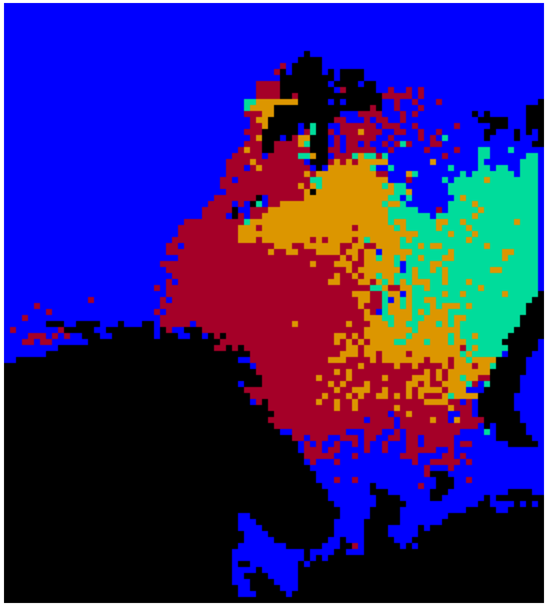
$T_{cod}=1x10^5$

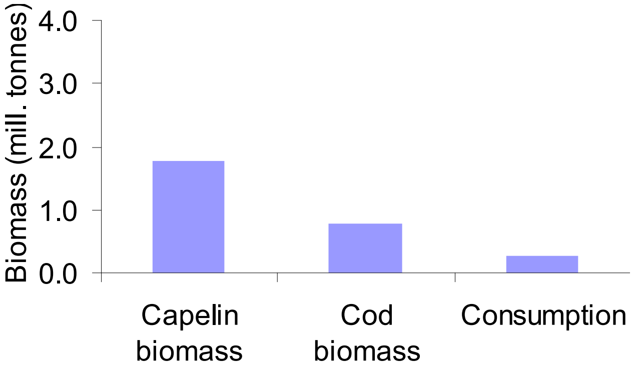


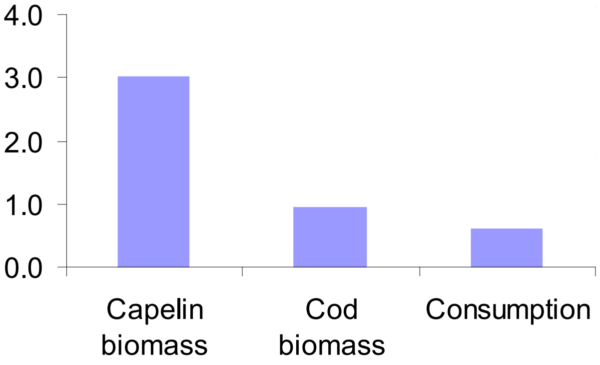
$T_{cod}=5x10^5$

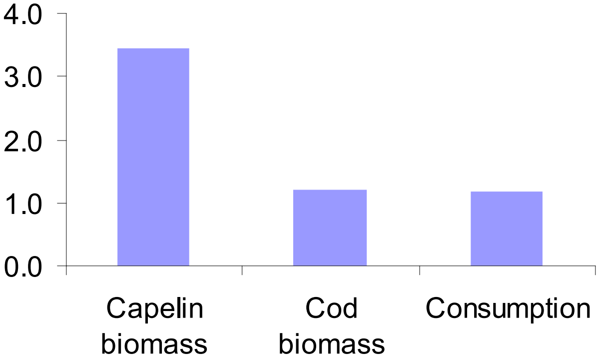


$T_{cod}=1x10^6$









nature climate change

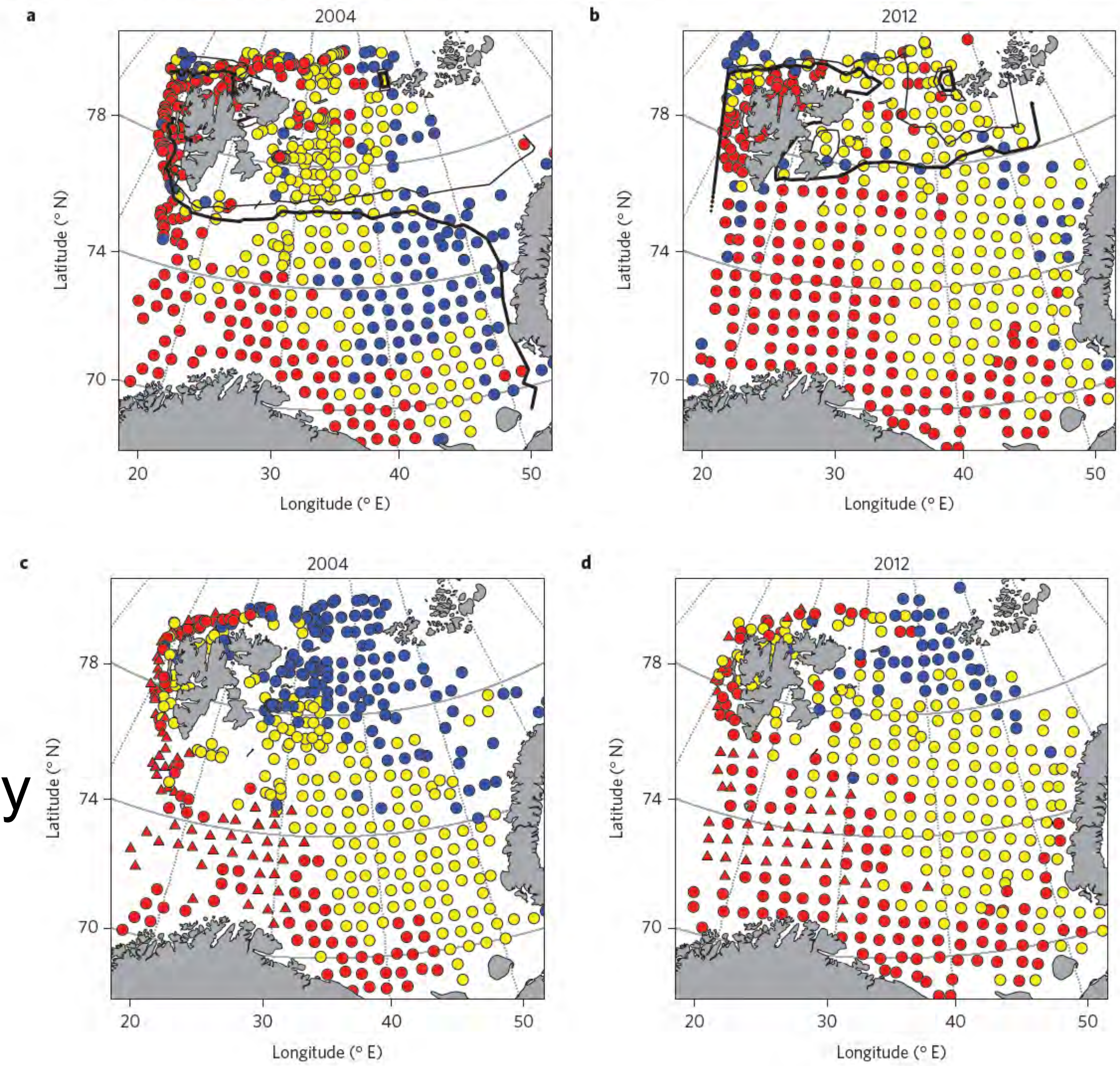
LETTERS

| DOI: 10.1038/NCLIMATE2647

Recent warming leads to a rapid borealization of fish communities in the Arctic

Water masses

Fish community



● Atlantic

● Mixed/ central

● Arctic

