Coastal and Estuarine Processes
http://ecowin.org/aulas/mega/pce

Ecological modelling

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Basic principles of ecological modelling

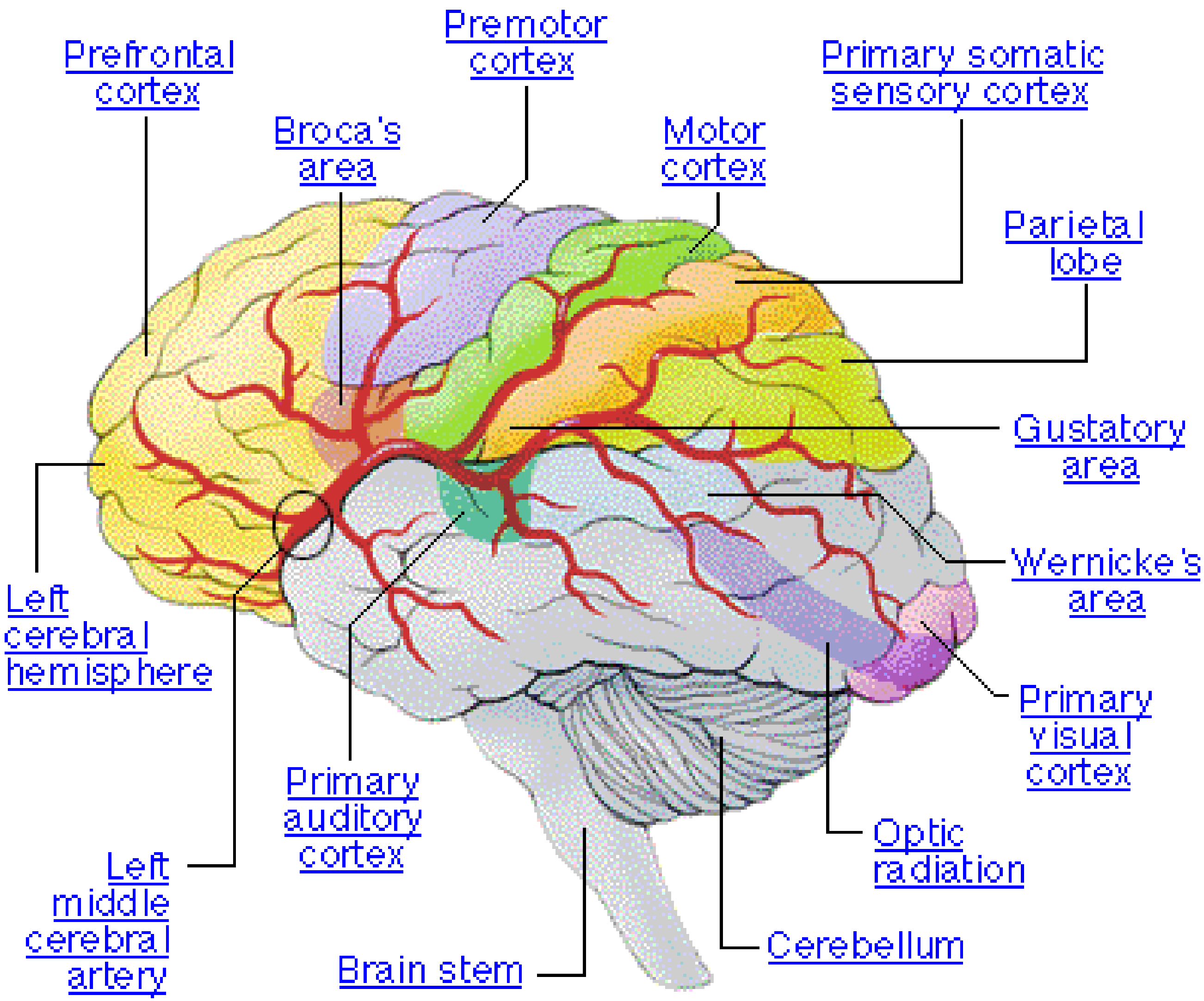
Concepts, examples, and applications

Topic

- General principles of ecological modelling
- Complex models(research models)
- Screening models (management models)
- Simulation platforms
- Synthesis

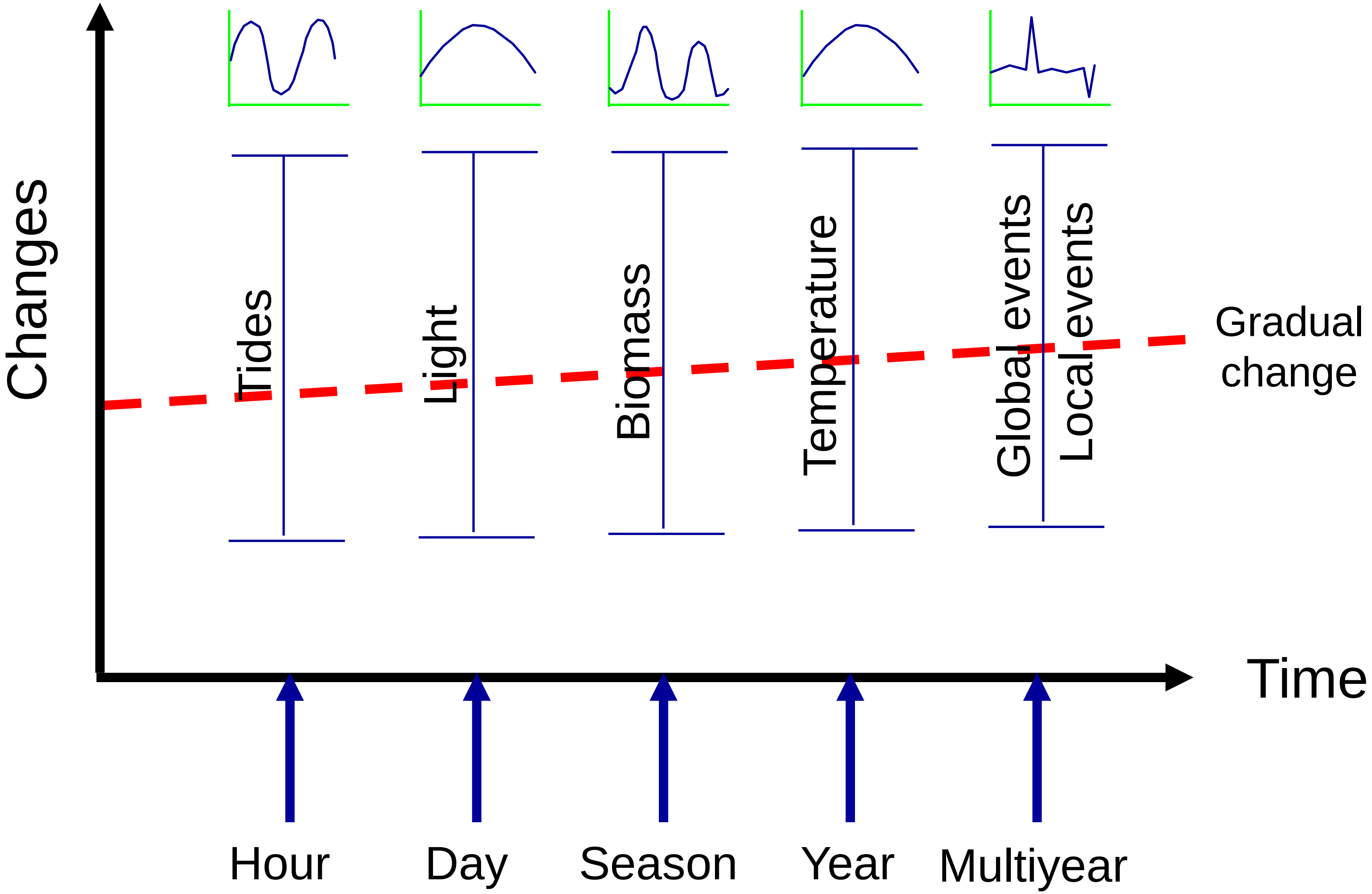
Different questions, different models. There is no silver bullet.

Here is the best model…



Turn your brain on. Turn your computer off.

Changes in coastal systems



The noise in the distributions masks the signal of change

Model diversity

When we talk about models, 49.9999% of the world sees this!

The other half sees this...

Lab models

- Incubations for primary production or BOD

GIS Spatial models

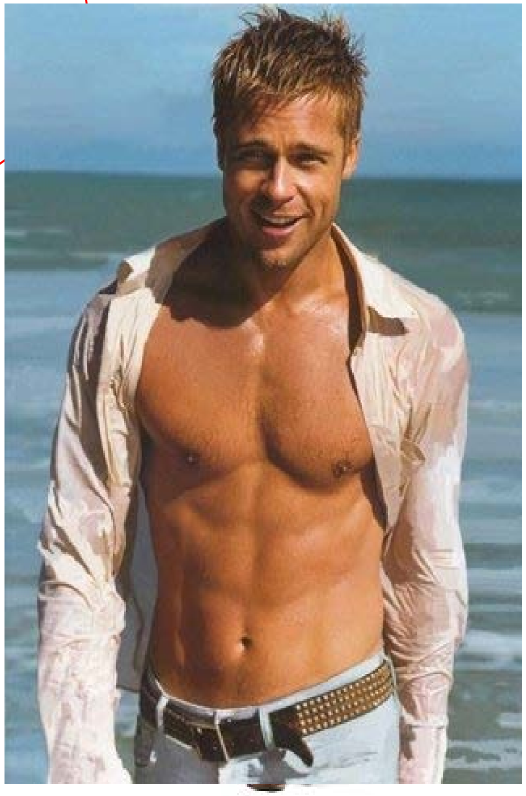
- Marine spatial planning, chlorophyll spatial distribution

Mathematical models

- dC/dt = -kC (dynamic, time varying)

Physical models

- Harbour scale models, toys

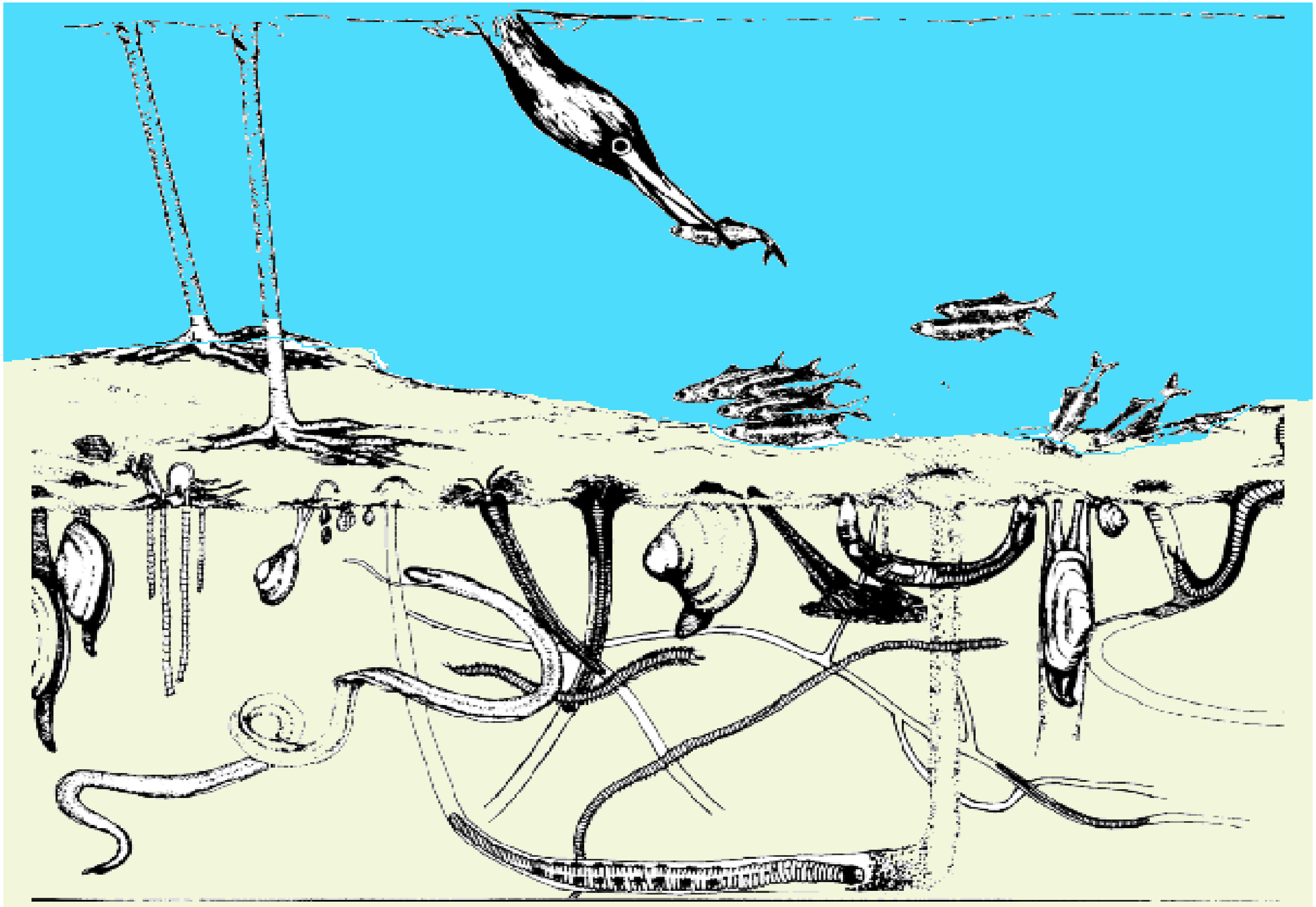


Other models

All models are wrong, but some are useful (George Box)

Ecological models are complex

even for simple systems...



How many state variables would you use in this system?

Why do we use models?

Measure state, perform experiments, simulate...

- Our conceptual understanding of ecosystems is often illustrated as a set of boxes (state) linked by arrows (processes)
- Processes such as primary production or grazing form the links between boxes (state), e.g. phytoplankton biomass, nutrient concentration
- Experimental approaches can help quantify these processes (e.g. P-I curves)
- This quantification can be used to mathematically “link” the boxes, and simulate ecological changes in time and space

No question, no model. A model is a tool, not an objective.

Ecological Modelling – A tool

- Measurement of chlorophyll (satellite), suspended matter (sampling), area of mussel culture (GIS) etc;

- Modelling of shellfish growth allows the determination of rates such as net phytoplankton removal, nutrient excretion, production, which often cannot be directly measured.

State can be measured, processes can be modelled.

Ecological Modelling - Objectives

Description and support

- Test and validate mental models
- Support sampling design
- Describe and hindcast
- Support data interpretation (e.g. laboratory models)

Forecasting

- Predict *general* behaviour of ecosystem
- Test and diagnose potential modifications
- Distinguish long-term signals from short-term variation

Make your model as simple as possible - but no simpler.

Characteristics of models

Four defining elements

- Generality → Models should be portable
- Realism → Loss of realism is expected
- Accuracy → Loss of accuracy due to smoothing, difficulty in accommodating stochastic events, etc
- Simplicity → Reduce complexity whenever possible (Occam's razor)

Building a model is a trade-off among these four characteristics.

Ecological Modelling

Different dimensions, different scales

Dimensions

- Statistical
- Zero-dimensional (time only)
- One-D (rivers, narrow estuaries)
- Two-D (non-stratified estuaries, coastal areas)
- Three-D (systems with pronounced horizontal and vertical gradients)

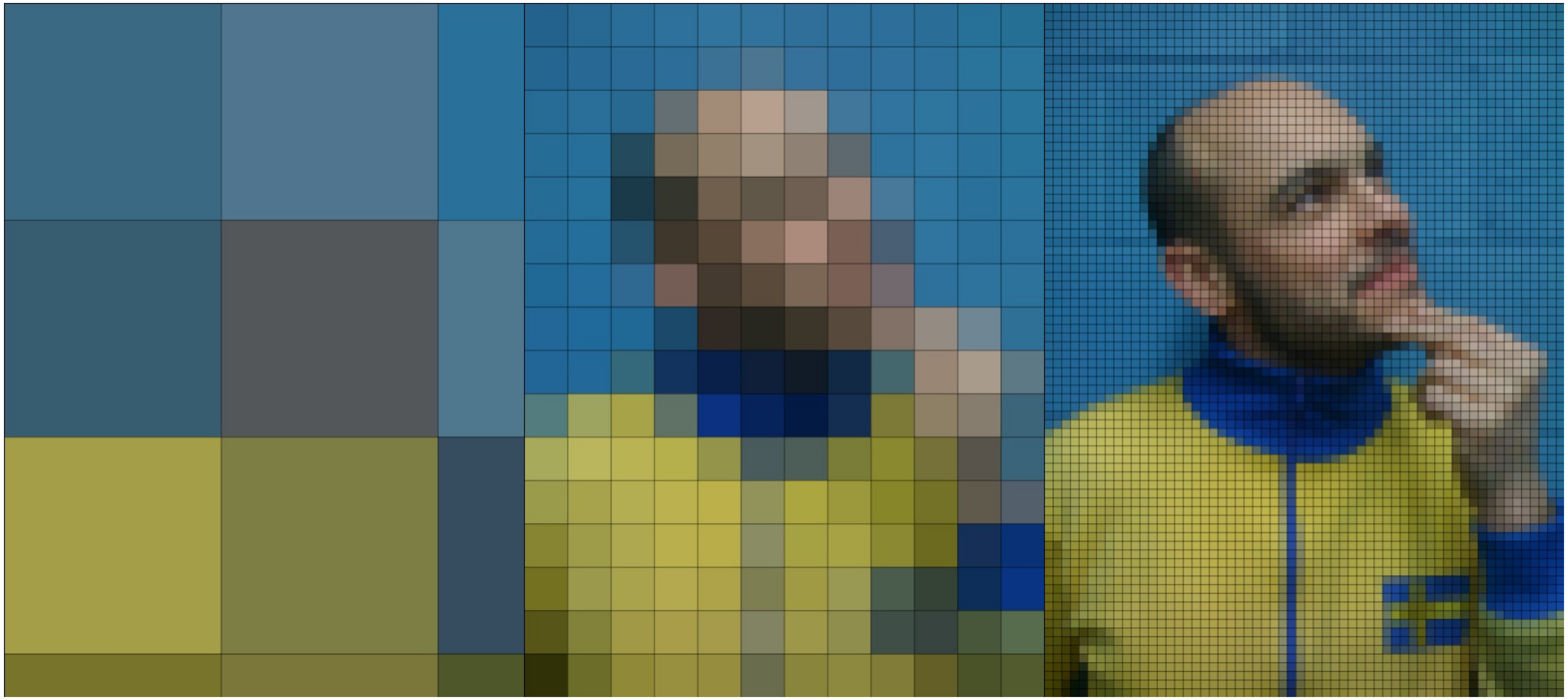
Time and space scales

- Hydrodynamics - Small cells, short timestep and time scale (tidal cycles, spring-neap cycles, localised case studies)
- Ecology - Larger boxes, longer timestep and time scale (seasonal cycles, annual patterns, multiannual variation)

Most people don’t solve the problem, they change the problem into something they know how to solve. This does not solve the problem.

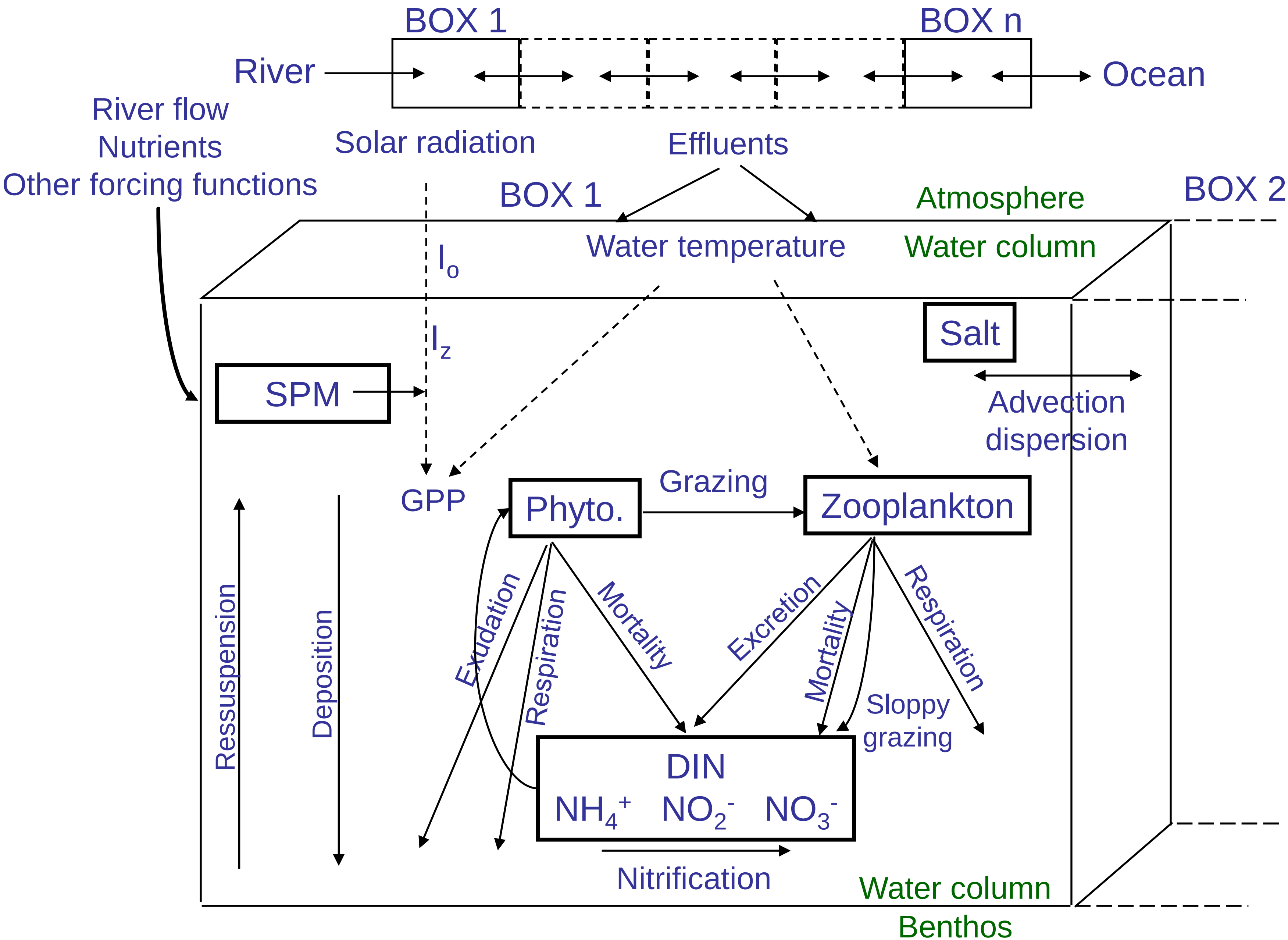
Ecological modelling in coastal environments:

At which spatial resolution do we need to represent an ecosystem?



Spatial resolution determines temporal resolution. There is a trade-off among physics, ecology, and economics.

General scheme of a simple ecological model



Even simple ecosystems are complex to model

Ecological Modelling

Elements and requirements

Model elements

- State variables (nitrate, phytoplankton)
- Forcing functions (light, temperature)
- Processes (production, mineralization)
- Parameters (light extinction cofficient, half-saturation constants, grazing rate)

Model requirements

- Physical framework (box volumes, areas, etc)
- Boundary conditions (concentration values at model limits)
- Initial conditions (starting values for model)

Operational models (a.k.a. data assimilation)

- Re-initialised at appropriate time steps

Conceptual framework + physical framework = Model

Ecological Models

Development stages

Model Conception

- Objectives of the model
- Components of the model (variables, forcing functions)
- Scope of the model (time and space)
- Limitations and closure

Model Implementation

- Problem decomposition, definition of appropriate sub-models
- Data handling and generation
- Model building (e.g. visual platform)
- Running and testing

Model Calibration

- Tuning parameters and functions using field data

Model Validation

- Testing against an independent dataset

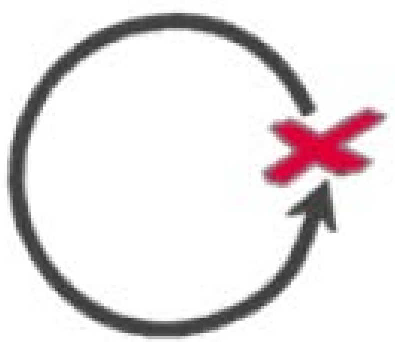
Re-use if possible, develop if necessary

Ecological Models

Spreadsheets and visual models

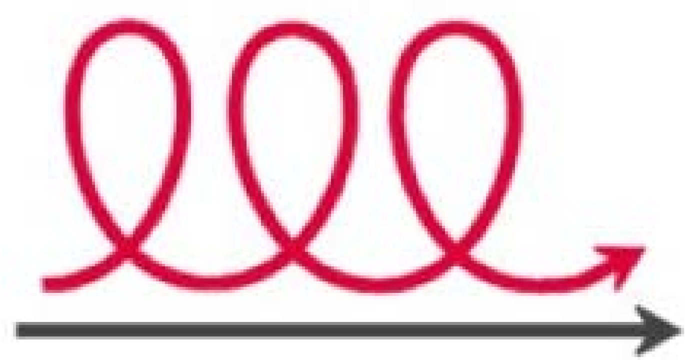
Spreadsheets

- Excel, Lotus123 etc
- Data in rows and columns, only formula for active cell is visible
- Feedback mechanisms are eliminated to avoid circular references



Visual models

- InsightMaker, Powersim, Stella etc
- Data (including data links) represented using visual elements
- Feedback is explicitly considered as a major factor in systems analysis



Models are all about feedbacks

Ecological models

Research models and screening models

Characteristics	Research models	Screening models
Resolution	High spatial and temporal resolution	Low resolution, or integrated in space and/or time
Complexity	Several-many state variables	Focus on a few diagnostic features
Difficulty of use	Substantial, usually have a “champion” group/groups	Minimal, require few parameters
Cost	High due to typical data requirements and complexity	Low cost
Application	Detailed management support, usually supplied as a service	Broad compliance analysis, scoping work, more a product than a service
Target audience	Academics, consultancy	Managers, public
Integrity	Hard to verify, hard to modify	Easy to do both, more prone to misuse

Both types of models play important roles in water quality management

Ecological research models

Integrated management

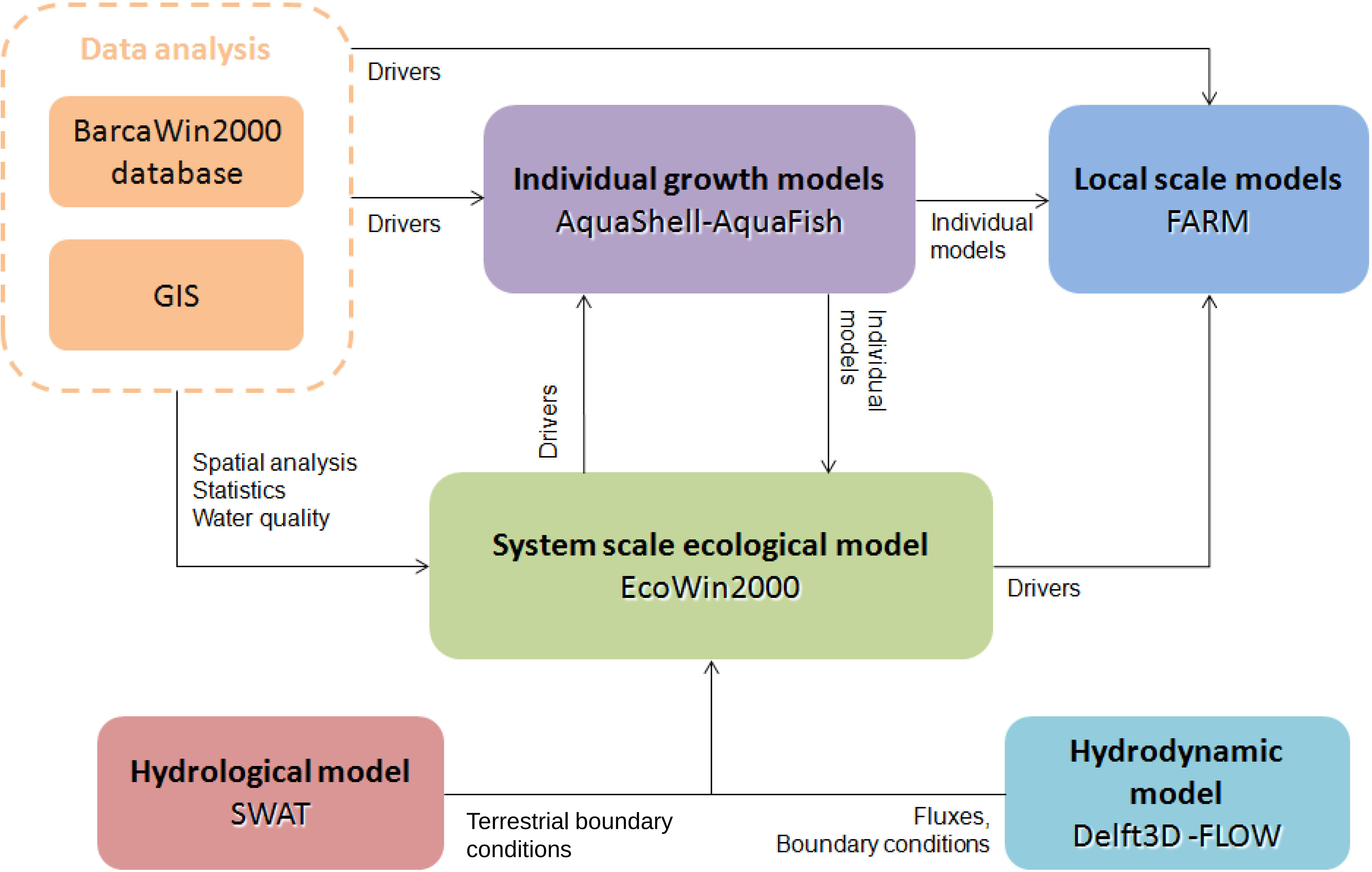
What is the question?

- How can sustainable development of natural resources by achieved for the Ria Formosa?
- Aquafarmers are worried about slow growth and high mortality
- Regulators are worried about nature conservation and exceeding carrying capacity
- No one is sure what would be the best management measures. If the cultivation needs to be reduced, then where and by how much?
- Such decisions impact livelihoods, and can have social consequences

Relevance: sustainable aquaculture

Ferreira et al., 2014. Interactions between inshore and offshore aquaculture. Aquaculture 426-427, 154-164.

FORWARD and COEXIST modelling framework

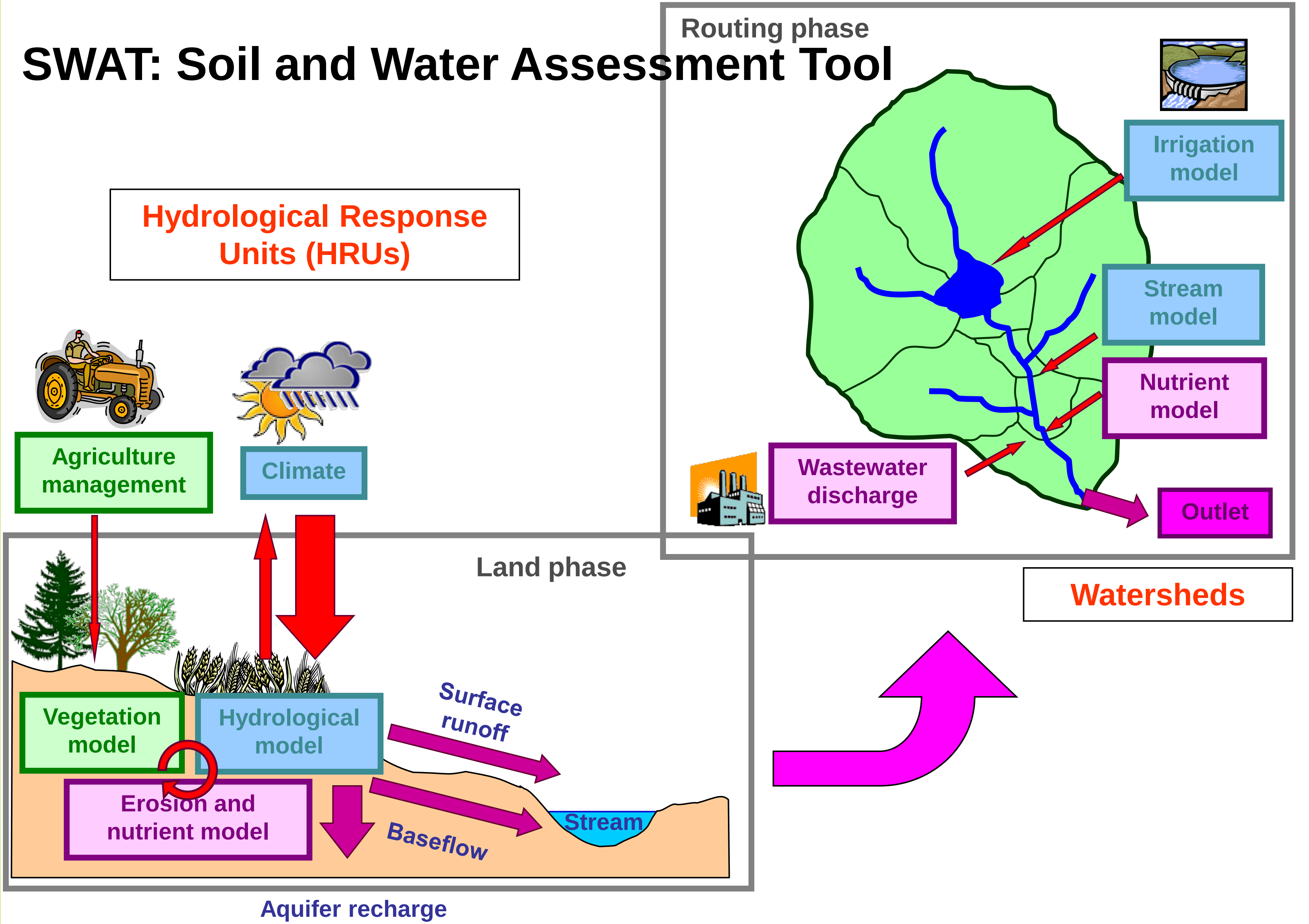


Different models for different questions. Scales are from minutes to decades.

Eco-hydrological model

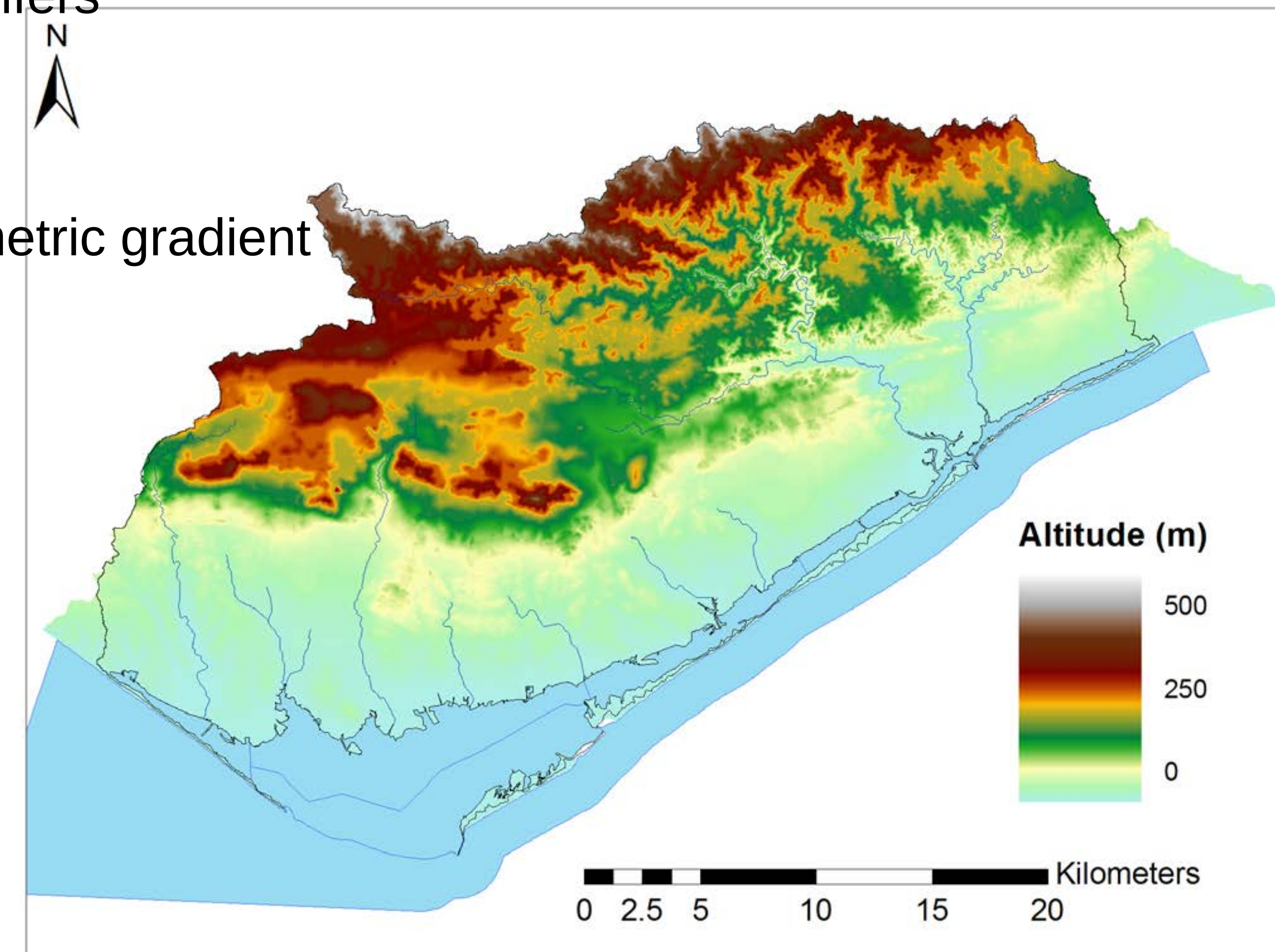
Modelling

SWAT: Soil and Water Assessment Tool



Catchment

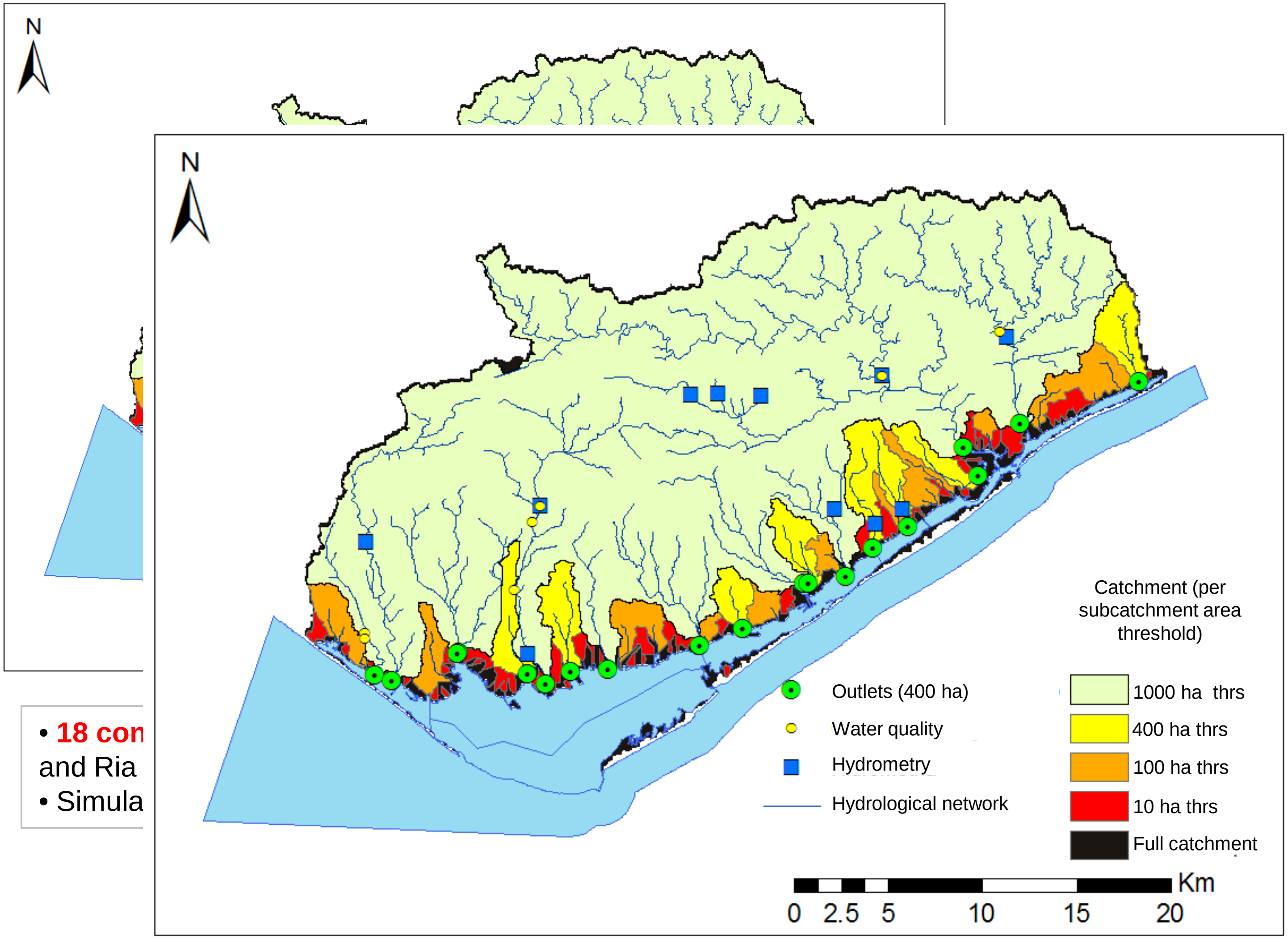
- Morphology:
  - 745 Km^2
  - N-S topographic gradient
  - Coastal aquifers
- Rainfall
  - Semi-arid
  - N-S pluviometric gradient