Capelin migrations and climate change – a modelling analysis (Huse & Ellingsen 2008)

Capelin (*Mallotus villosus*)

Small (13 cm), short lived, planktivorous, migratory

*“The quick and consistent response of **capelin** to temperature change, its importance to the North Atlantic foodweb, and established monitoring methods suggest this species as a **sea** "**canary**" for northern boreal marine ecosystem responses to climate variability and Change”.* Rose 2005

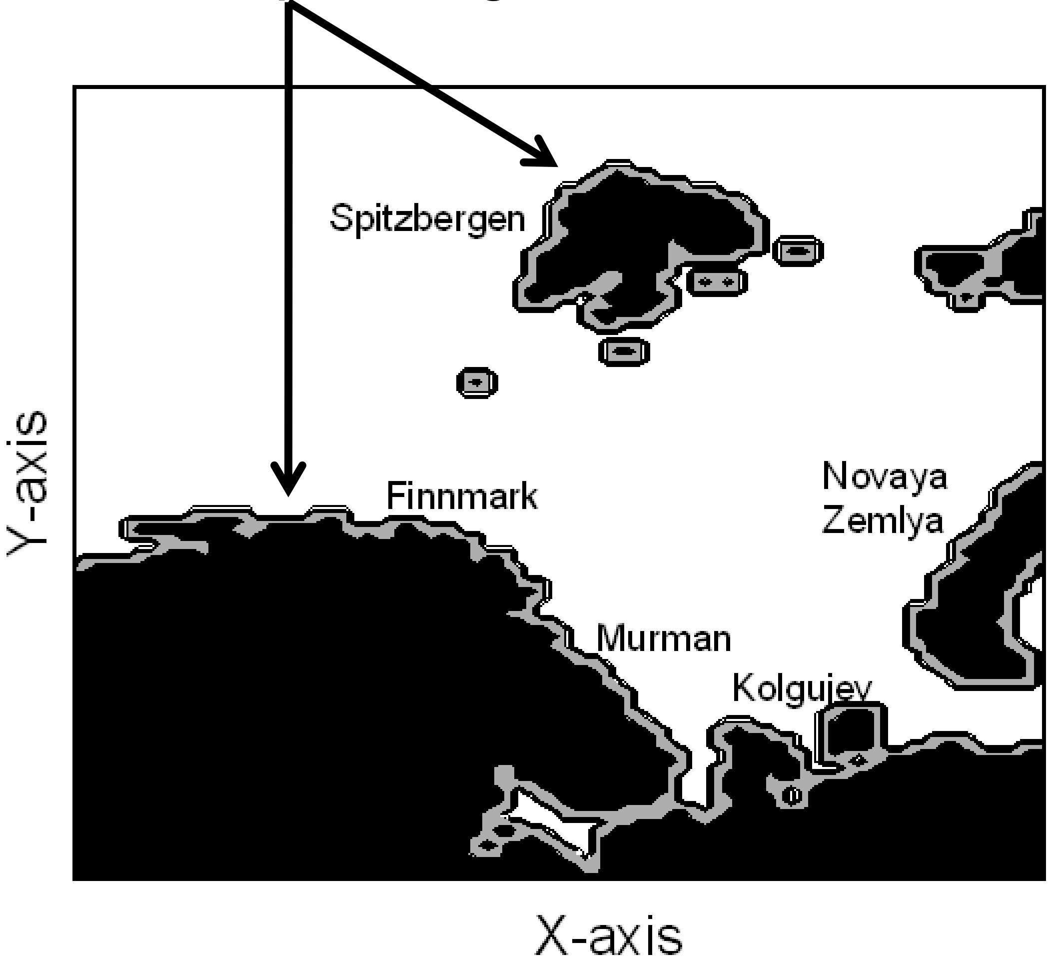
Spawning

Reproduction if:

- Individual>= 4 years
- In a spawning square
- Date ±30 days of spawning date
- If so a batch of eggs proportional to body length and energy level is laid

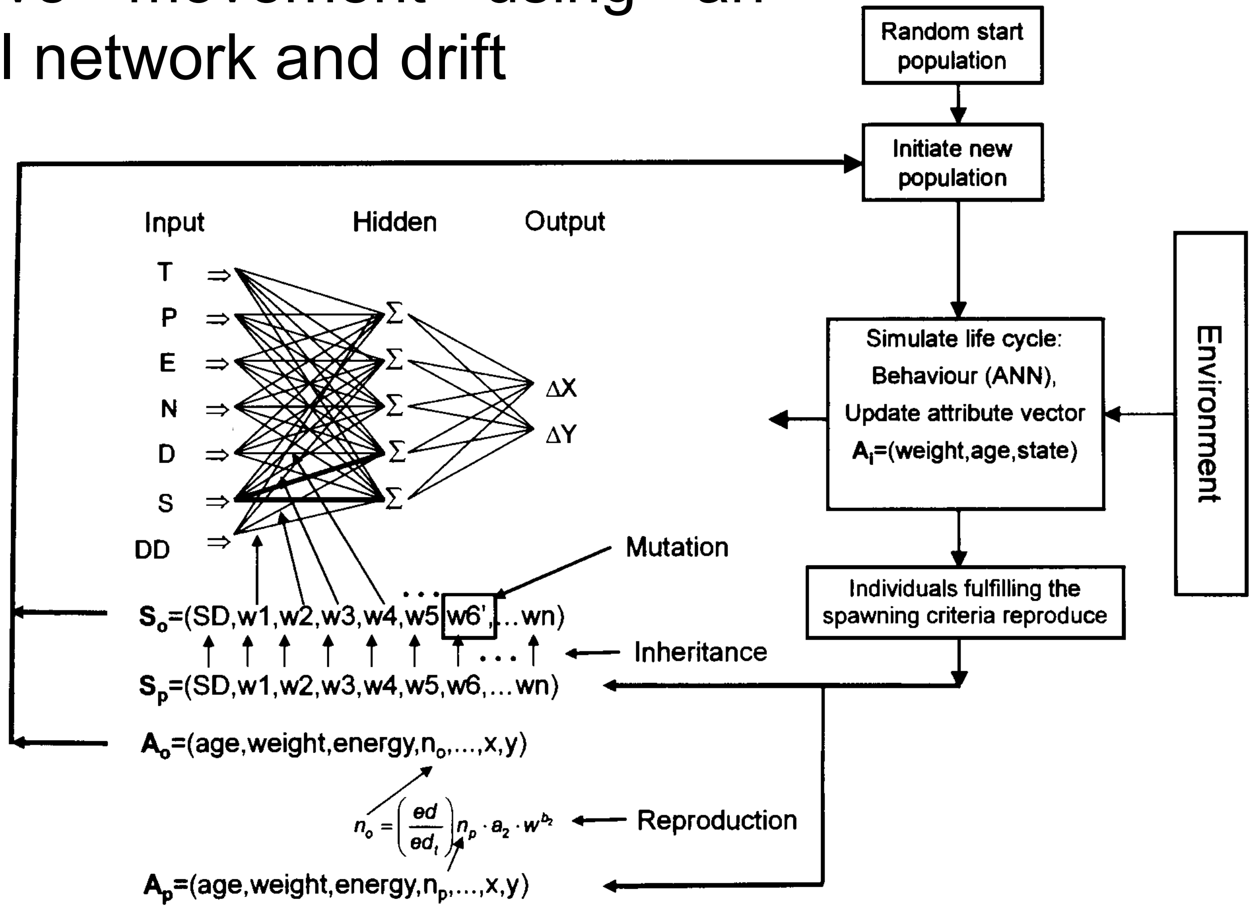
- *Batch survival to the end of the year is the fitness criterion*

- Capelin is known to spawn near shore
- All squares next to shore (grey) were allowed spawning areas



Individual Based Model (IBM) - Movement

- **Eggs:** Benthic
- **Larvae:** Drift
- **Adults:** Active movement using an Artificial neural network and drift



Random start population

Initiate new population

Simulate life cycle:
Behaviour (ANN),
Update attribute vector
A_i=(weight,age,state)

Environment

Individuals fulfilling the spawning criteria reproduce

Mutation

S_o=(SD,w1,w2,w3,w4,w5,w6',...wn)

Inheritance

S_p=(SD,w1,w2,w3,w4,w5,w6,...wn)