Overview

SWAT domain

Modelling



• **18 con**
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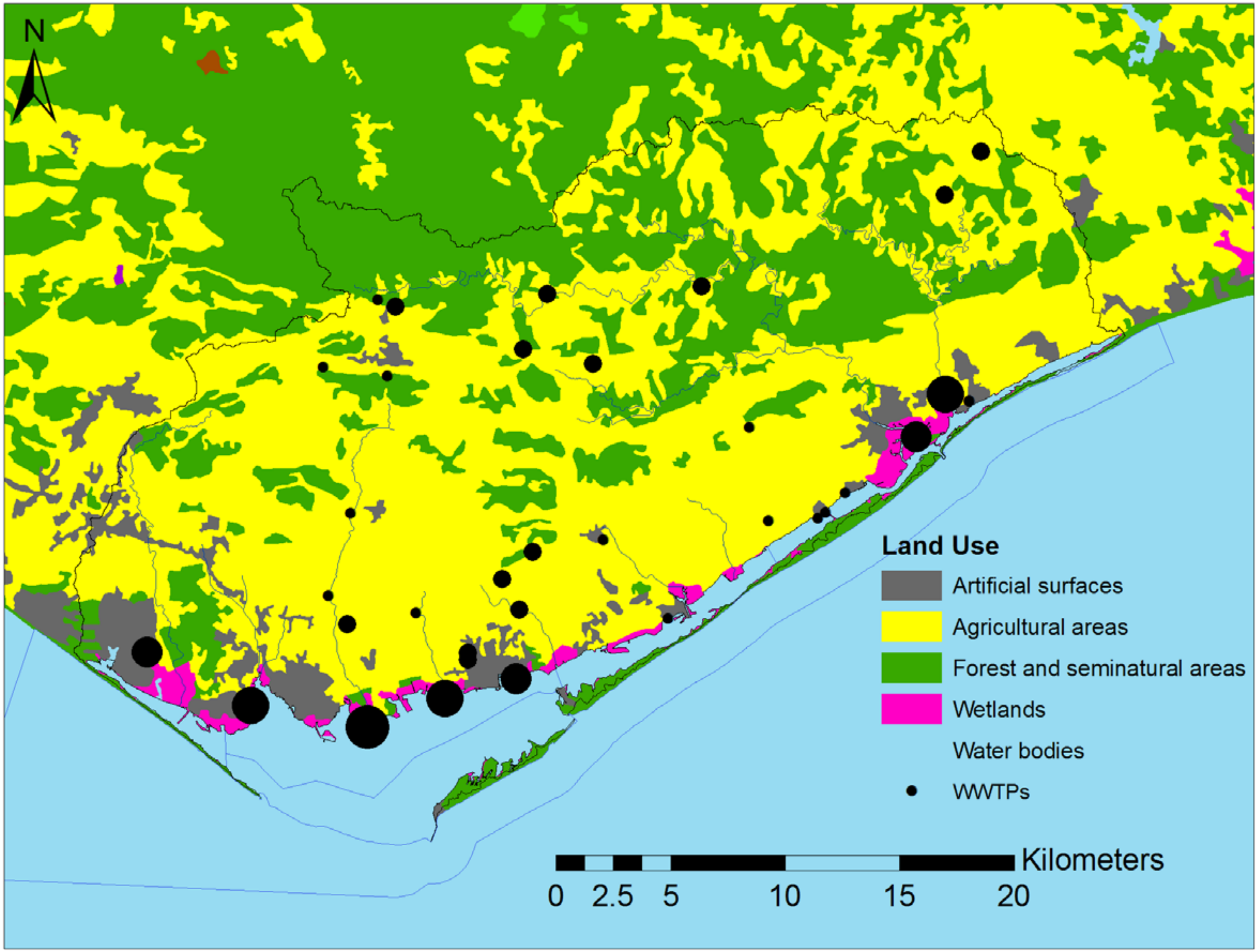
allenges:
tidal influence
Dune barrier
Salt pans
Urban areas

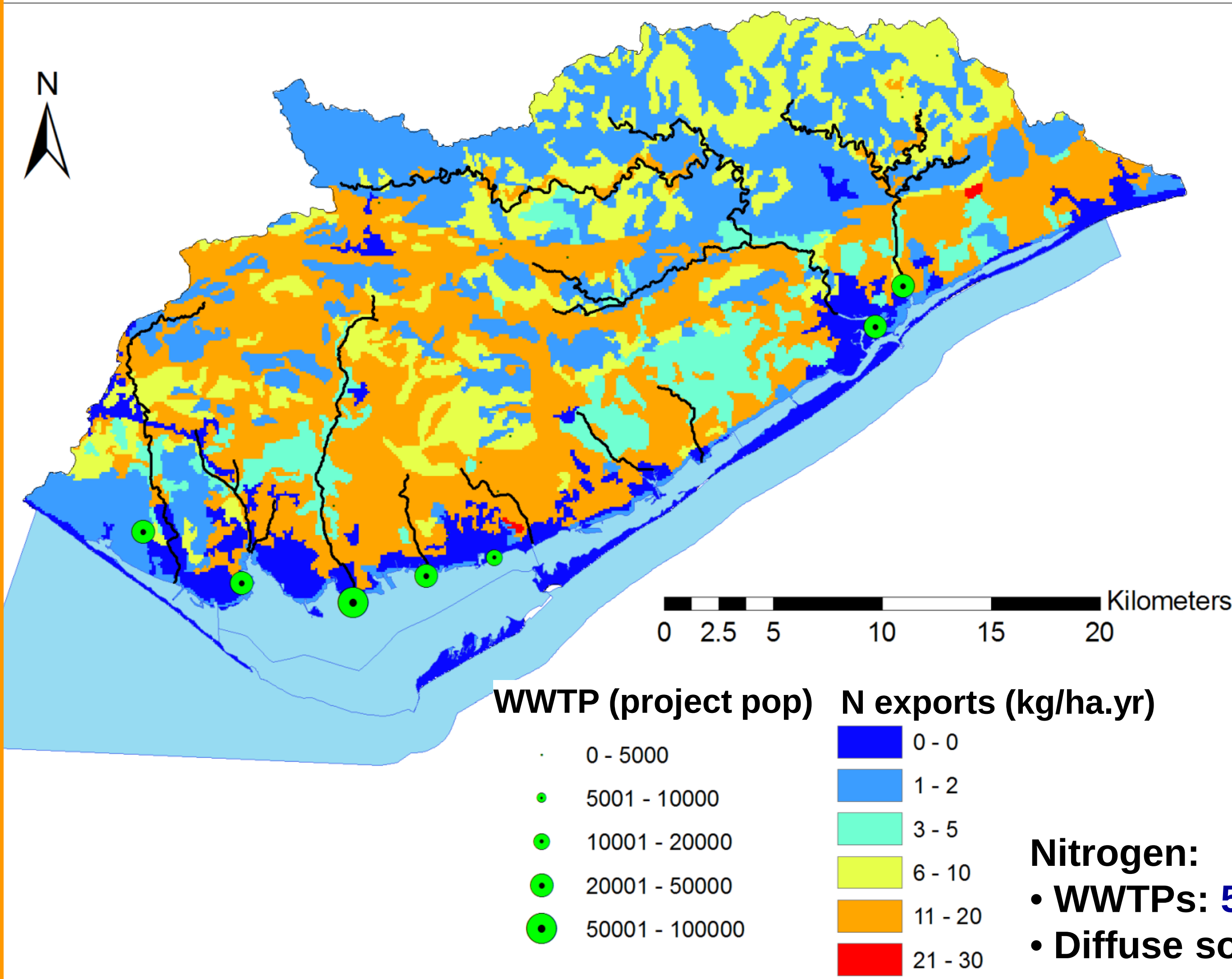
Overview

Catchment



Overview

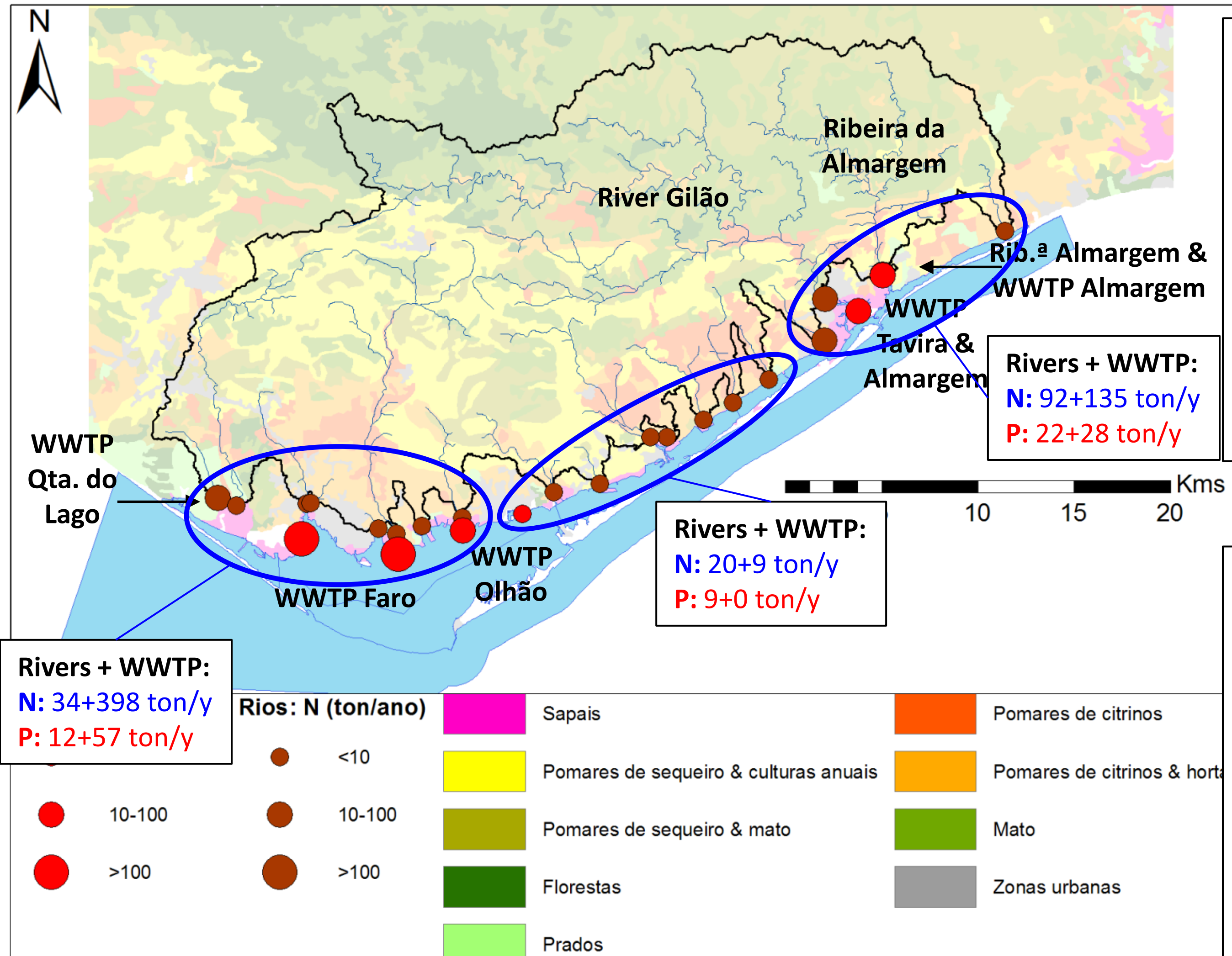
Catchment: Nutrient Load



Nitrogen:
- **WWTPs:** **590** ton N/yr
- **Diffuse sources:** **560** ton N/yr

Phosphorus:
- **WWTPs:** **85** ton P/yr
- **Diffuse sources:** **180** ton P/yr

Nutrient discharge: 2007/08

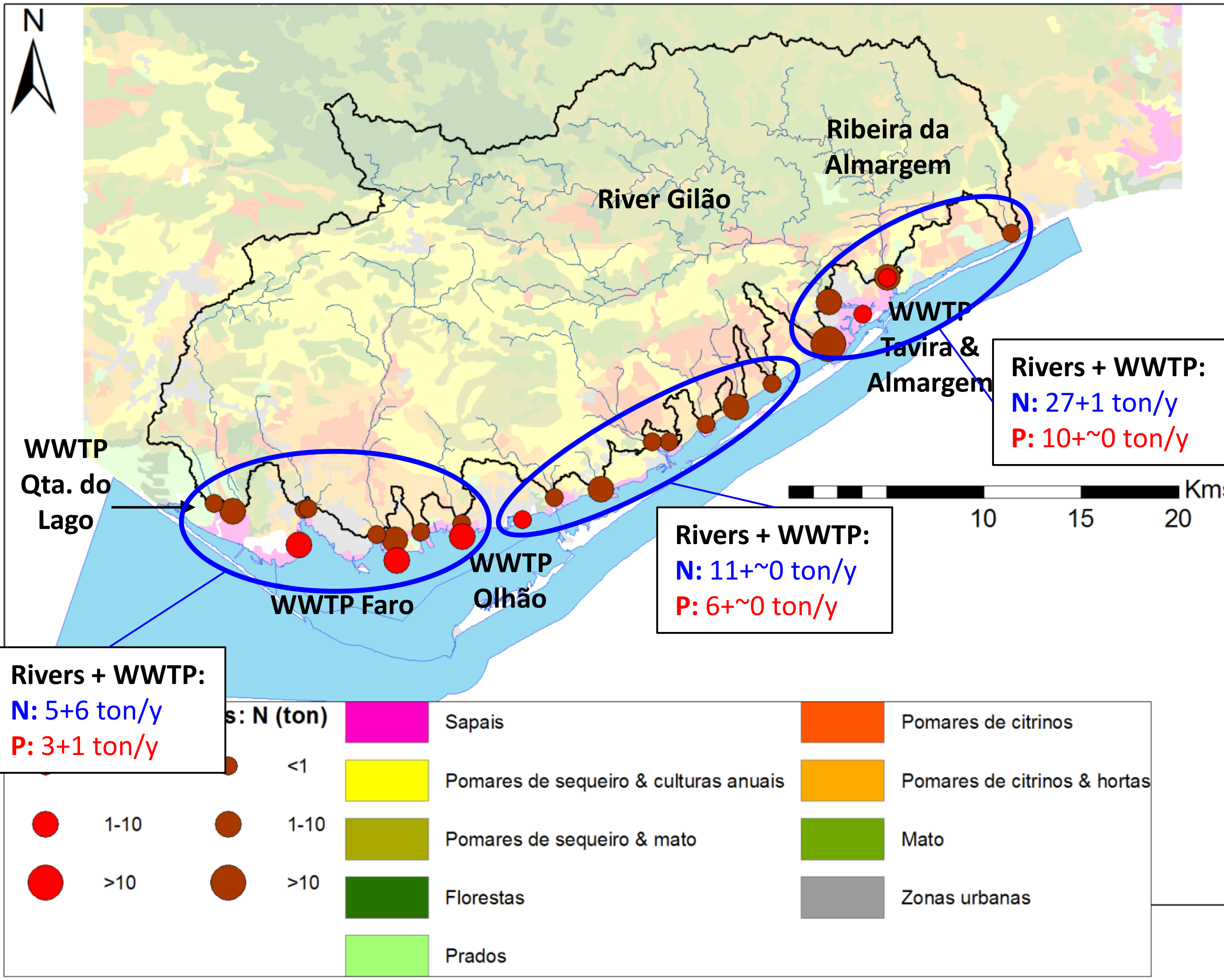


- Export distributed across rivers along the shoreline of the Ria Formosa
- River Gilão e Ribeira da Almargem are important compared to other waterways

Nitrogen (ton N/y):
- WWTP: **450**
- Rivers: **146**
- Sediment: **414**

Phosphorus (ton P/y):
- WWTP: **67**
- Rivers: **44**
- Sediment: **98**

Nutrient discharge: 8-12 April 2008

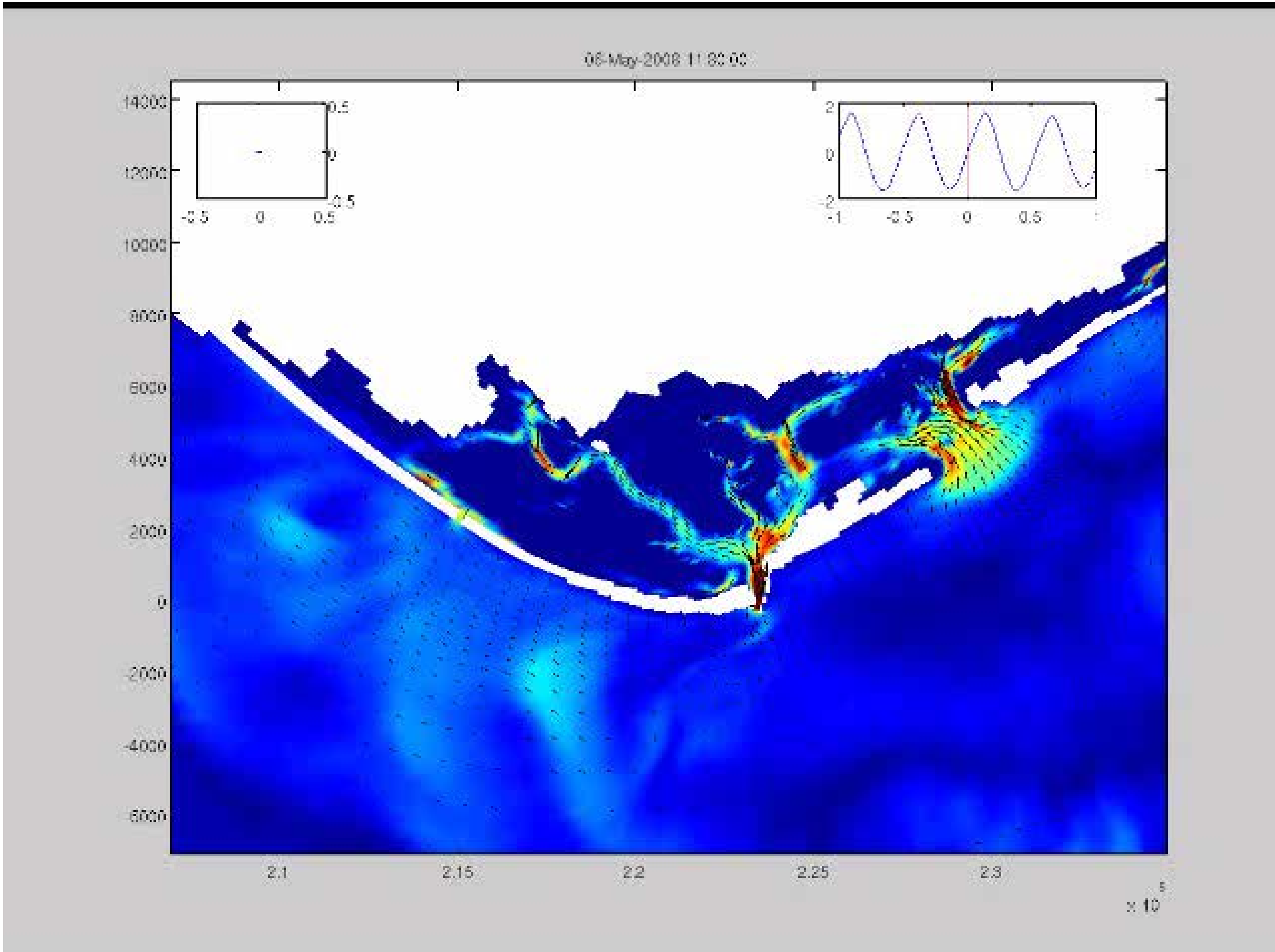


- Peak flow period
- Greater importance of rivers relative to other contributions
- Greater importance of small coastal streams draining agricultural areas

Nitrogen (ton N):
- WWTP: **6.5**
- Rivers: **43.4**
- Sediment: **5.4**

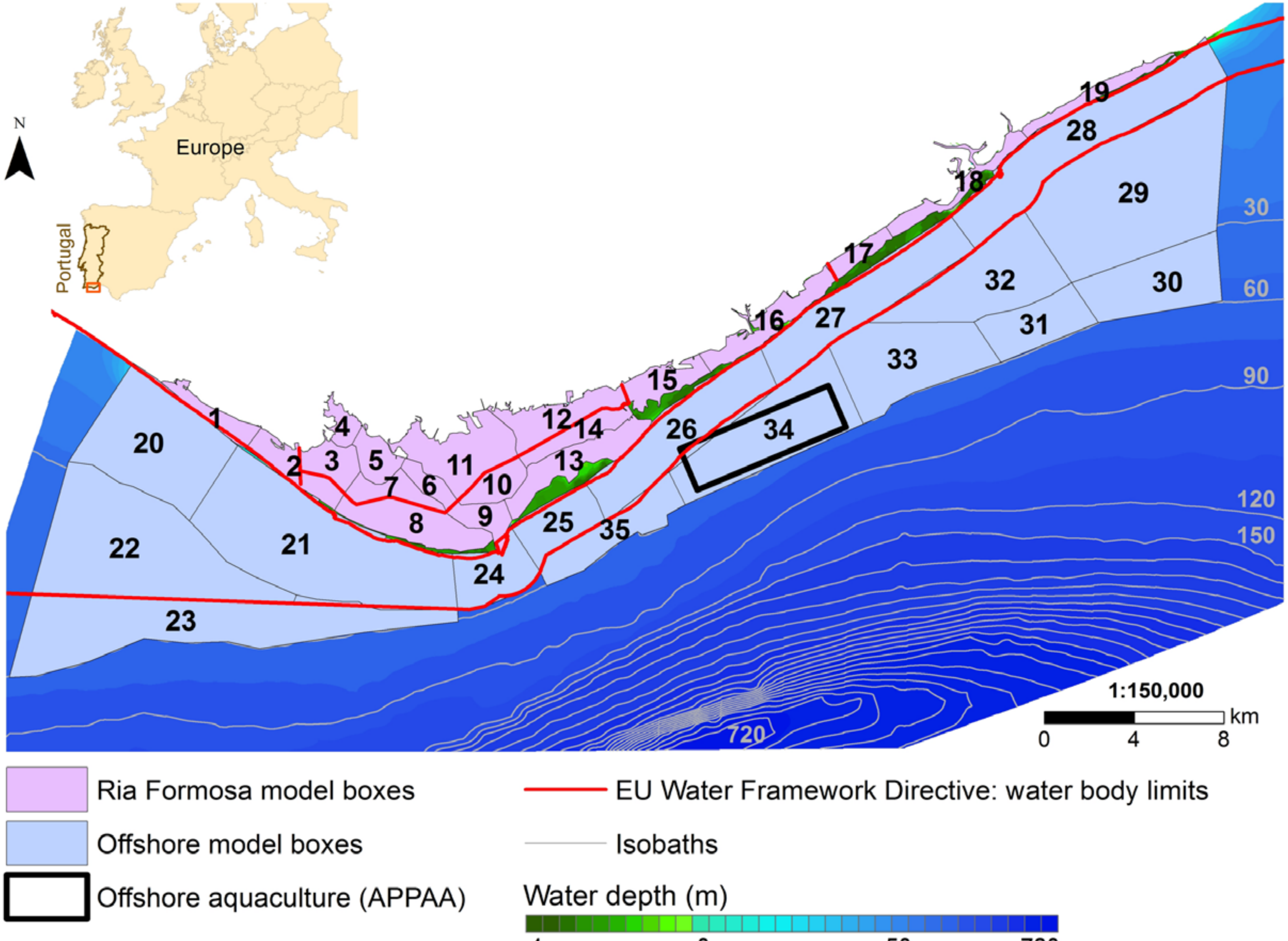
Phosphorus (ton P):
- WWTP: **0.9**
- Rivers: **18.8**
- Sediment: **1.1**

Connectivity: Offshore- Ria Formosa (circulation model)



Tidal circulation in the Ria Formosa, Algarve. Water residence time of 1-2 days.

EcoWin2000 system-scale model – spatial framework

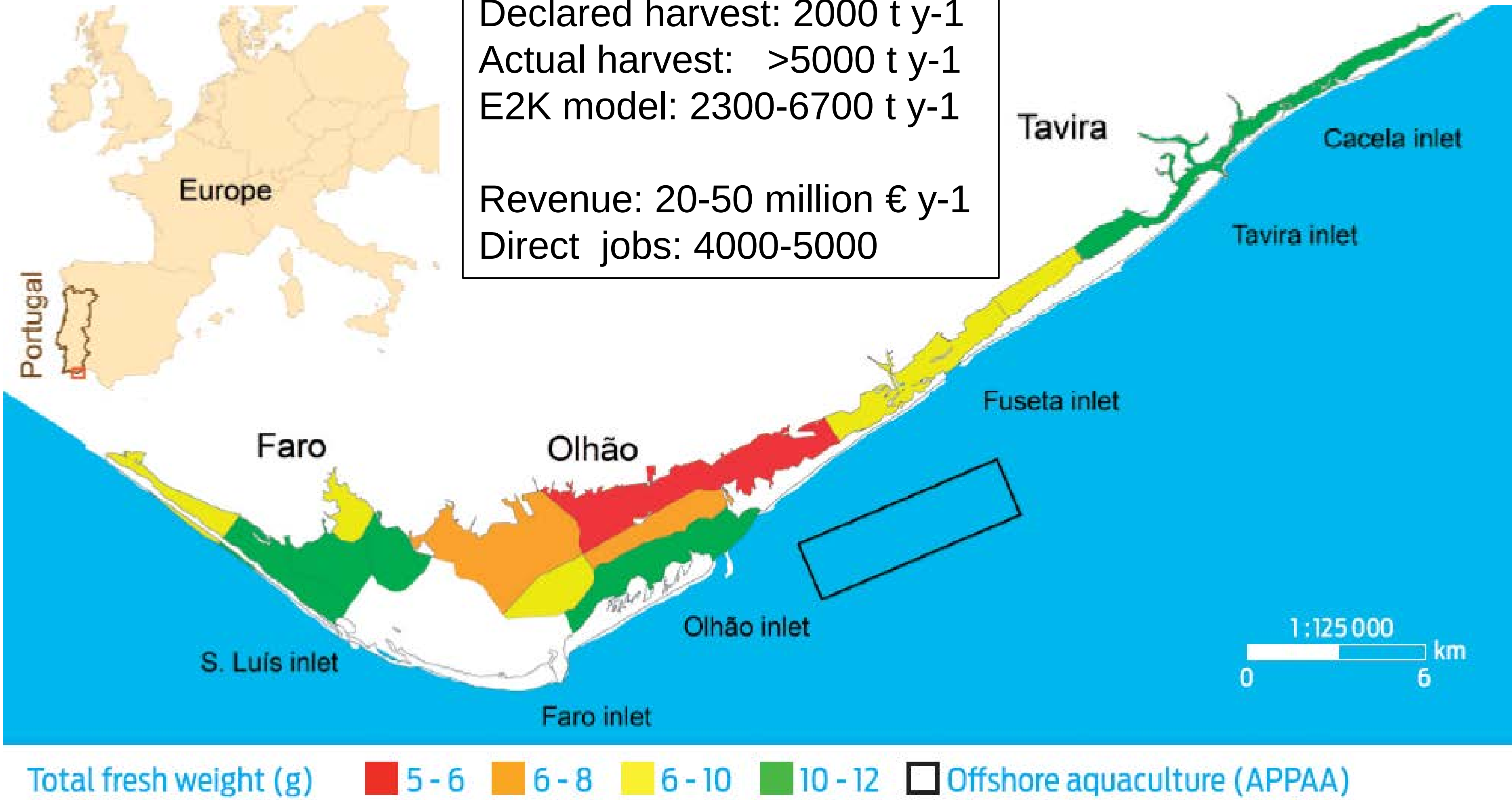


The system is divided into 34 boxes, two vertical layers. Boxes were defined using GIS based on uses, legislation, water quality, and hydrodynamics.

EcoWin2000 model – system-scale clam production

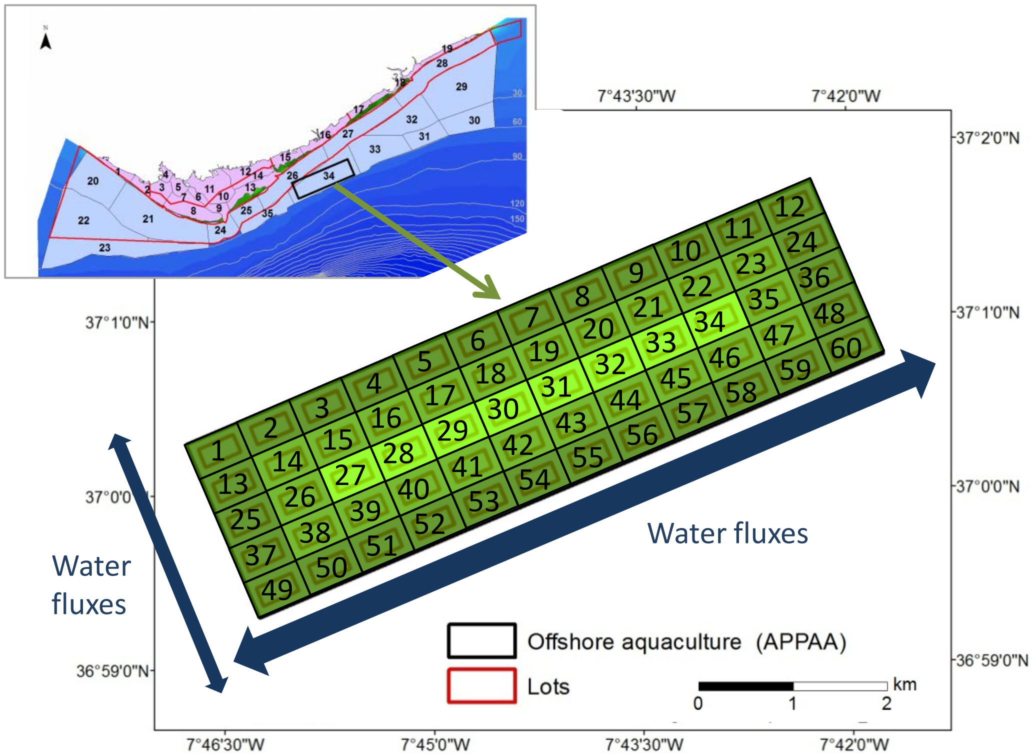
Declared harvest: 2000 t y-1
Actual harvest: >5000 t y-1
E2K model: 2300-6700 t y-1

Revenue: 20-50 million € y-1
Direct jobs: 4000-5000



System-scale carrying capacity is spatially variable, depends on ocean connections.

Goods and services from bivalves

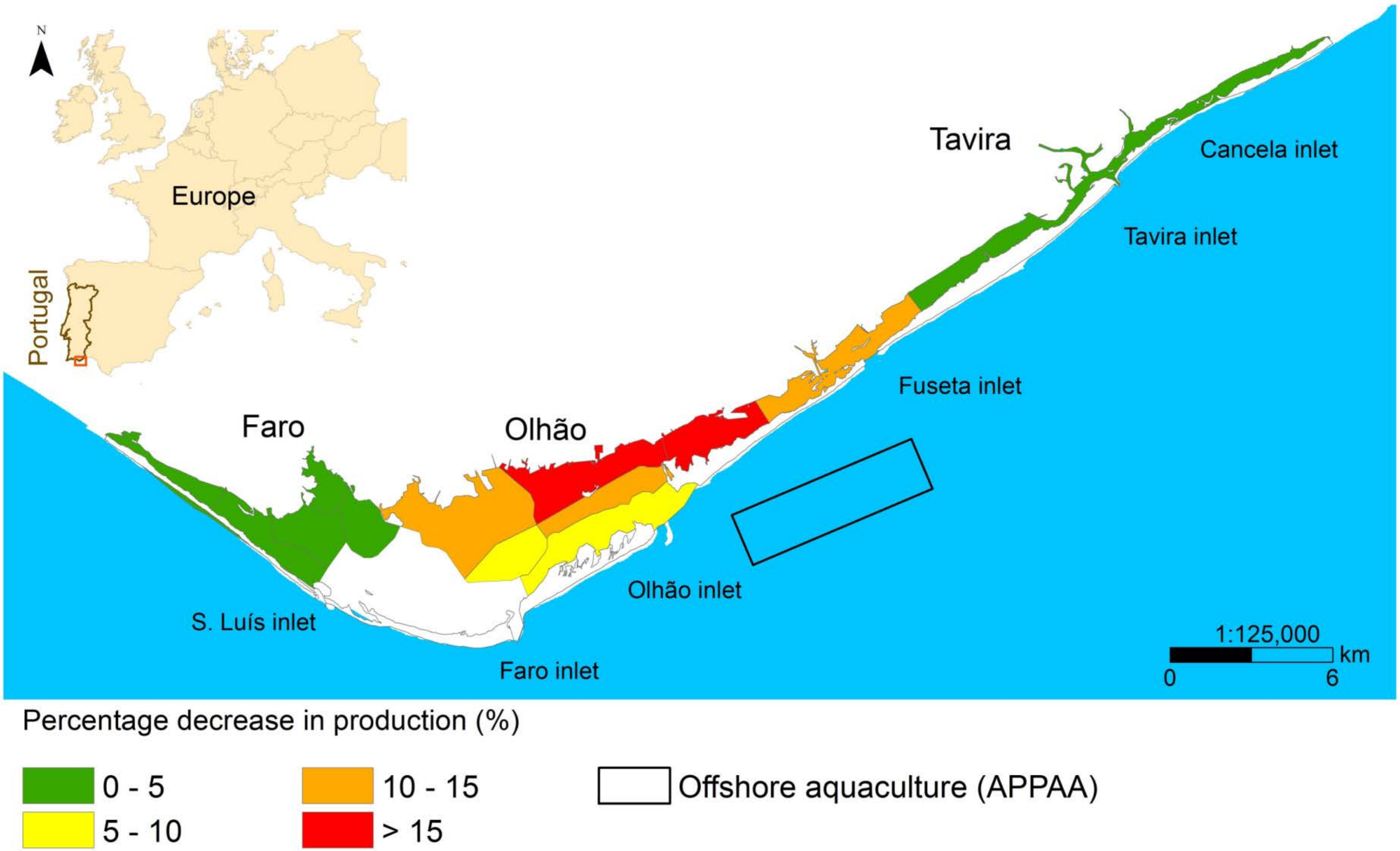


- Removal of organic waste from finfish aquaculture
- Detrital organic material enhances shellfish growth
- Bivalves may act as a firewall to prevent disease spread

Up to 70% finfish
At least 30% bivalves

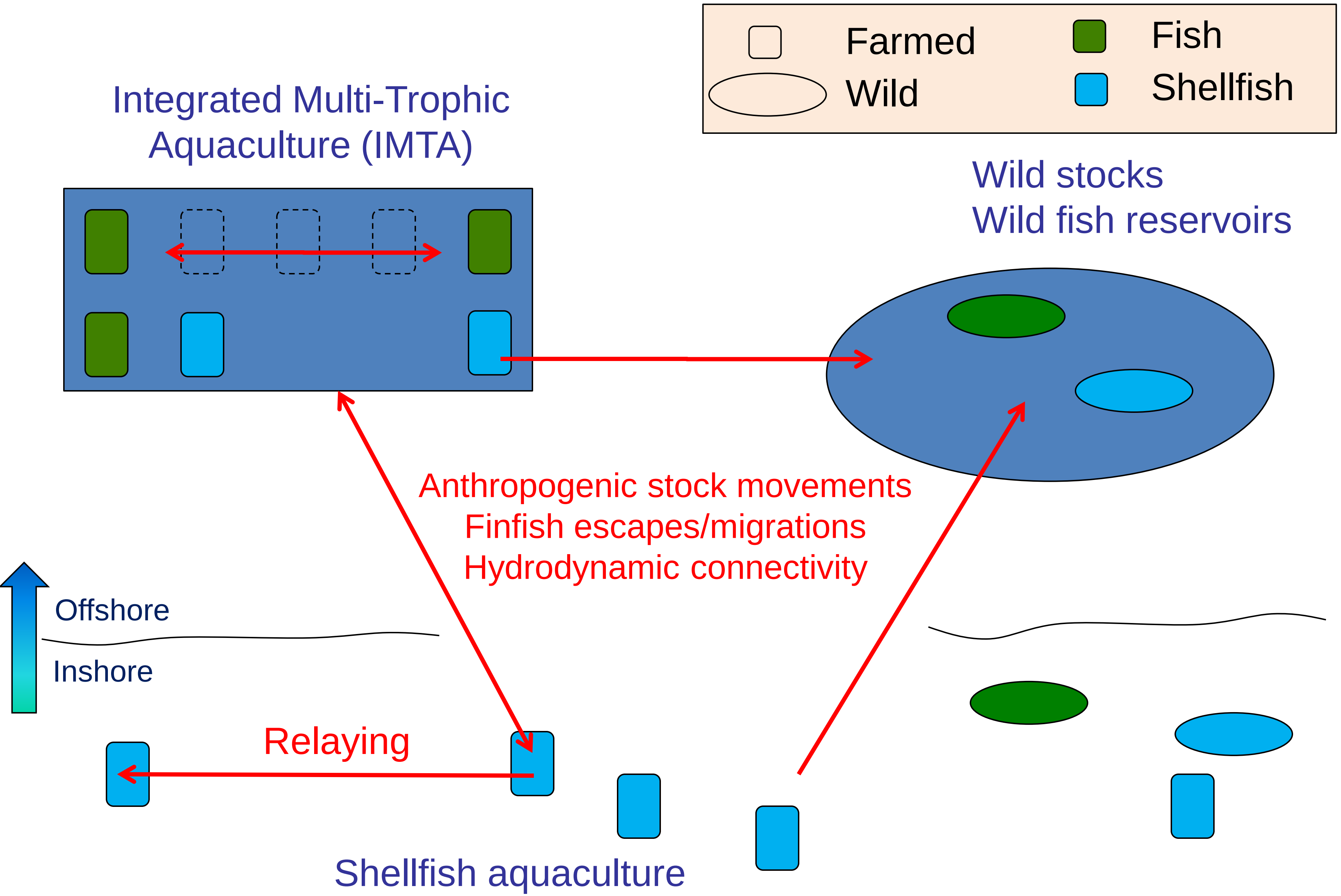
Several large areas in the Algarve are currently designated for offshore aquaculture

EcoWin2000 - Simulated change in clam harvest due to offshore aquaculture of mussels



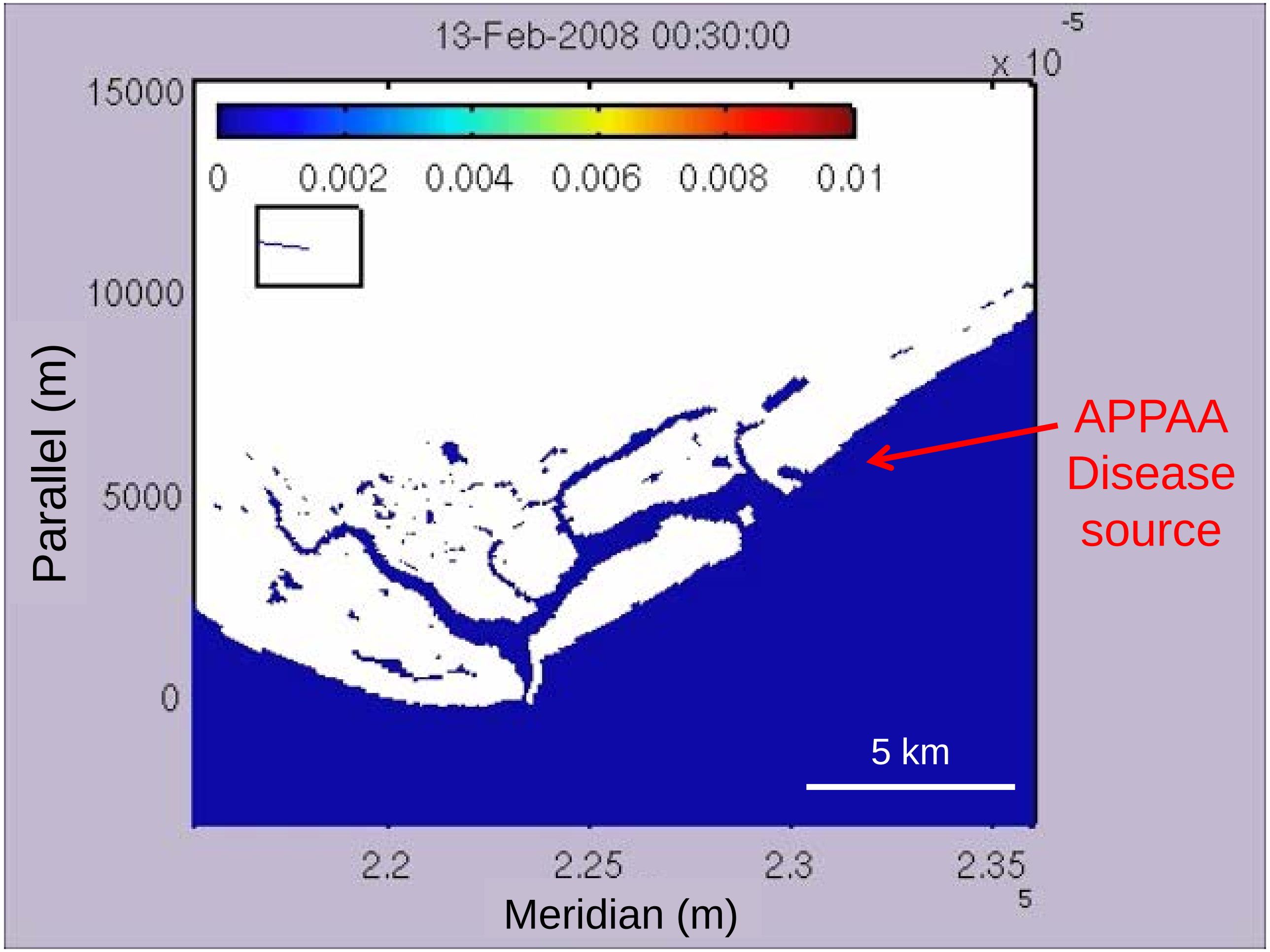
An annual loss of 120 t of clams (1.2 million €) is offset by 13,000 t of mussels

Disease modelling approach



Virus Particle tracking:

Ratio between concentrations at XYZ and emission concentration



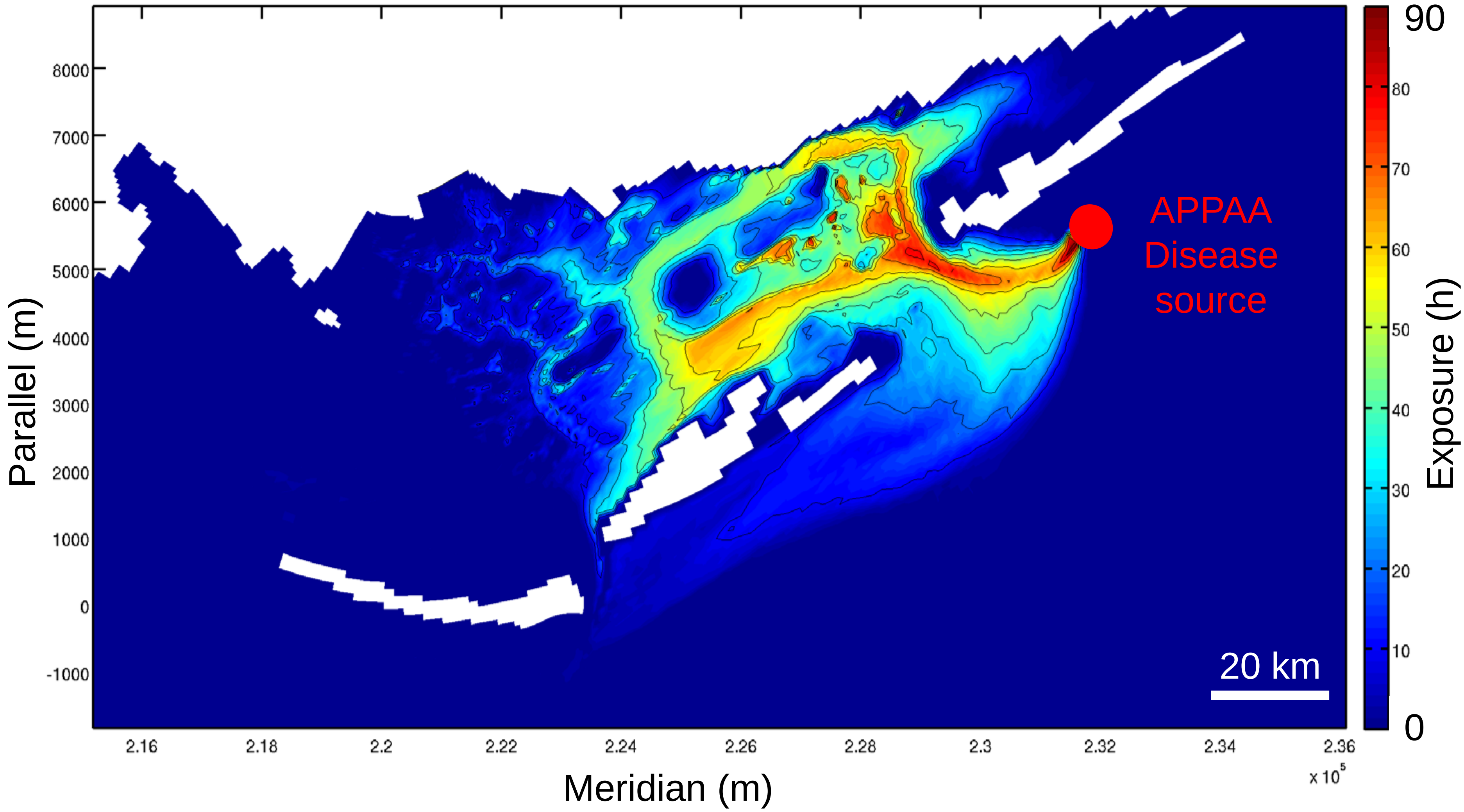
- Disease source: APPAA
- Virus concentration:

Up to 2×10^6 ml^{-1}

- Forcing functions wind and tide
- No decay
- 6 day model run
- Release in mid-water layer

Background virus release the first 2 days, high release on days 3,4 and 5, then a reduction by a factor of a hundred on the last day.