A_o=(age,weight,energy,n_o,...,x,y)

$$n_o = \left(\frac{ed}{ed_t}\right) n_p \cdot a_2 \cdot w^{b_2}$$

Reproduction

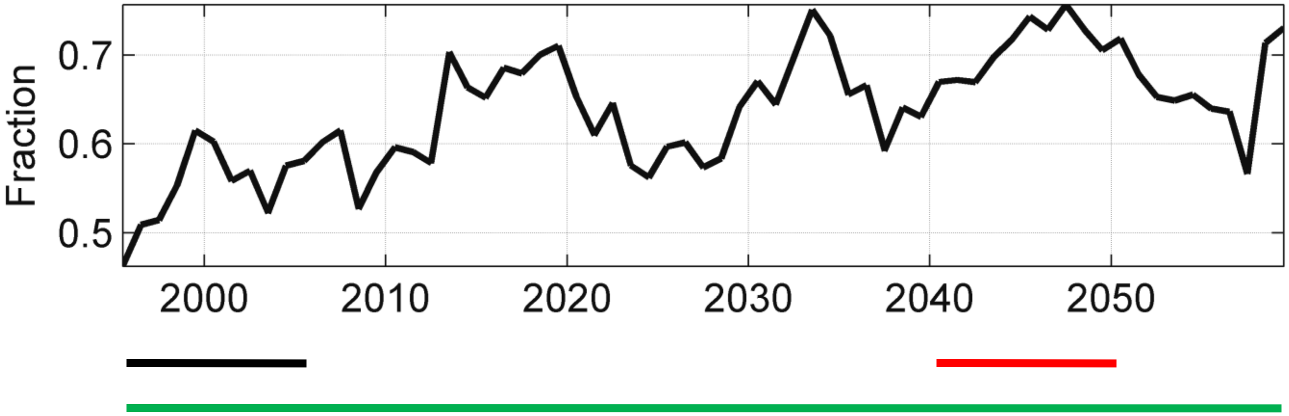
A_p=(age,weight,energy,n_p,...,x,y)

Simulations

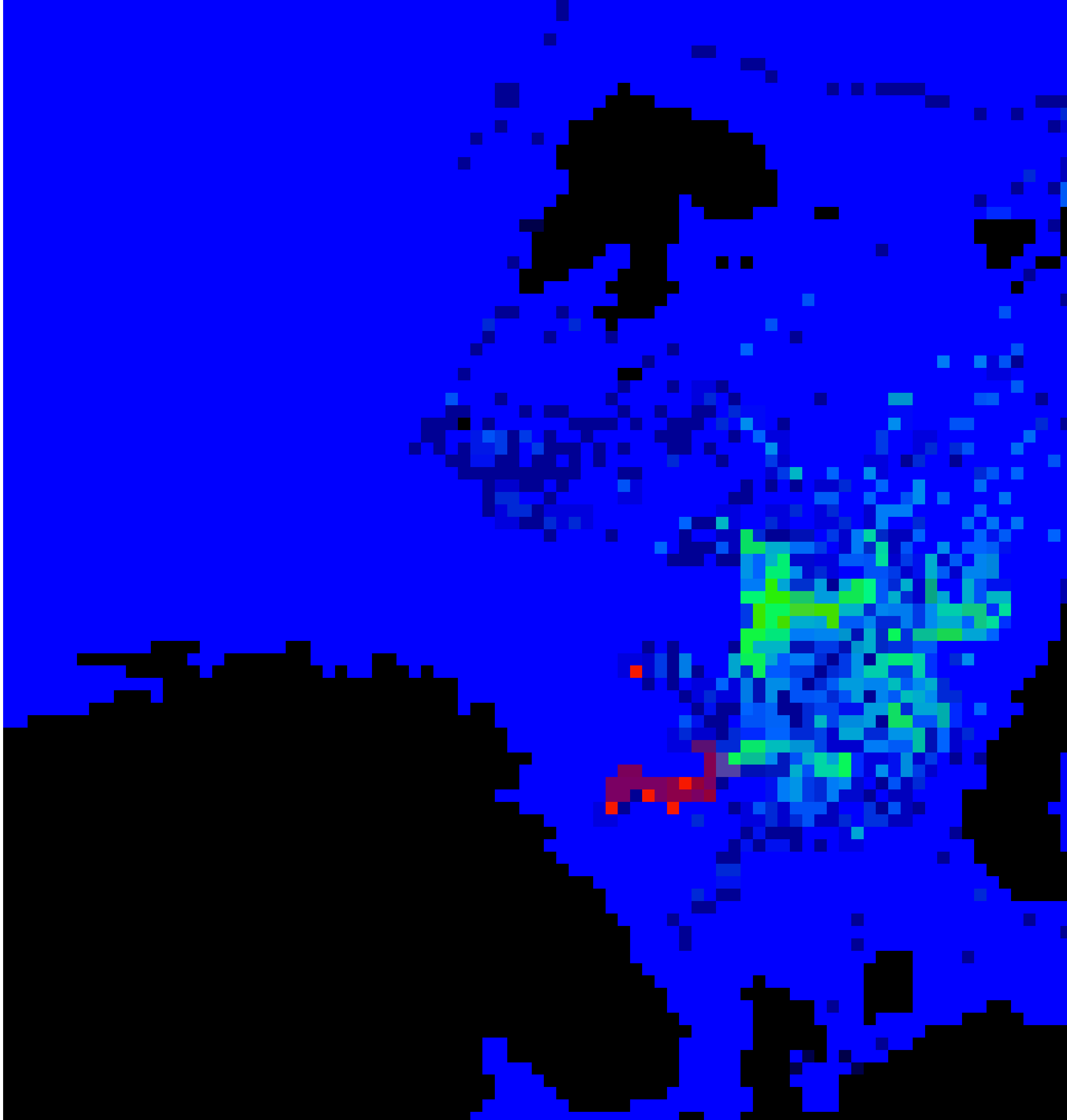
Three simulations were performed, each over 300 years (four replicates) based on:

1. Present day climate (1996-2005)
2. Future (warmer) climate (2040-2049)
3. Entire period simulated (1996-2059)

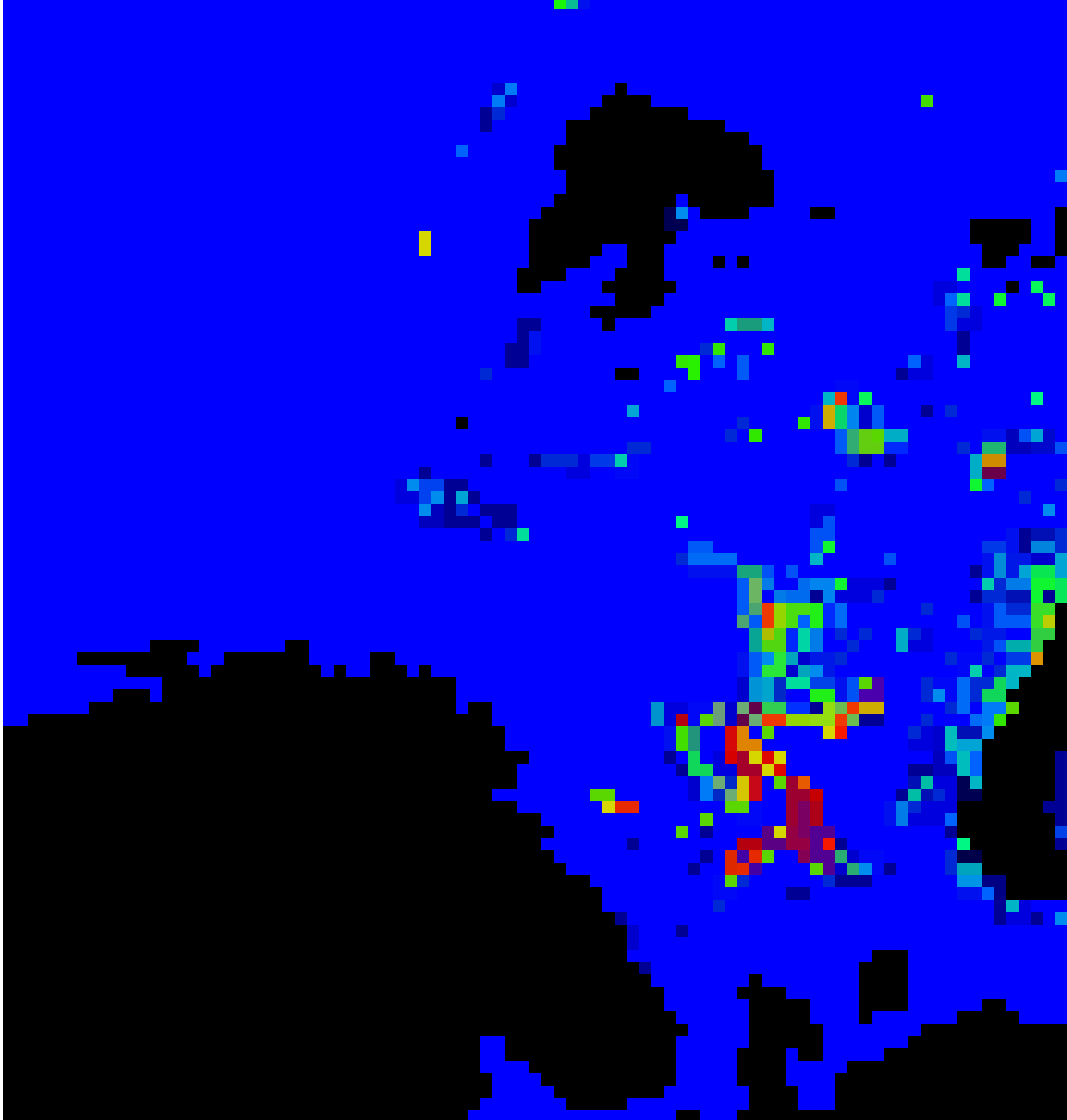
Fraction of water warmer than 1C