Virus exposure



Number of hours of exposure to 0.5% of the shedding concentration as a measure of potential infection.

The revenge of the killer mussels…

Huge mussel fouling in the summer of 2012. Spat from offshore culture?

The revenge of the killer mussels – part II

February 19th 2013: mussel fouling on untreated fish culture nets. The nets sank under the weight of mussels.

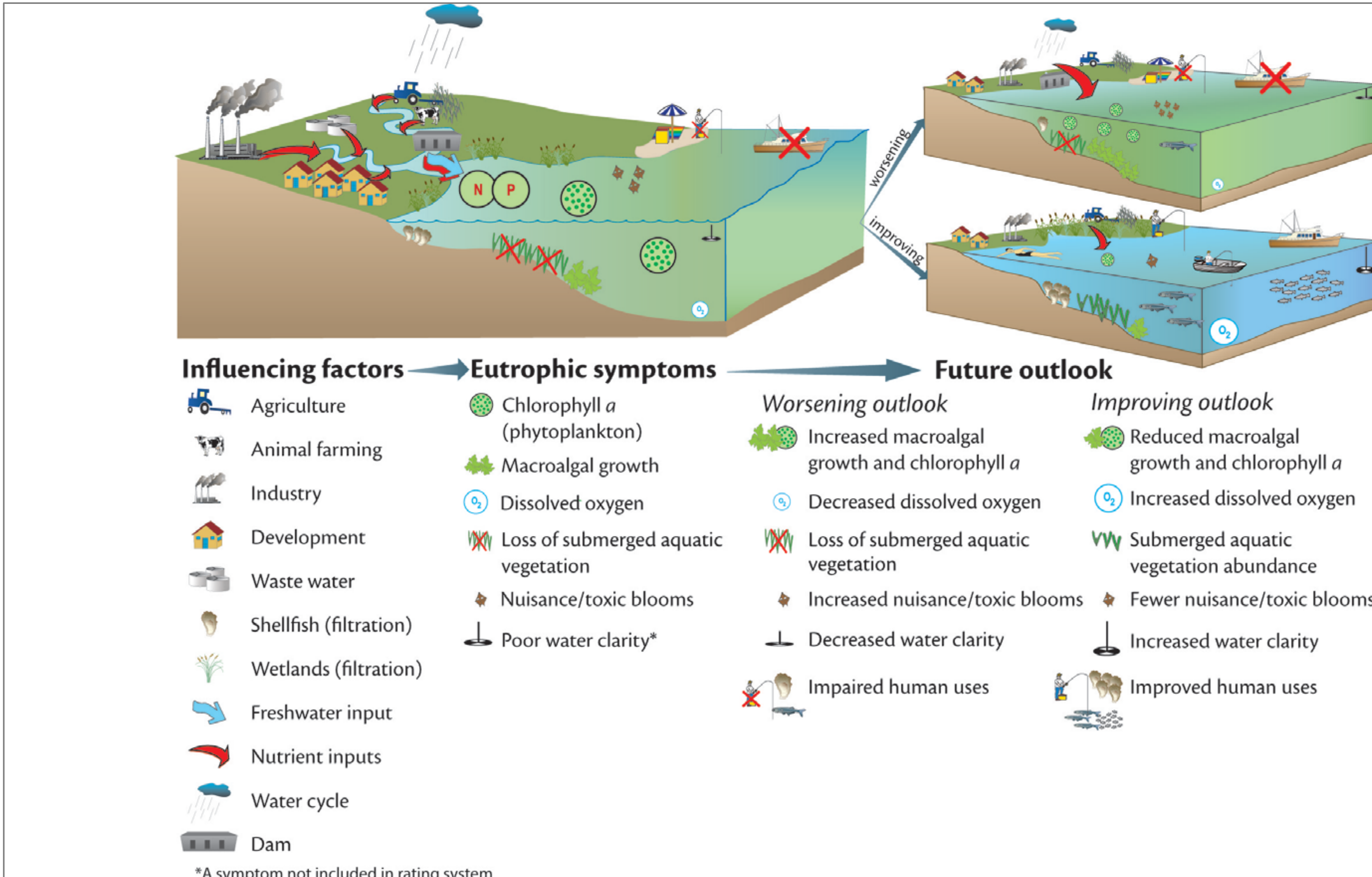
Screening models

Distilling information

- Used for broad comparison and assessment
- Relate pressure, state and response
- May be ecosystem scale or other scales, e.g. regional, fish farm
- Are highly aggregated and easy to apply
- Can be data-driven or use inputs from more complex models
- Are easily understood and interpreted by managers

Screening models synthesise information, and are quick and easy to apply

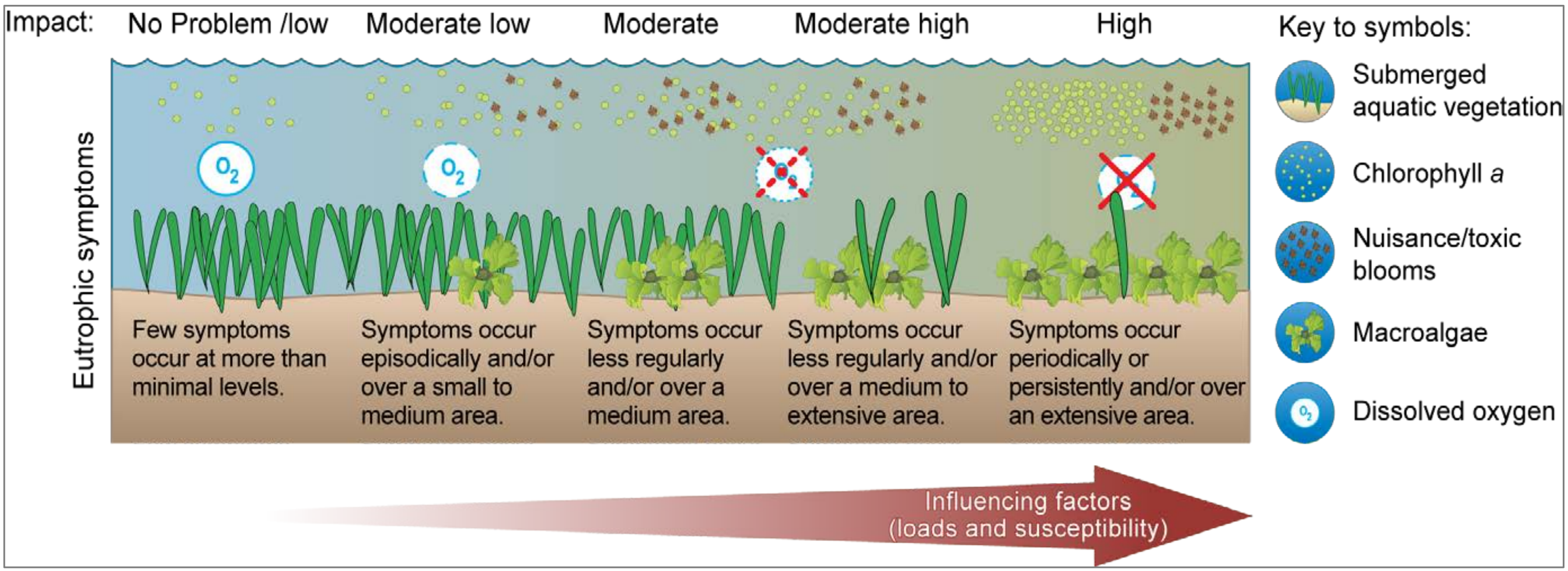
The Eutrophication Process



From: Bricker et al. 2007. National Estuarine Eutrophication Assessment Update

http://www.eutro.us http://www.eutro.org/register

Eutrophication
Stages of environmental degradation



From: Bricker et al.2007. National Estuarine Eutrophication Assessment Update

http://www.eutro.us http://www.eutro.org/register

Indicators used by various assessment methods

Indicators（评价指标）	Nutrient Index I*	Nutrient Index II*	EPA NCA	OSPAR COMPP	ASSETS
Nutrient (N,P) load, conc.	X	X	X	X	X
Chemical oxygen demand	X	X			
Chlorophyll a	X		X	X	X
Dissolved oxygen	X	X	X	X	X
Water clarity			X		
HABs (nuisance/toxic)				X	X
Phytoplankton indicator sp.				X	
Macroalgal abundance				X	X
Seagrass loss				X	X
Zoobenthos-fish kills				X	
Temporal focus	Unspecified	Unspecified	Summer	Spring/winter	Full year
Integration	Additive	Ratio	Ratio	Integration	PSR

* Commonly applied in China

Methods with red crosses fall short of a full eutrophication assessment

Adapted from: Xiao et al. 2007, Estuaries. and Coasts 30:901-918

MSFD guidance synthesis

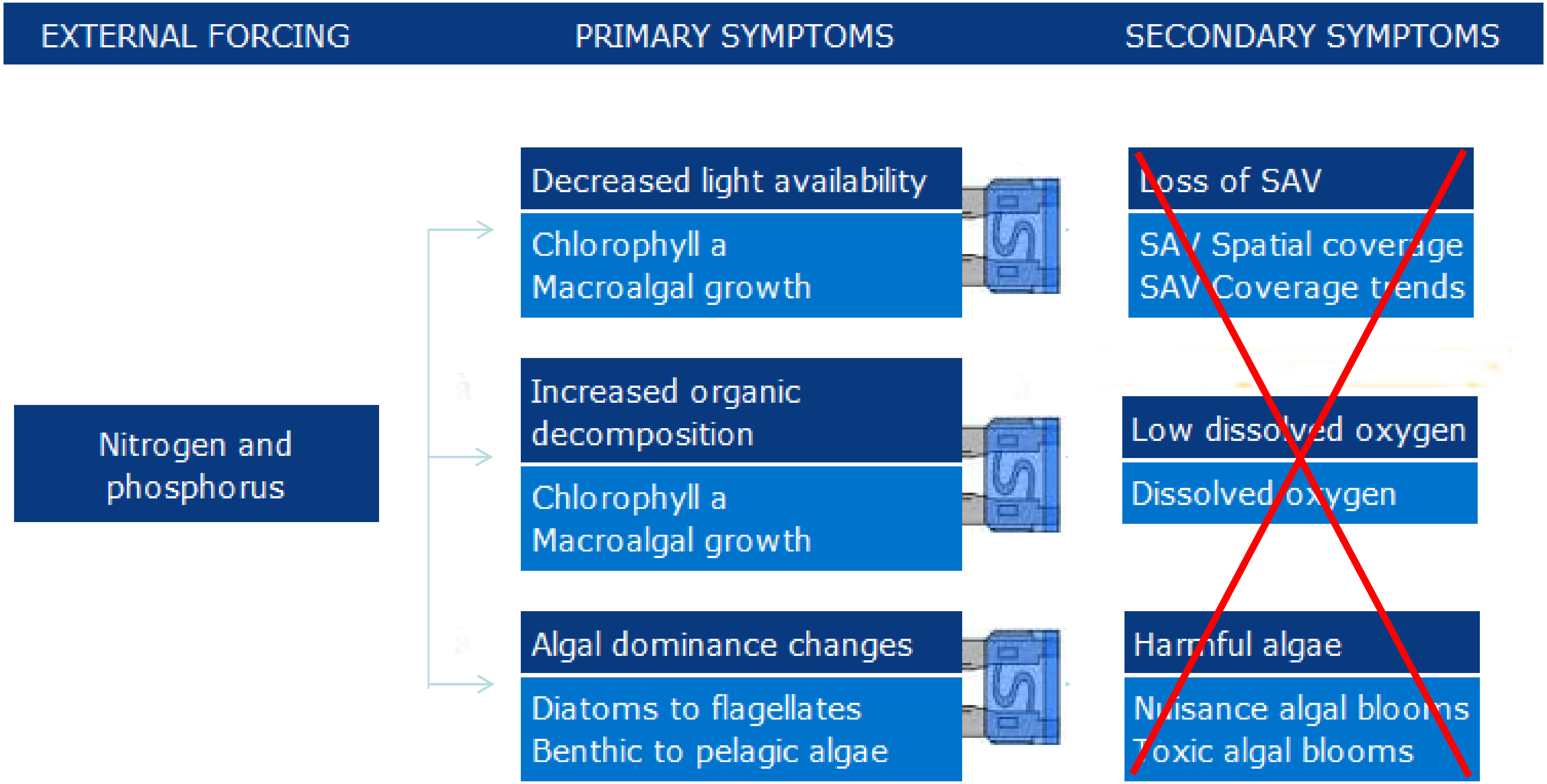
Eutrophication assessment models

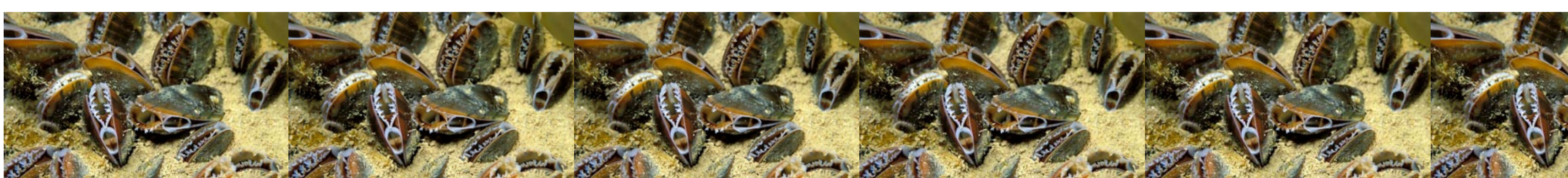
Method	Biological Indicators	Physico - Chemical Indicators	Load related to WQ	Integrated final rating
TRIX	Chlorophyll (Chl)	DO, DIN, TP	No	Yes
EPA NCA WQ Index	Chl	Water clarity, DO, DIN, DIP	No	Yes
ASSETS	Chl, macroalgae, seagrass, HAB	DO	Yes	Yes
LWQI/TWQI	Chl, macroalgae, seagrass	DO, DIN, DIP	No	Yes
OSPAR COMPP	Chl, macroalgae, seagrass, PP indicator spp.	DO, DIN, DIP, TP, TN,	Yes	Yes
UK “WFD”	Primary production, Chl, macroalgae, benthic invertegrates, seagrass	Water clarity, DO, DIN, DIP, TN, TP	No	Yes
HEAT	Chl, macroalgae, benthic invertegrates, seagrass, HAB	Water clarity, DO, DIN, DIP, TN, TP, C	No	Yes
IFREMER	Chl, seagrass, macrobenthos, HAB	Water clarity, DO, DIN, SRP, TN, TP, sediment organic matter, sediment TN, TP	No	Yes

Some methods do not consider pressure-state relationships

Ferreira et al. 2011, Estuarine Coastal and Shelf Science, 93, 117-131.

ASSETS screening model





Top-down control : the circuit-breaker between primary and secondary symptoms.

Key aspects of the ASSETS approach

Three stages...

The ASSETS approach may be divided into three parts:

- ✓ **Division of coastal systems into homogeneous areas**
  - **Tidal freshwater (<0.5 psu)**
  - **Mixing zone (0.5-25 psu)**
  - **Seawater zone (>25 psu)**
- ✓ **Evaluation of data completeness and reliability**
  - Spatial and temporal quality of datasets: completeness
  - Confidence in results: sampling and analytical reliability
- ✓ **Application of indices**

Influencing Factors (IF) index	------------------	**Pressure**
Eutrophic Condition (EC) index	------------------	**State**
Future Outlook (FO) index	------------------	**Response**

S.B. Bricker, J.G. Ferreira, T. Simas, 2003. An integrated methodology for assessment of estuarine trophic status. Ecol. Modelling 169: 39-60.

ASSETS Influencing Factors (Pressure)

Calculate m_h, the expected nutrient concentration due to land based sources (i.e. no ocean sources);

Calculate m_b, the expected background nutrient concentration due to the ocean (i.e. no land-based sources);

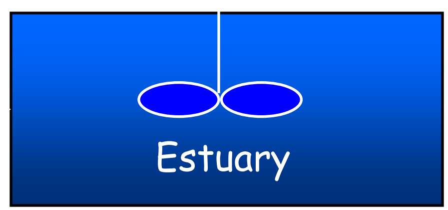
Calculate OHI as the ratio of $m_h/(m_h+m_b)$;

Class	Thresholds
Low	0 to <0.2
Moderate low	0.2 to <0.4
Moderate	0.4 to < 0.6
Moderate high	0.6 to < 0.8
High	>0.8

Equations are based on a simple Vollenweider approach, modified to account for dispersive exchange:

Anthropogenic inputs

$$m_h = \frac{m_{in}(s_o - s_e)}{s_o}$$



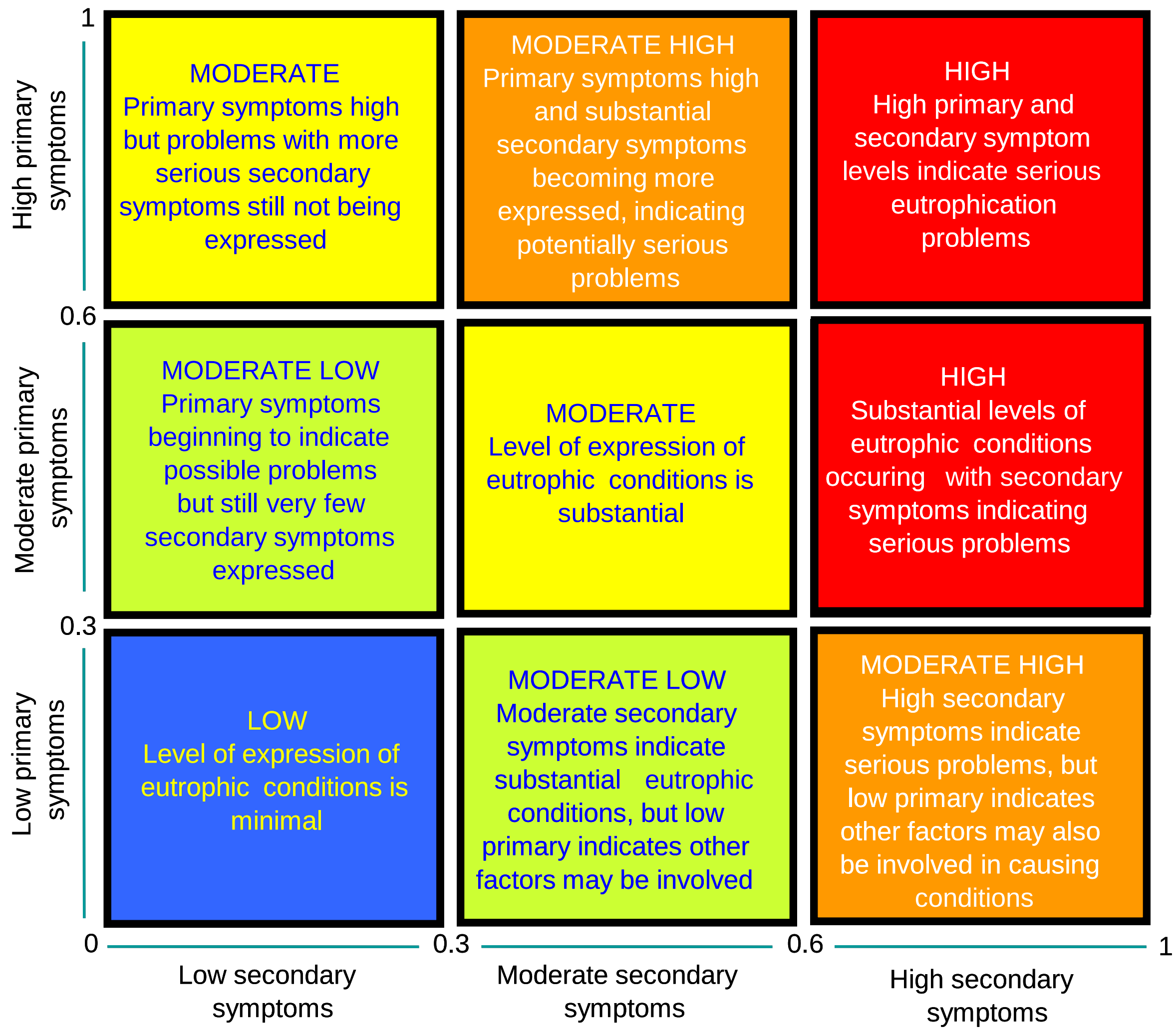
Ocean inputs

$$m_b = \frac{m_{sea} s_e}{s_o}$$

Bricker, S.B., Ferreira, J.G. & Simas, T. - An Integrated Methodology for Assessment of Estuarine Trophic Status. Ecol. Modelling 169: 39-60.

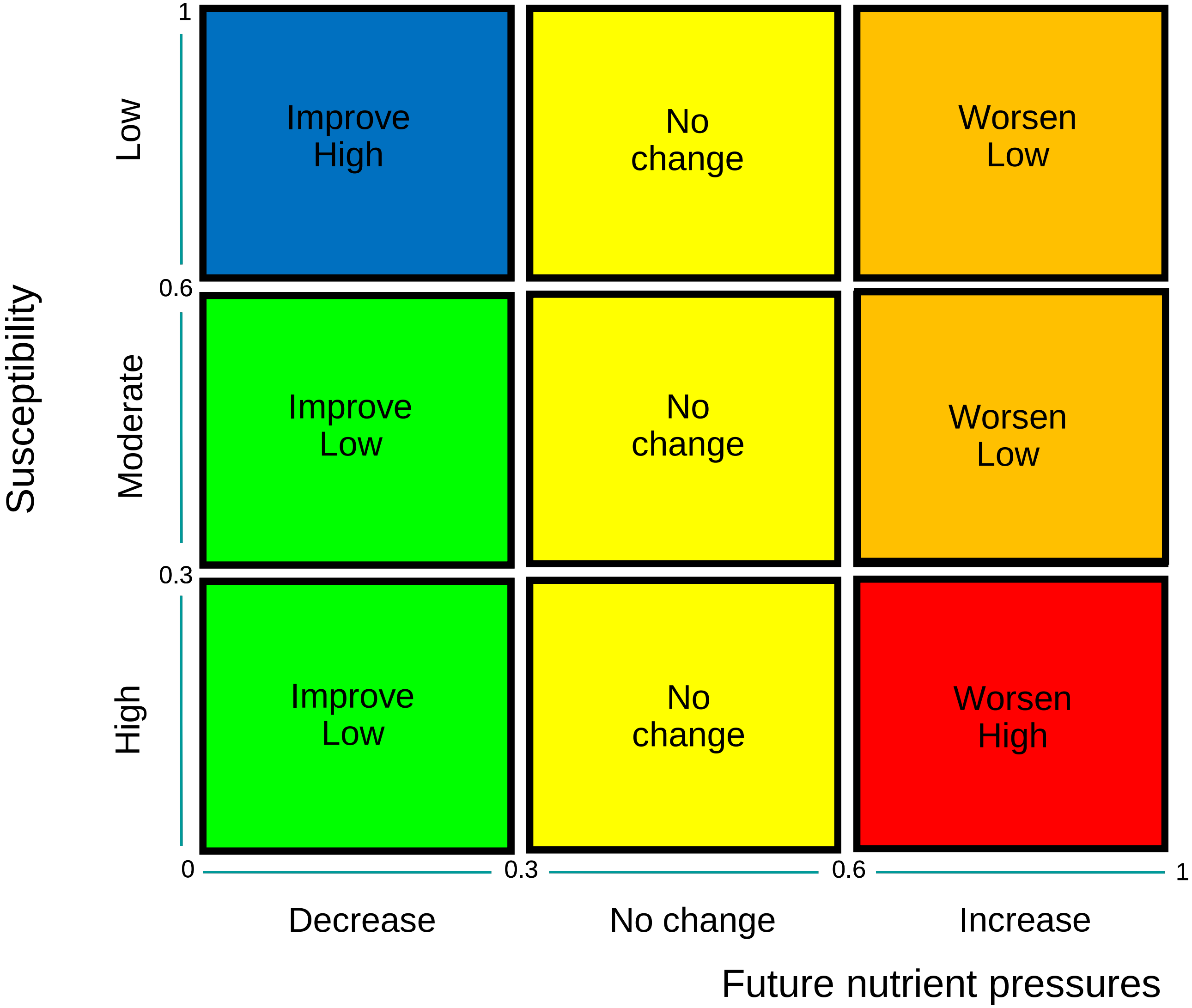
ASSETS – Assessment of State

Eutrophic condition



Combinatorial matrix for primary and secondary symptoms.

ASSETS Future Outlook matrix



Takes into account susceptibility and planned management actions.

ASSETS Approach: Pressure - State - Response

Influencing Factors (IF)

Susceptibility \ Nutrient Pressures	Low	Moderate	High
High	Moderate	Moderate High	High
Moderate	Moderate Low	Moderate	Moderate High
Low	Low	Low	Moderate Low

<u>Susceptibility</u>
dilution & flushing
+
<u>Nutrient Inputs</u>
land based or
oceanic
↓
Influencing Factors

Eutrophic Condition (EC)

Primary Symptoms \ Secondary Symptoms	Low	Moderate	High
High	Moderate	Moderate High	High
Moderate	Moderate Low	Moderate	High
Low	Low	Moderate Low	Moderate High

<u>Primary Symptoms</u>
Chl and Macroalgae

Average of ratings

<u>Secondary Symptoms</u>
D.O., HABs, SAV
change

Worst case

Future Outlook (FO)

Susceptibility \ Future Nutrient Pressures	Decrease	No Change	Increase
Low	Improve High	No Change	Worsen Low
Moderate	Improve Low	No Change	Worsen Low
High	Improve Low	No Change	Worsen High

<u>Susceptibility</u>

<u>Nutrient pressure changes</u>
population , management, watershed use (particularly agricultural)

IF + EC + FO = ASSETS

Full accounting of eutrophication symptoms, including time and space

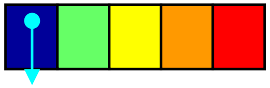
Adapted from: Bricker et al. 2003, Ecological Modelling, 169(1), 39-60

ASSETS scoring system for PSR

Grade	5	4	3	2	1
Pressure (IF)	Low	Moderate low	Moderate	Moderate high	High
State (EC)	Low	Moderate low	Moderate	Moderate high	High
Response (FO)	Improve high	Improve low	No change	Worsen low	Worsen high

Metric	Combination matrix	Class
P	5 5 5 4 4 4	High (5%)
S	5 5 5 5 5 5	
R	5 4 3 5 4 3	
P	5 5 5 5 5 5 5 4 4 4 4 4 3 3 3 3 3 3	Good (19%)
S	5 5 4 4 4 4 4 5 5 4 4 4 5 5 5 4 4 4	
R	2 1 5 4 3 2 1 2 1 5 4 3 5 4 3 5 4 3	
P	5 5 5 5 5 4 4 4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 2 2 2 1 1	Moderate (32%)
S	3 3 3 3 3 4 4 3 3 3 3 3 5 5 4 4 3 3 3 4 4 4 4 4 3 3 3 2 3 3	
R	2 1 5 4 3 2 1 5 4 3 2 1 2 1 2 1 5 4 3 5 4 3 2 1 5 4 3 5 5 4	
P	4 4 4 4 4 3 3 3 3 3 3 3 2 2 2 2 2 2 1 1 1 1 1	Poor (24%)
S	2 2 2 2 2 3 3 2 2 2 2 2 3 3 2 2 2 2 3 3 3 2 2	
R	5 4 3 2 1 2 1 5 4 3 2 1 2 1 4 3 2 1 3 2 1 5 4	
P	3 3 3 3 3 2 2 2 2 2 1 1 1 1 1 1 1 1	Bad (19%)
S	1 1 1 1 1 1 1 1 1 1 2 2 2 1 1 1 1 1	
R	5 4 3 2 1 5 4 3 2 1 3 2 1 5 4 3 2 1	

ASSETS – Strangford Lough, N. Ireland



ASSETS: HIGH

Indices	Methods	Parameters	Rating	Expression	Index
Influencing Factors (IF) ASSETS: 5	Susceptibility	Dilution potential	High	Low susceptibility	LOW
		Flushing potential	Moderate		
	Nutrient inputs		Low		
Eutrophic Condition (EC) ASSETS: 5	Primary	Chlorophyll *a*	Moderate	Moderate	LOW
		Macroalgae	Problems observed		
	Secondary	Dissolved Oxygen	No problems	Low	
		Submerged Aquatic Vegetation	Losses observed		
		Nuisance and Toxic Blooms	No		
Future Outlook (FO) ASSETS: 4	Future nutrient pressures	Future nutrient pressures decrease			Improve Low

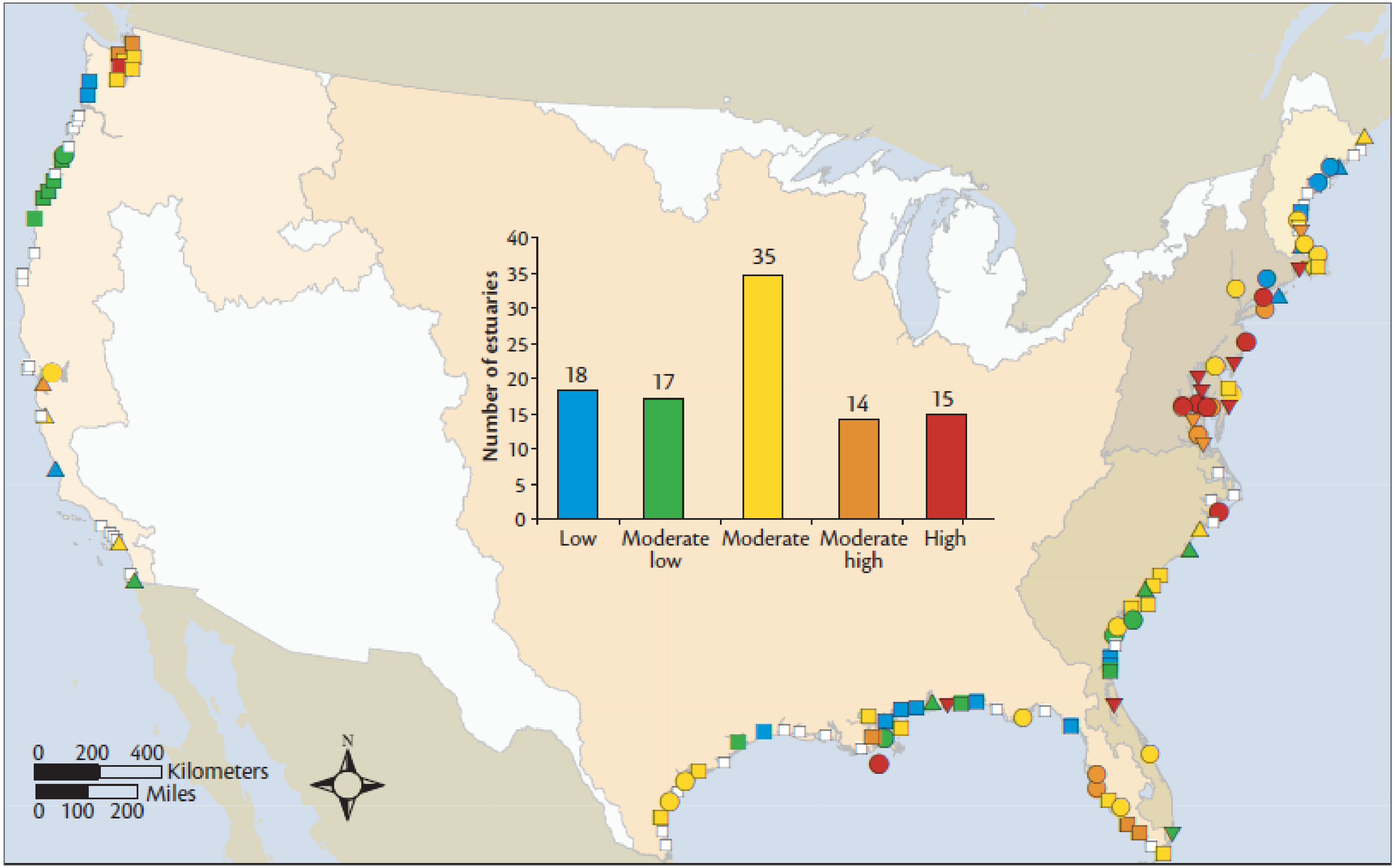
High status system, classified as an SAC under UK law.

ASSETS
Combination of research and screening models

	Methods	Parameters	Value	Level of expression	Index
Eutrophic Condition (OEC)	PSM	Chlorophyll *a*	0.25	0.57 Moderate	MODERATE LOW
ASSETS OEC: 4	*Field data*	Epiphytes	0.50		
		Macroalgae	0.96		
	SSM	Dissolved Oxygen	0	0.25 Low	
		Submerged Aquatic Vegetation	0.25		
		Nuisance and Toxic Blooms	0		
Eutrophic Condition (OEC)	PSM	Chlorophyll *a*	0.25	0.58 Moderate	MODERATE LOW
ASSETS OEC: 4	*Research model*	*Epiphytes*	*0.50*		
		Macroalgae	1.00		
	SSM	Dissolved Oxygen	0	0.25 Low	
		Submerged Aquatic Vegetation	0.25		
		Nuisance and Toxic Blooms	0		
Eutrophic Condition (OEC)	PSM	Chlorophyll *a*	0.25	0.42 Moderate	MODERATE LOW
ASSETS OEC: 4(5)	*Model green scenario*	*Epiphytes*	*0.50*		
		Macroalgae	0.50		
	SSM	Dissolved Oxygen	0	0.25 Low	
		Submerged Aquatic Vegetation	0.25		
		Nuisance and Toxic Blooms	0		

28% lower

ASSETS multiple site comparisons

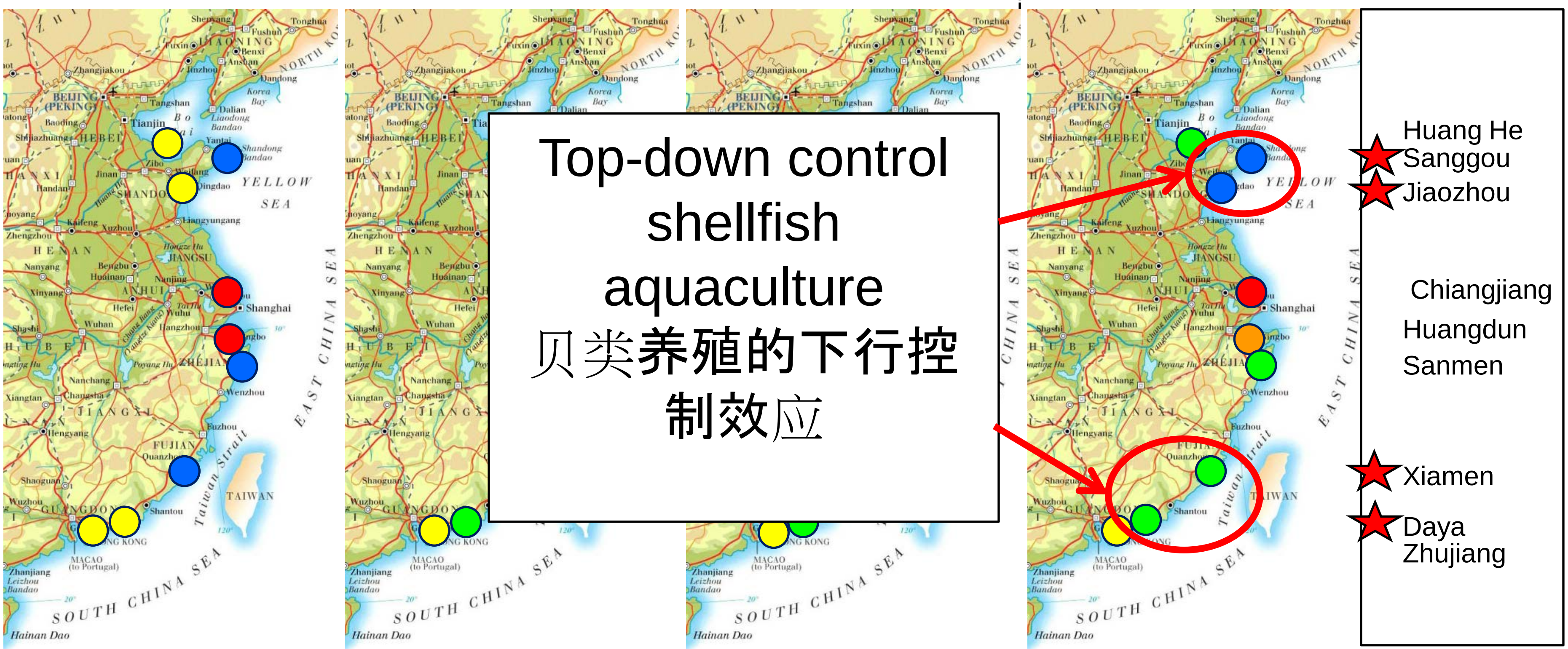


http://ian.umces.edu/neea **http://www.eutro.us**

The most recent assessment shows problems in the NEA and Gulf of Mexico

ASSETS Pressure-State-Response

压力	状态	反馈	ASSETS结果
Influencing Factors	Eutrophic Condition	Future Outlook	ASSETS



High
Moderate High
Moderate
Moderate Low
Low or No Problem
Unknown

Worsen High	Bad	(WFD)
Worsen Low	Poor	
No Change	Moderate	
Improve Low	Good	
Improve High	High	
Unknown	Unknown or Not Applicable	

Bivalve ecosystem services in Europe

Country	Net N removal ($t\ N\ y^{-1}$)	Total PEQ (y^{-1})	Nutrient credits ($k€\ y^{-1}$)
Bulgaria	125	37,929	1356
Denmark	31	9,340	334
Ireland	1179	357,252	12,768
Germany	270	81,805	2924
Greece	1306	395,735	14,143
Spain	11,536	3,495,777	124,936
France	7248	21,96,318	78,494
Croatia	138	41,968	1500
Italy	6227	1,886,994	67,439
Netherlands	2156	653,251	23,347
Portugal	415	125,612	4489
Romania	1	340	12
Slovenia	0	21	1
Sweden	94	28,386	1014
United Kingdom	1464	443,736	15,859
Total ($t\ N\ y^{-1}$)	32,190		
Total PEQ (y^{-1})		9,754,462	
Total nutrient credits ($k€\ y^{-1}$)			348,615

Bivalve aquaculture accounts for about 1.5% of the OSPAR/HELCOM N loading.

Finfish versus Bivalves
The battle of the bands

Nitrogen sources or sinks	Aquaculture (t N y^{-1})	Notes
OSPAR Regions II & III	*260*	Excluded from overall input estimate
Baltic Sea	2500	Included in overall input estimate
Atlantic salmon (Northern Europe)	55906	Production: 1.45 X 10^6 t FW y^{-1} (Eurostat) Emissions: 212.8 g N $fish^{-1}$ y^{-1} (AquaFish model)
Gilthead bream (Southern Europe)	4288	Production: 87463 t FW y^{-1} (Eurostat) Emissions: 17.2 g N $fish^{-1}$ y^{-1} (AquaFish model)
European seabass (Southern Europe)	3137	Production: 63981 t FW y^{-1} (Eurostat) Emissions: 17.2 g N $fish^{-1}$ y^{-1} (AquaFish model)
Total Fed Input	65832	From fed aquaculture
Shellfish	-31190	
Total Extractive Output	-31190	From organically extractive aquaculture
Mass balance	34642	Net nitrogen input to European waters

Bivalve aquaculture removes half the finfish N input, a service of 350 X 10^6 € y^{-1}.


McCORMICK

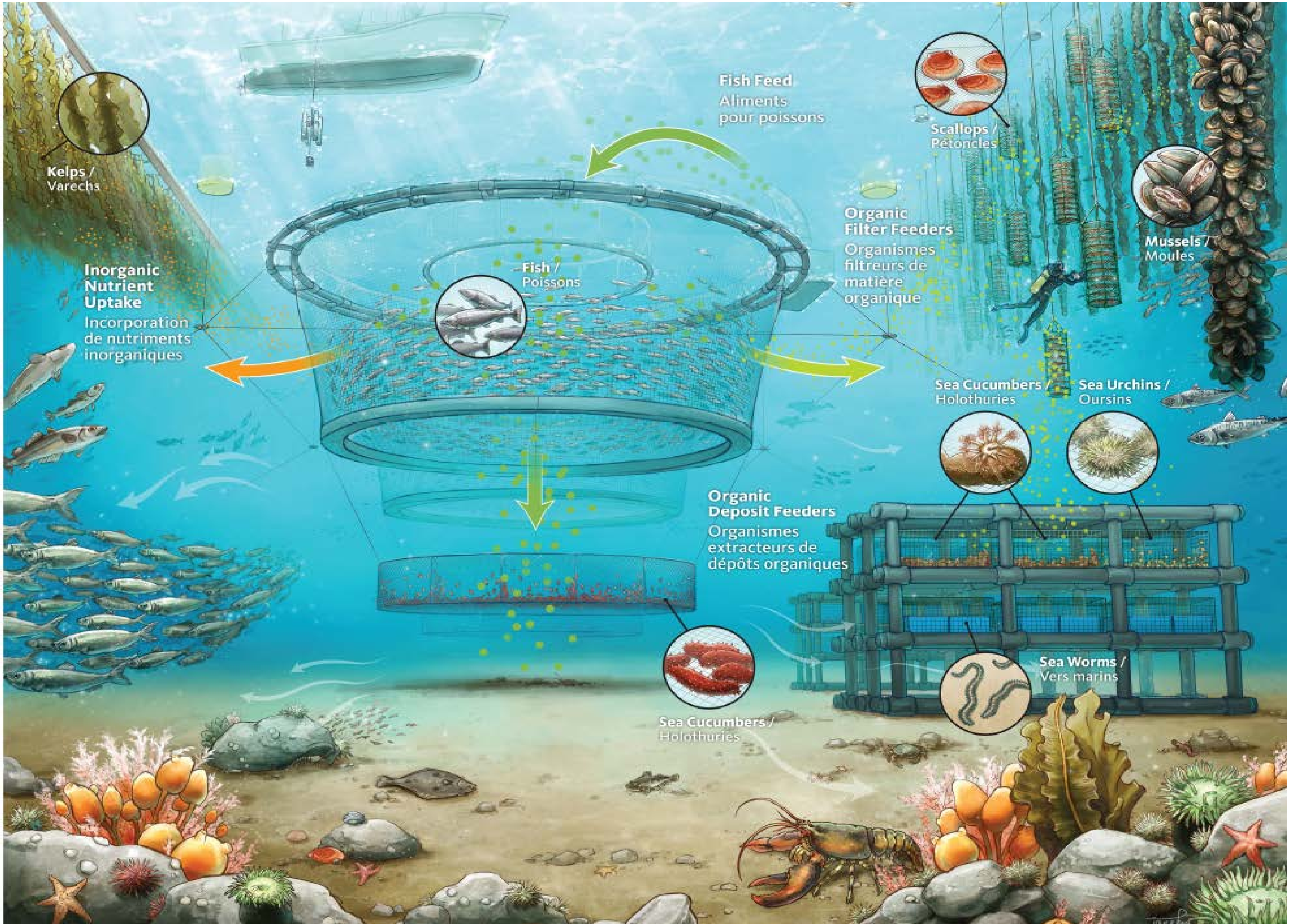
Summary

- Eutrophication of coastal areas is widespread;
- Migration to coastal areas and the requirement for increased food production increase nutrient pressures;
- Screening models such as ASSETS contribute to broad-scale management;
- Research models such as EcoWin provide detailed management tools;
- Models can (and often should) be combined, which often adds huge value to the end product;
- Bottom-up and top-down approaches should be used together, and the benefits of each should be leveraged.