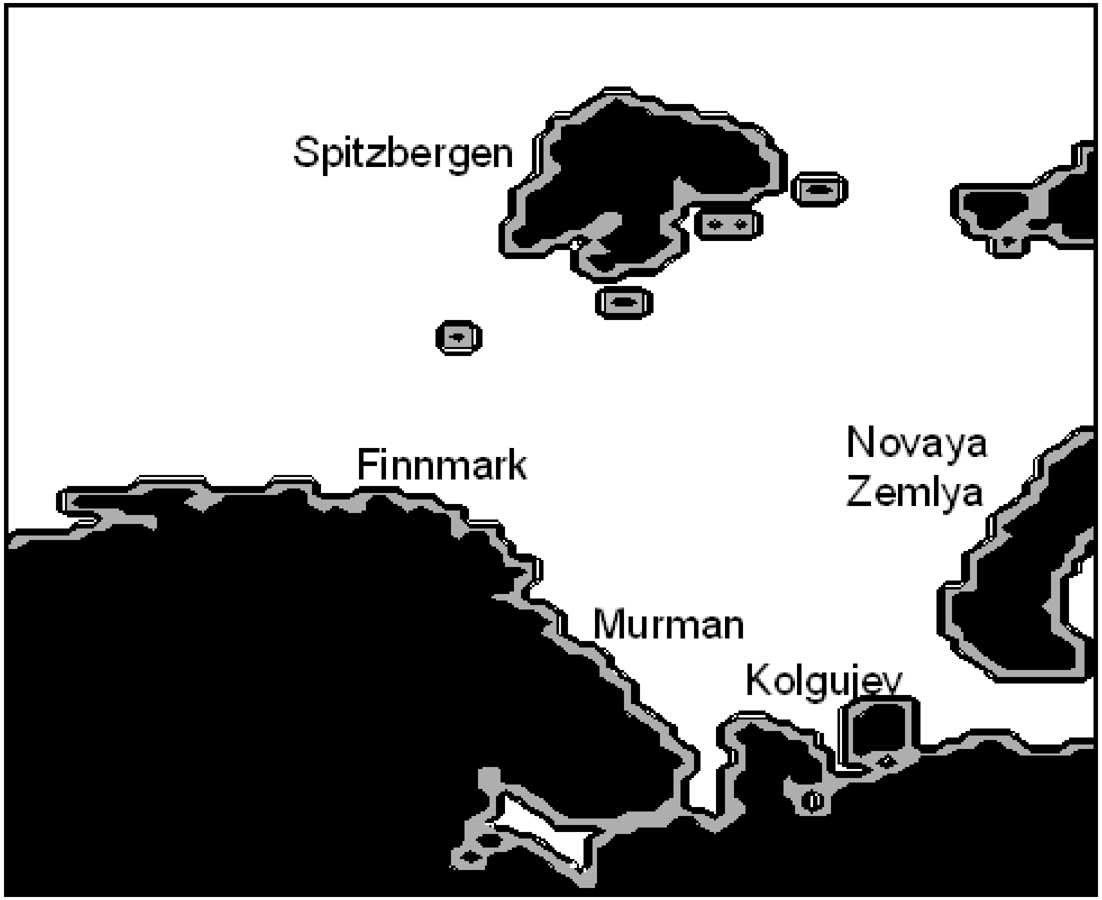
Sim1: Present climate



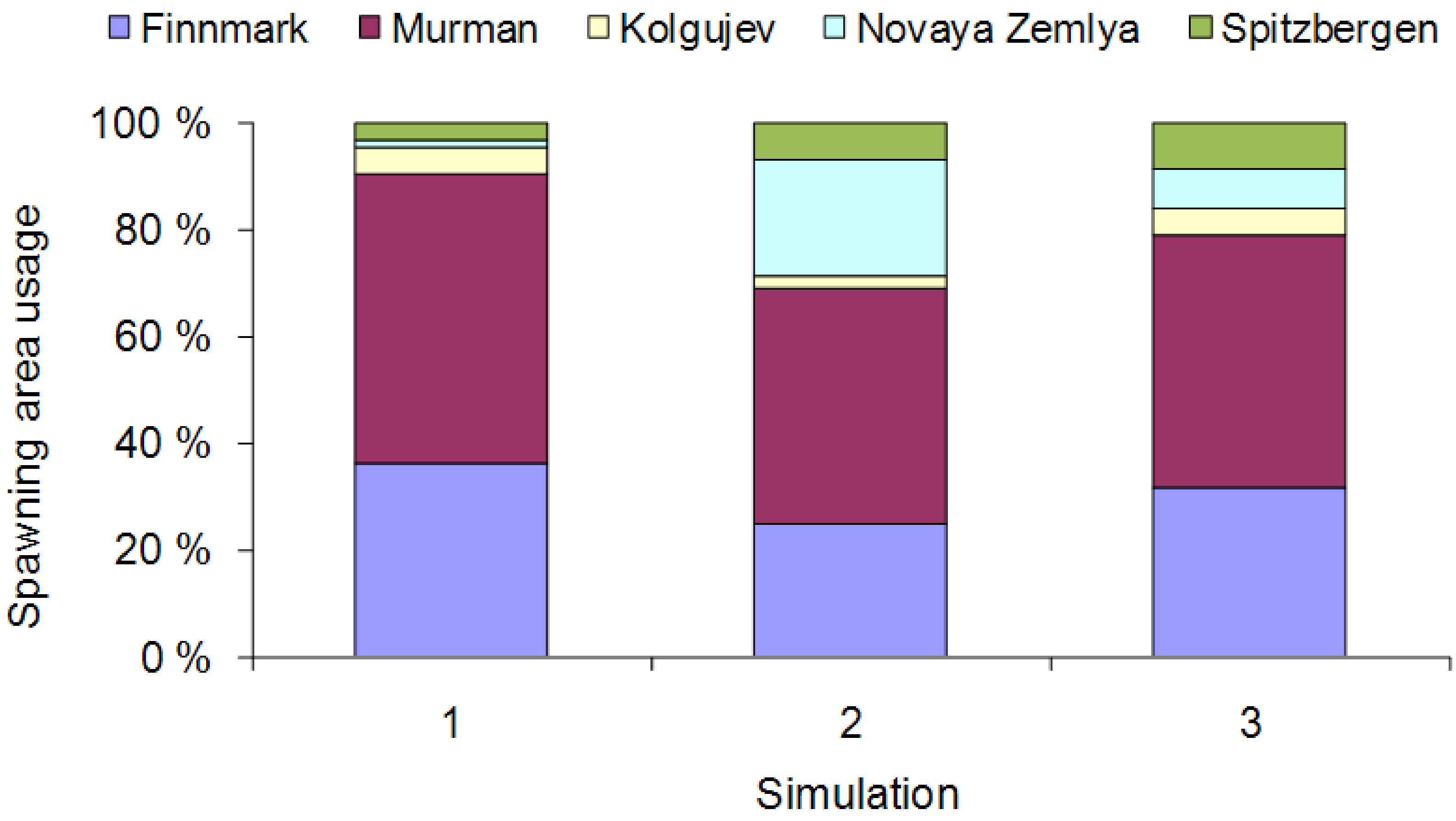
Sim2:
Future
warmer
climate



Spawning divided into five sub-areas



Average spawning area usage (all replicates)