Role of Deposit Feeders in Integrated Multi-Trophic Aquaculture

- Integrated Multi-Trophic Aquaculture in the West
- Supply of organic matter to the benthos
- Individual model for deposit feeders
- FARM model for population in monoculture and IMTA

Conceptual diagram for IMTA



The I in IMTA

How can INTEGRATION work in the west?

<u>IMTA can mean different things…</u>

- Indiana Monster Truck Agency
- Irish Massage Therapists Association
- Integrated Multi-Trophic Aquaculture

• Does integrated explicitly mean direct recycling, or can it be a system-scale (water body scale) budget?
• Interactions among fish cages and extractive culture in open water at densities acceptable in the West are difficult to quantify
• For shellfish and seaweeds, if your layout has a budget role, do we need structures close together?
• Perhaps the only direct coupling is with the benthos, after all that's where the impact concerns are greater.

Different layout models and stocking densities constrain the word *Integrated*.

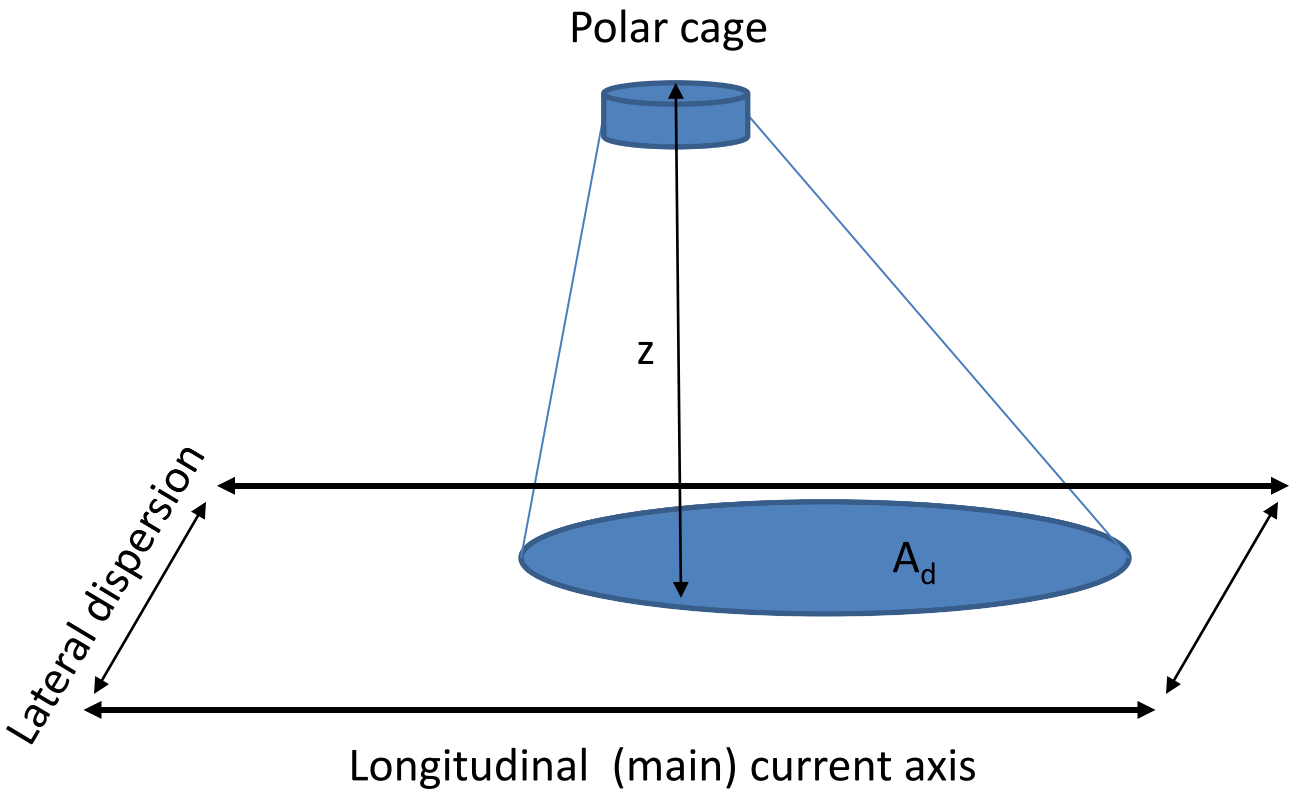
Integration

Southeast Asia and China

- In onshore ponds (70% of world production): effective internal re-use of materials – IMTA is almost a necessity, and was essential before electricity and diesel-driven aerators;
- In lakes and bays: whole water body re-use of materials can be seen due to scale and stocking density (e.g. 140 km^2 Sanggou Bay, NE China, produces 150,000 tons of shellfish, finfish, and seaweed per year (~ 1 kg m^{-2}).

The social license does not exist in the West to replicate this approach.

Allochtonous supply of organic material to deposit-feeders under a fish cage

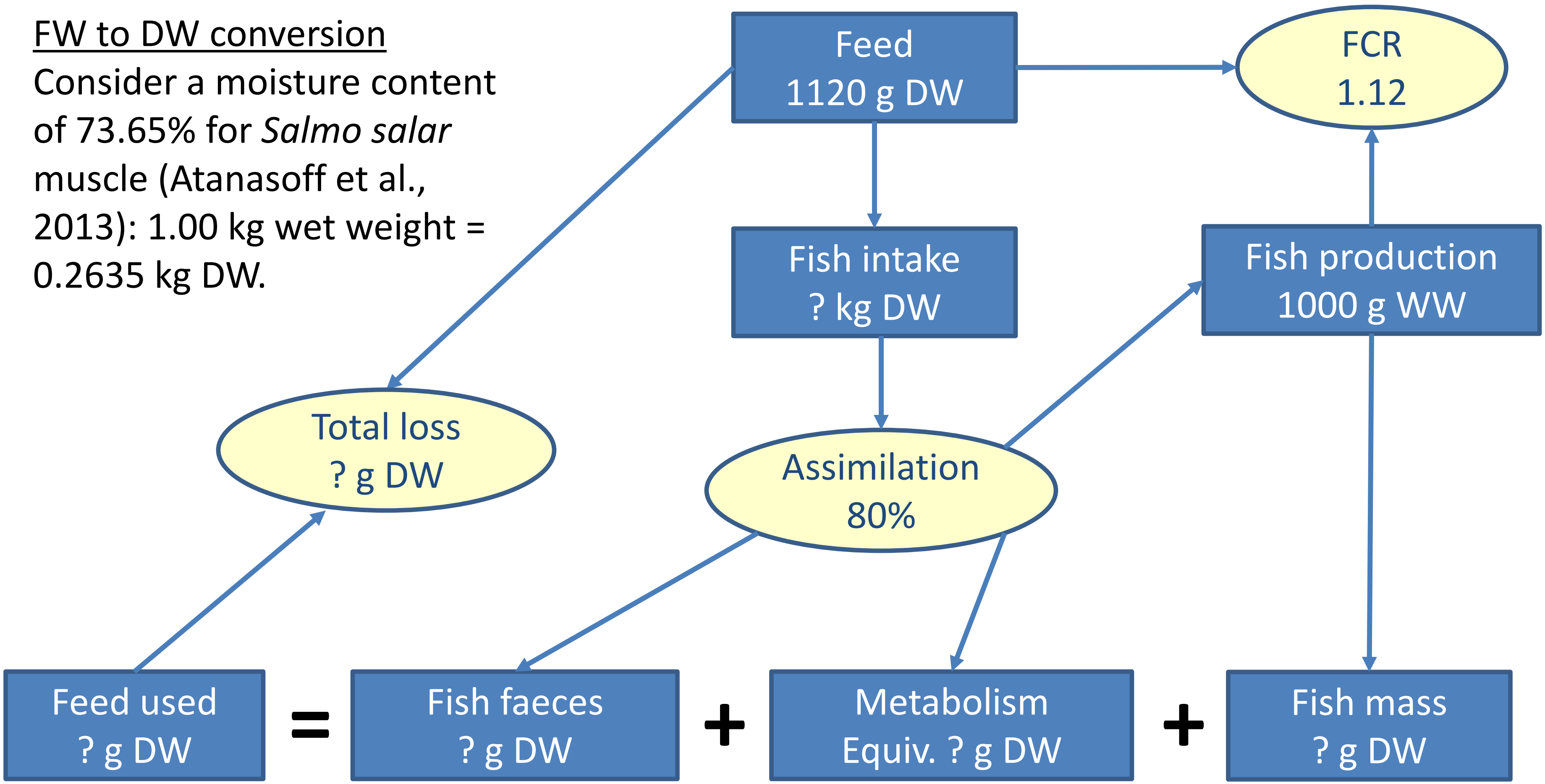


Advection shifts the dispersion footprint as a function of the residual current.

Feed Conversion Ratio (FCR) and mass apportionment
Example for 1kg of fish, FCR = 1.12

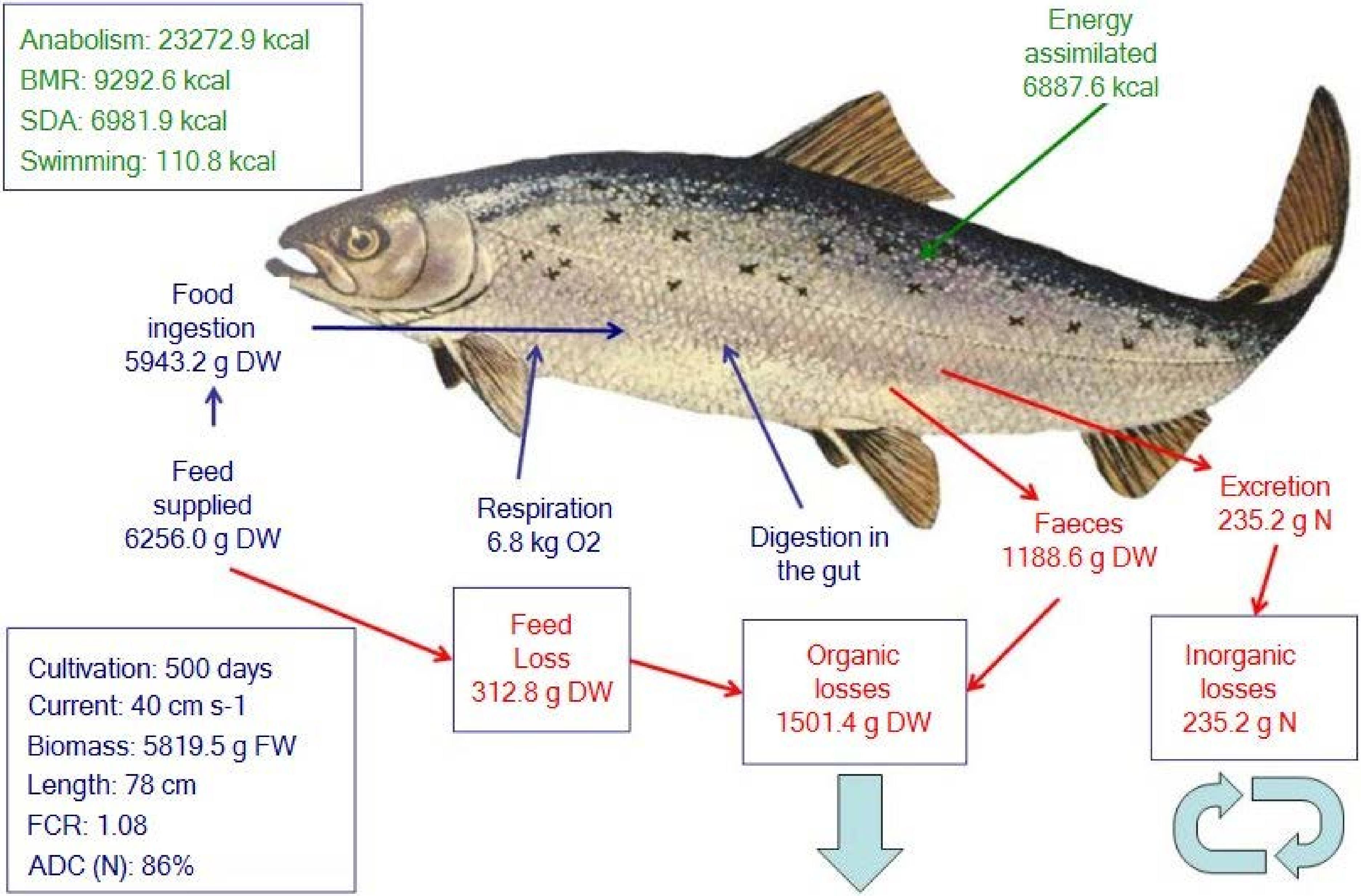
<u>FW to DW conversion</u>

Consider a moisture content of 73.65% for *Salmo salar* muscle (Atanasoff et al., 2013): 1.00 kg wet weight = 0.2635 kg DW.



FCR is the result of Input/Output. Input-Output = Total loss

Mass balance for an Atlantic salmon growth cycle

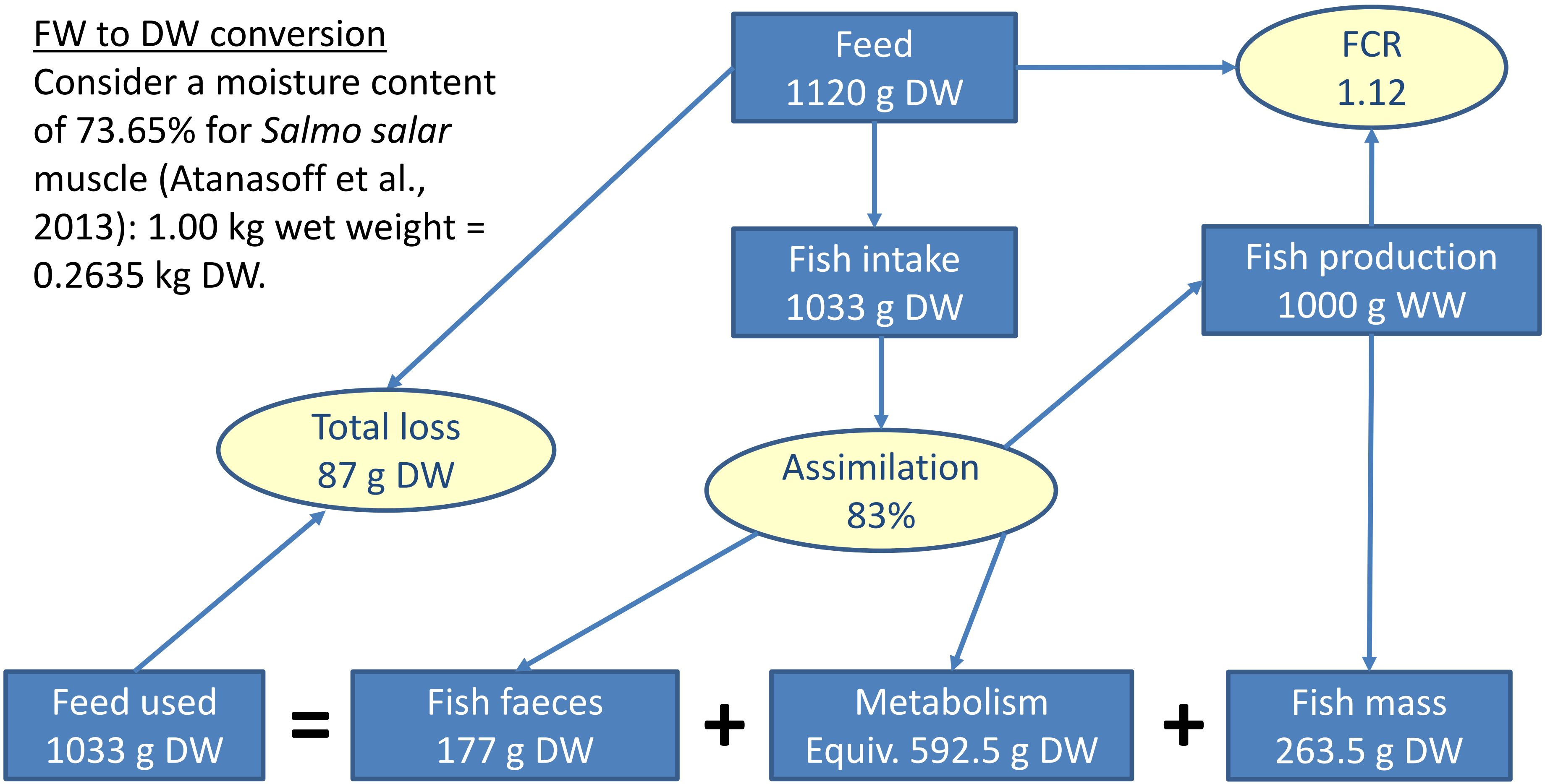


Matched FCR and end-point weight.

Feed Conversion Ratio (FCR) and mass apportionment
Example for 1kg of fish, FCR = 1.12

<u>FW to DW conversion</u>

Consider a moisture content of 73.65% for *Salmo salar* muscle (Atanasoff et al., 2013): 1.00 kg wet weight = 0.2635 kg DW.



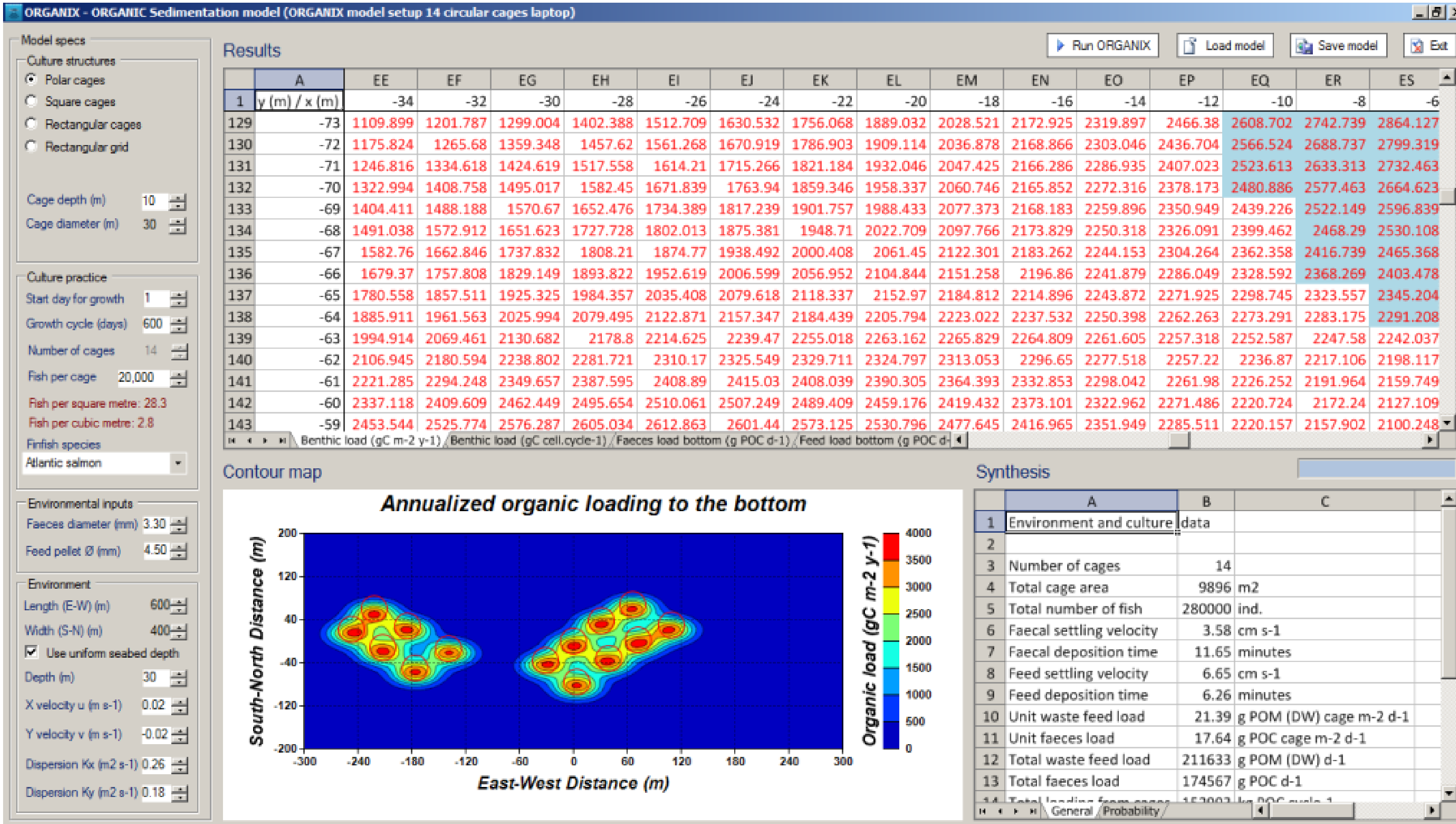
FCR is the result of input/output. Input-Output = Total Loss

Organic Sedimentation Model - ORGANIX

- ORGANIX predicts the benthic loading footprint. Many other models (Gowen, Silvert, Cromey, Corner, and respective co-workers) do this;
- Dispersion in 2 dimensions is based on Gaussian distribution functions;
- Advection is based on residual circulation;
- Model algorithm determines time to settle based on fall velocity. Probability distribution (dispersion) and advective shift is determined at each timestep until the plume reaches the bottom;
- Loading from culture structures is distributed over the modelled surface;
- Calibration for Atlantic Salmon, experimental data from DFO and literature. feed pellets fall faster than faeces;
- ORGANIX does not account for physiological variation.