PELagic Fish Observation System Simulator (PELFOSS)

Prosject leader:
Morten Skogen

Test monitoring strategy

IMR surveys

Develop simulation system

Tagging data

IMR survey data

Catches in real time

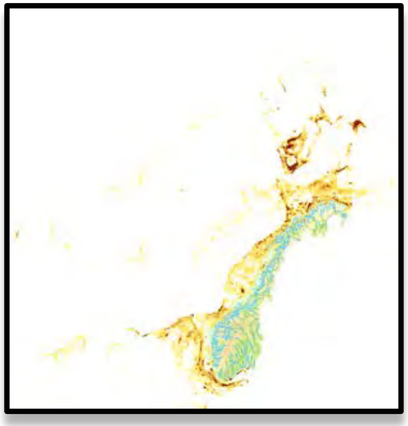
Data from fishing fleet (acoustics, AIS)

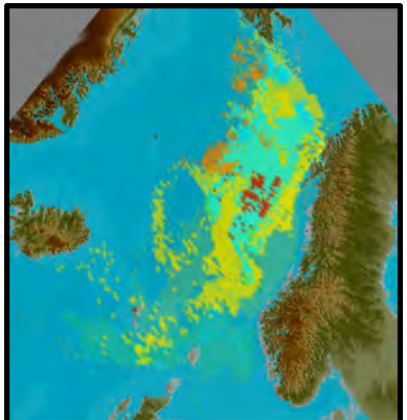
Other platforms (Stationary systems, SOP)

Data from fishing fleet (acoustics, catches)

PELFISH SIMULATOR

EVALUATOR

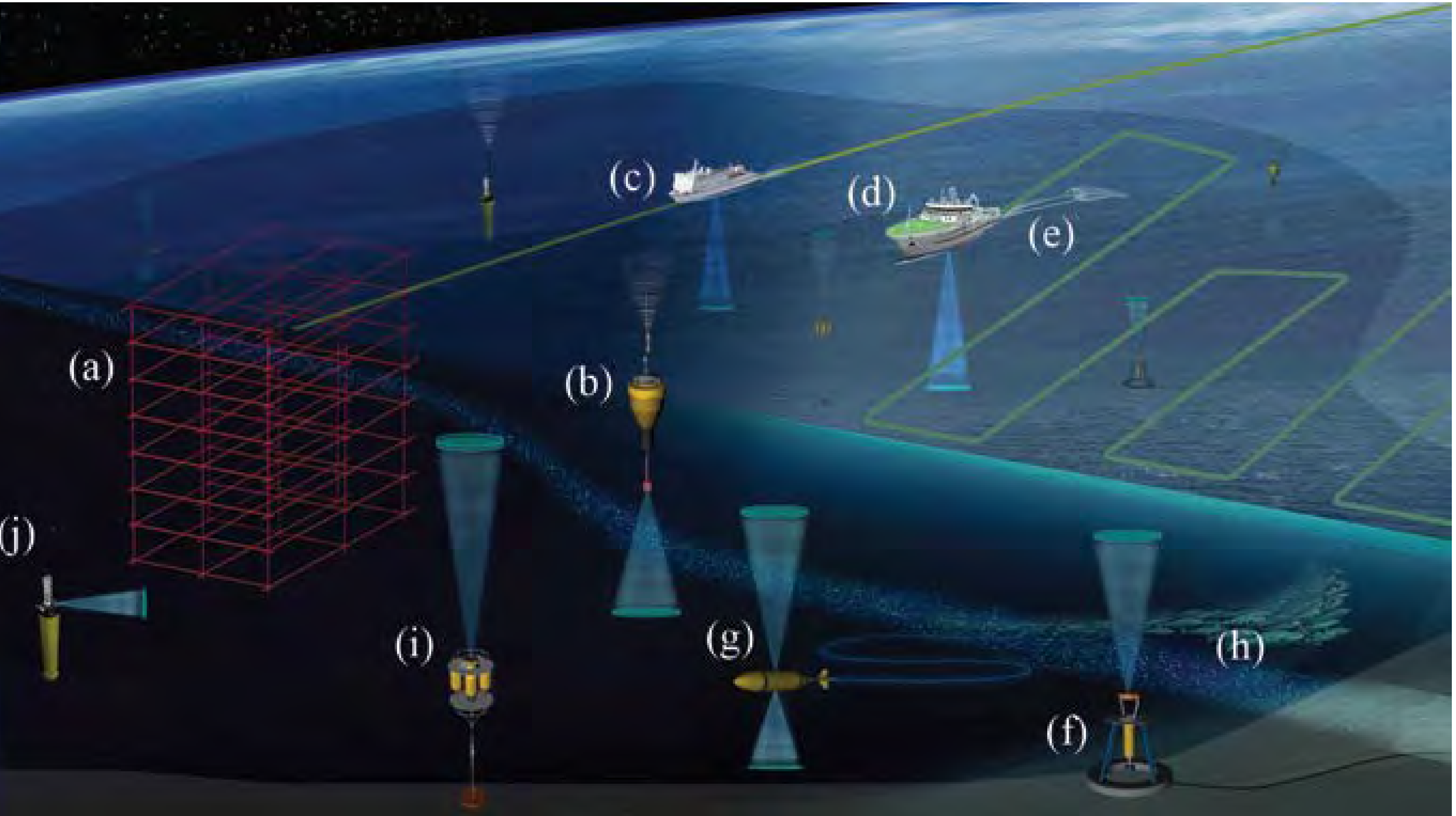




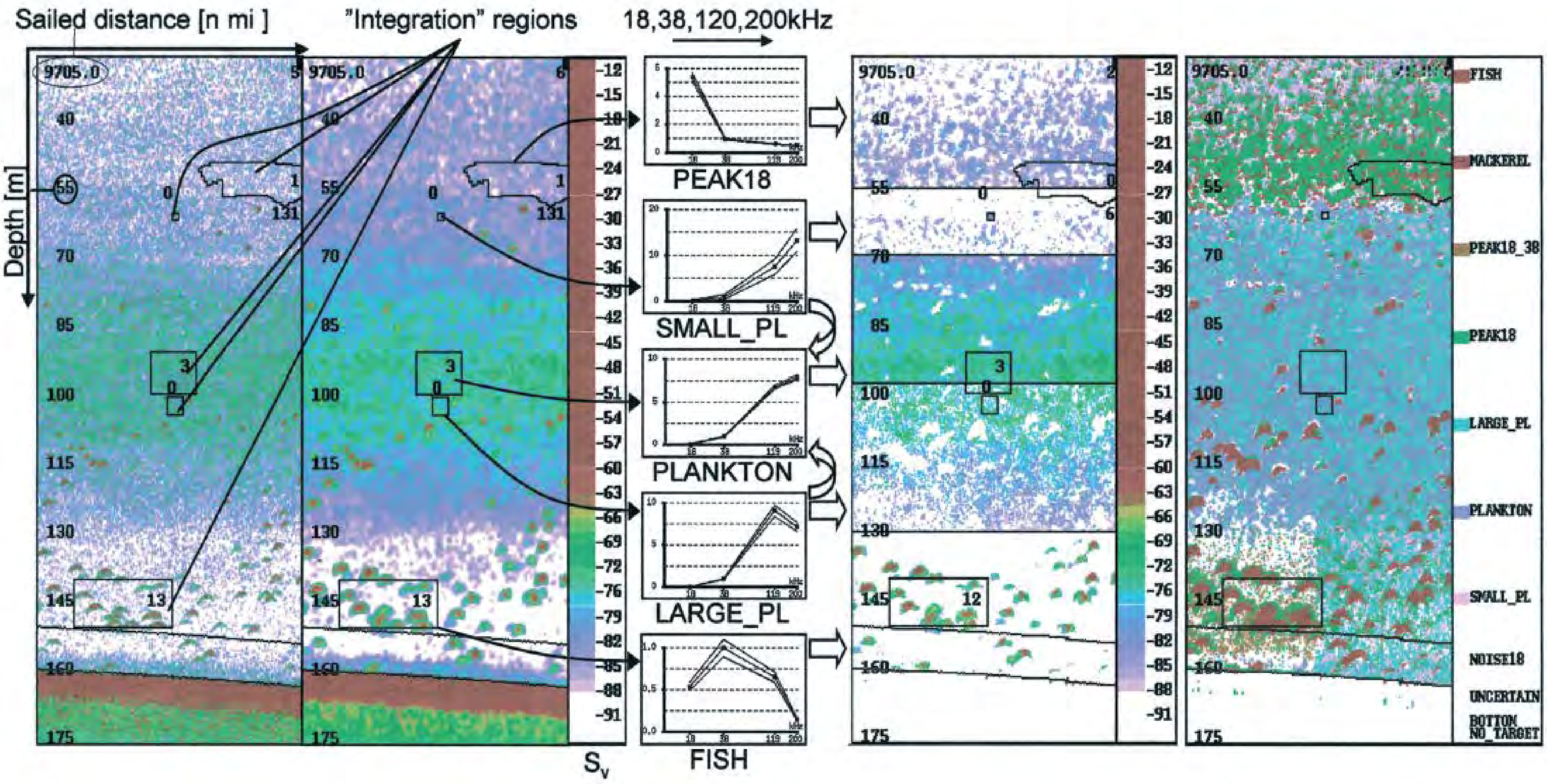
WHERE?

- More code sharing and community effort (WGIPEM trying to achieve this)
- Standardise test cases for comparing efficiency of movement algorithms
- Develop approaches for using available data most efficiently in achieving realistic models of fish
- Local processing and machine learning

Linking models and observations: Observation System Simulation Experiments (OSSE)



Scrutiny of acoustics with machine learning



a) 200 kHz (original)

b) 200 kHz (smoothed)

c) $\langle r(f)\rangle = \langle s_v/s_{v,38}\rangle$
Mean r(f) of region.
Dominating
category denoted.

d) 200 kHz smoothed
data masked with
acoustic category

e) Acoustic categories
in artificial colours

WHERE?

- More code sharing and community effort (WGIPEM trying to achieve this)
- Standardise test cases for comparing efficiency of movement algorithms
- Develop approaches for using available data most efficiently in achieving realistic models of fish
- Increased usage of data from various sources – local processing and machine learning
- Still a lot of remaining issues..

Issues with Super-individual modelling..

Bookeeping

- Representing populations as super-individuals
- Spatial representation of SI
- Creation of new SI
- Scaling from SI to population output

Process representation

- Super individuals feeding in Eularian fields
- Interactions between super individuals
- Mortality & growth

Computational issues

- Keeping the number of super-individuals manageable
- Ensuring numerical convergence of results for different number of simulated SI
- Implications of using super-individuals with parallel computing or ways to speed up calculations?
- Uncertainty

From Huse & Rose in prep.

Thanks for your attention!