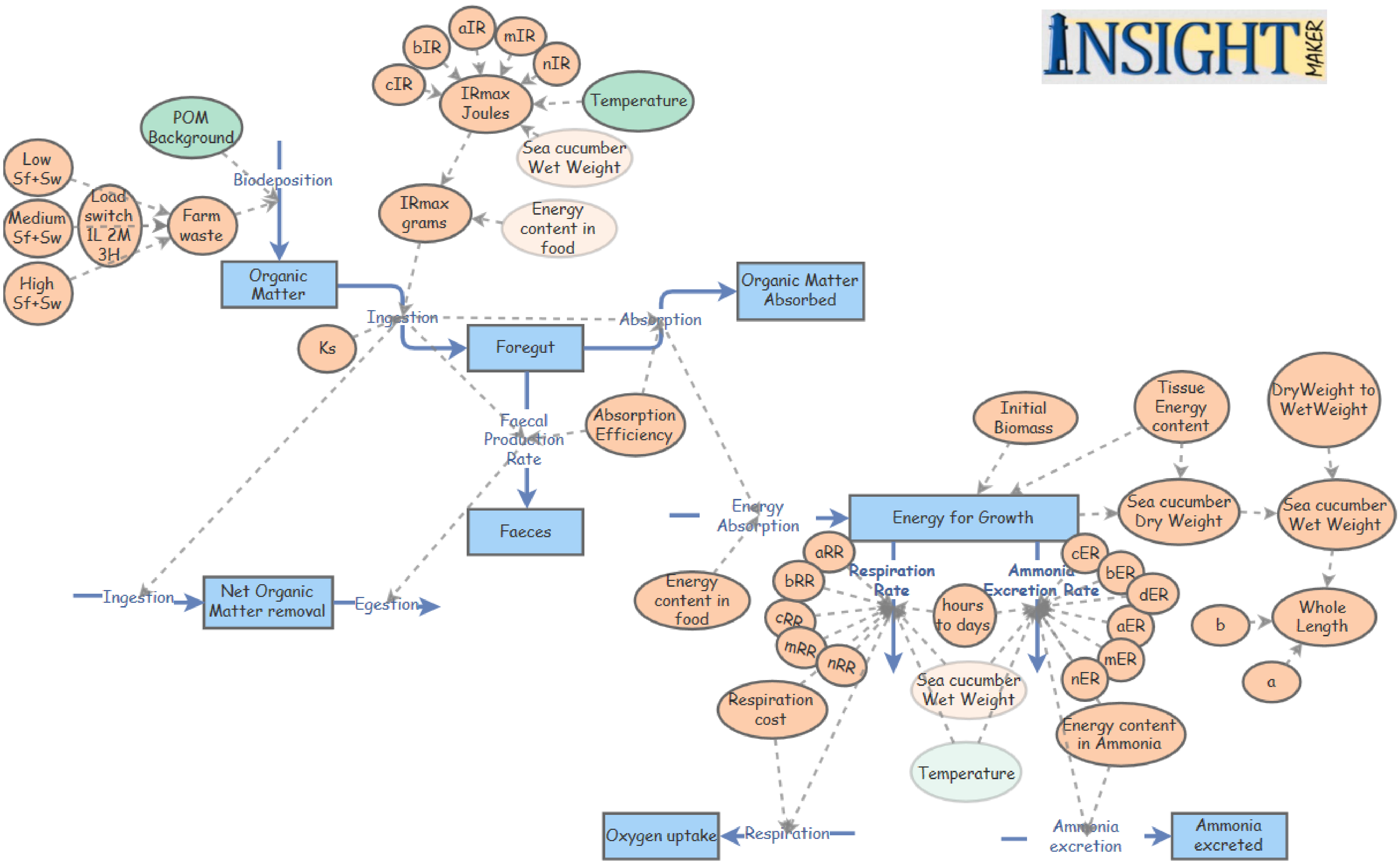
Calculation of bottom loading and spatial distribution under different culture and environmental conditions is essential for deposit feeder model.

ORGANIX – ORGANIC Sedimentation model

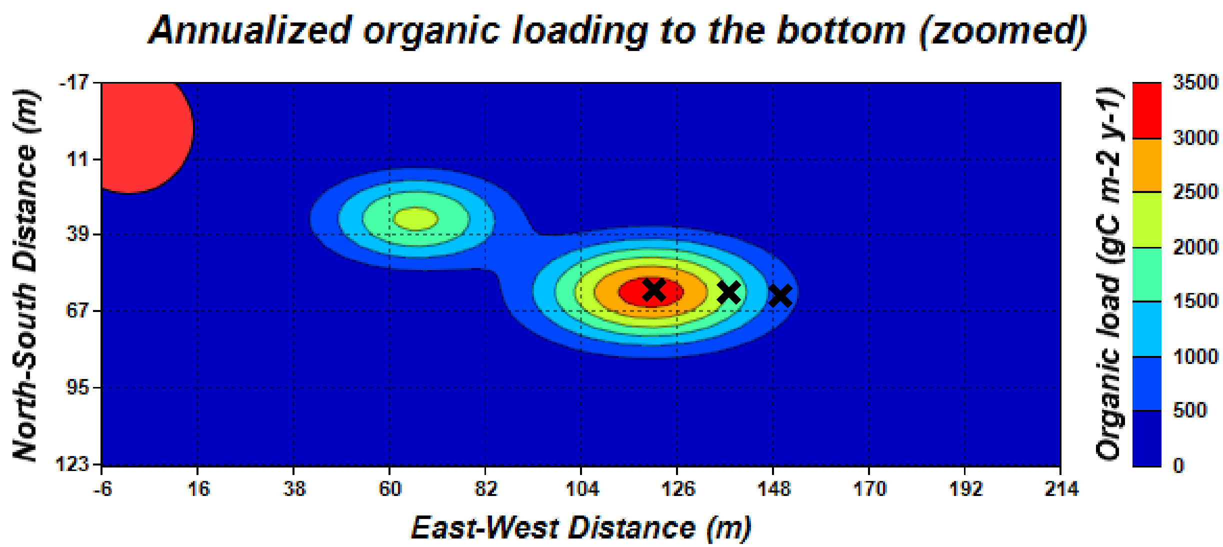


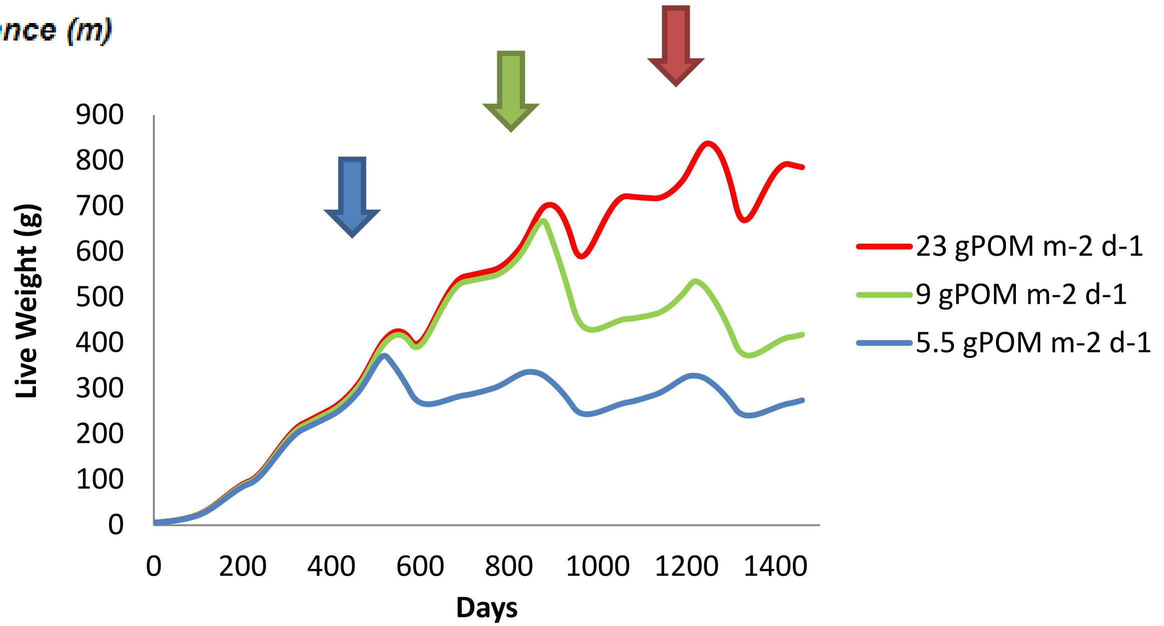
Composite benthic footprint (loading) from a farm with 14 salmon cages.

Parastichopus californicus individual growth model

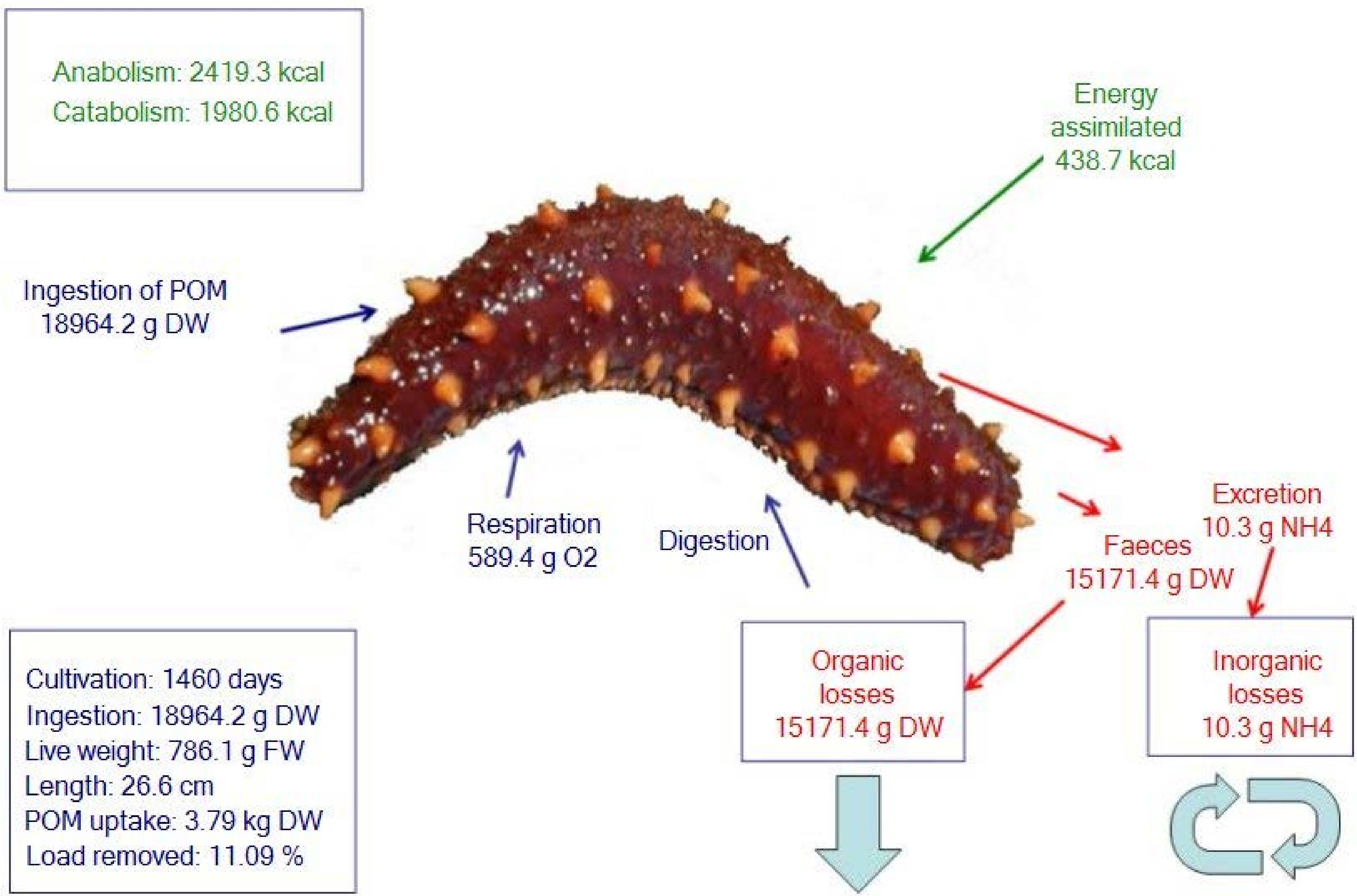


Simulation of sea cucumber growth in integrated culture under salmon farms





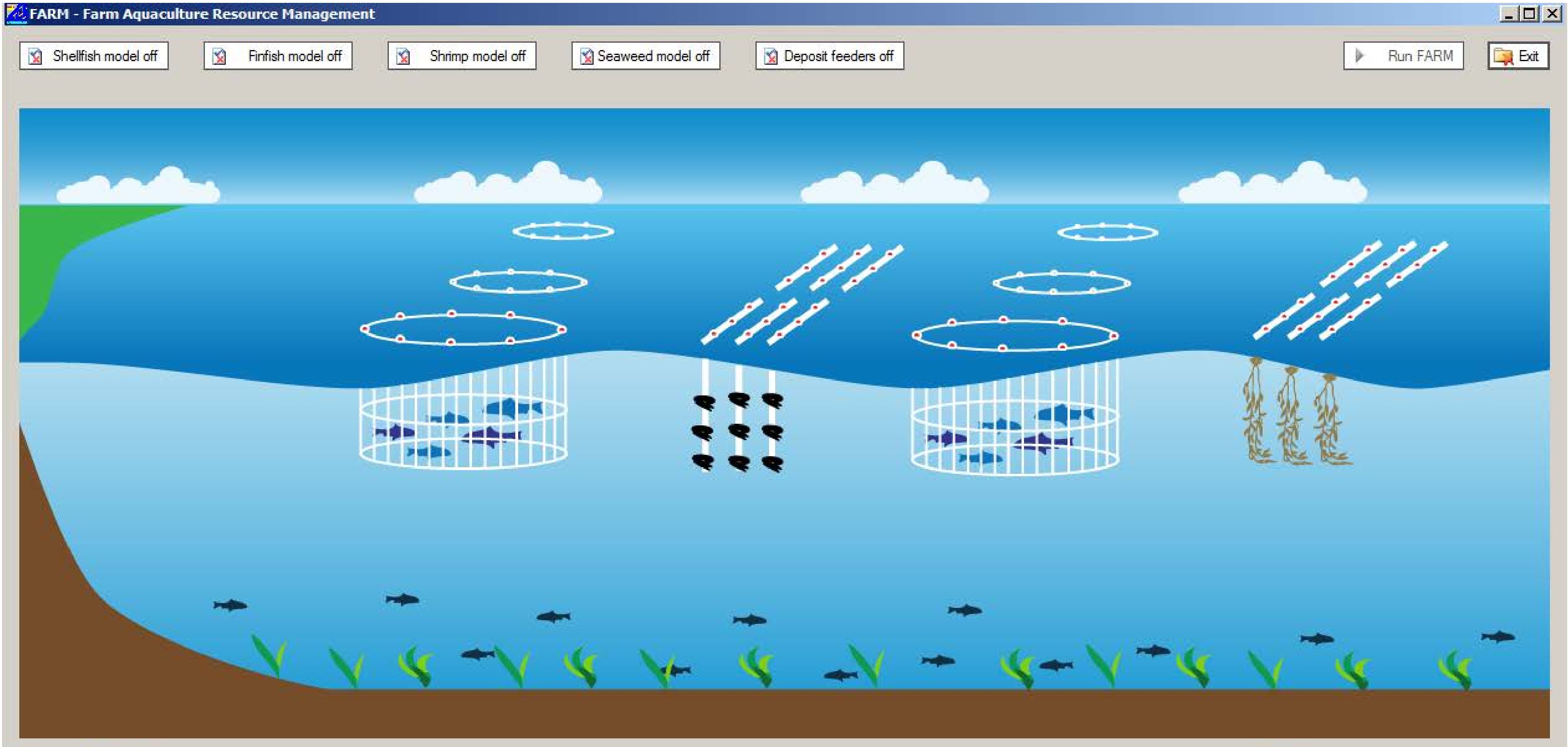
Mass balance for a four year sea cucumber growth cycle



***Parastichopus californicus* weight data - large animals:100-565 g WW (Hannah et al, 2013), 793-1483 g WW (Hannah et al., 2012).**

FARM model

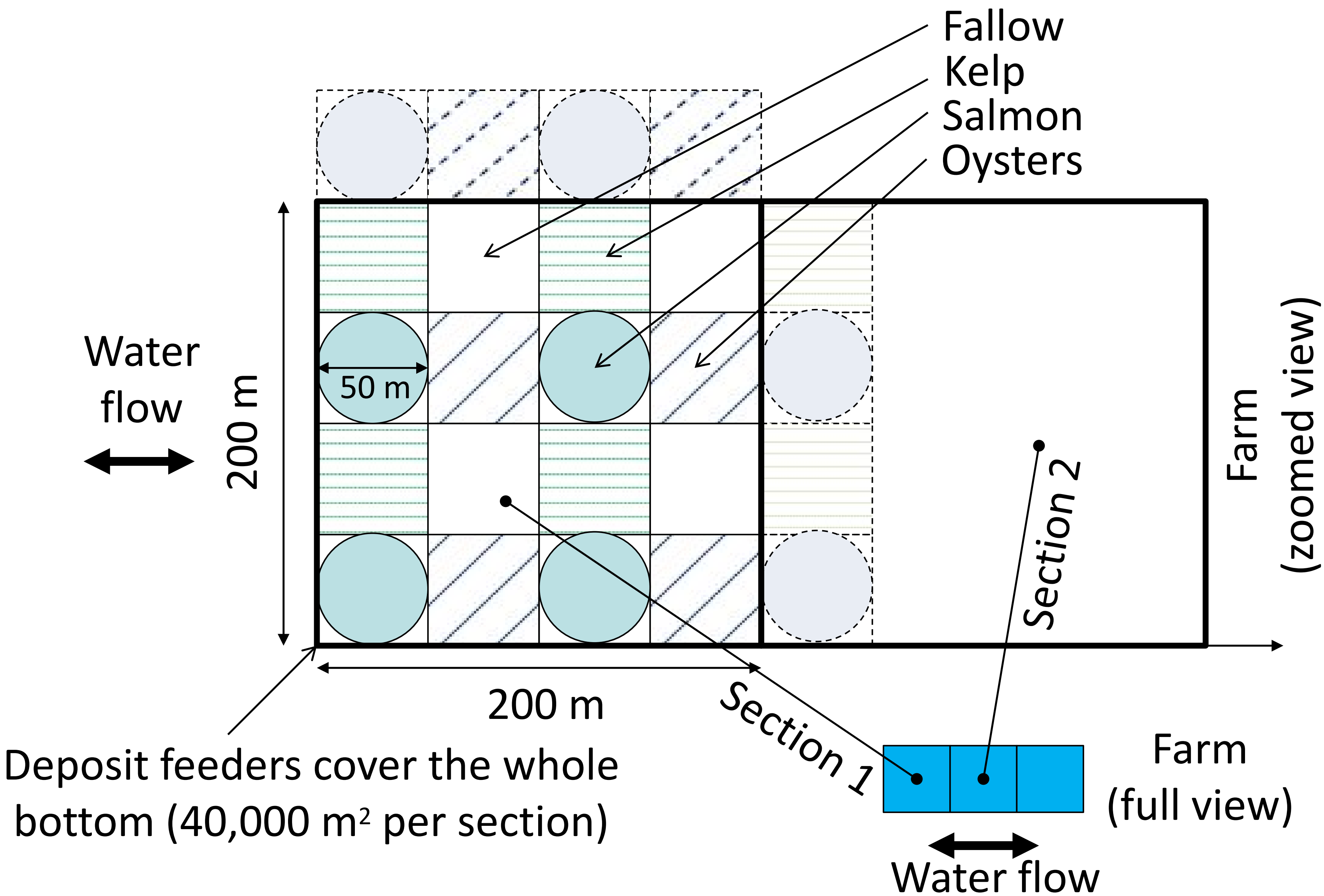
Application to Integrated Multi-Trophic Aquaculture (IMTA)



FARM model for finfish, shellfish, seaweed, and deposit feeders.

Ferreira et al., 2012. Cultivation of gilthead bream in monoculture and integrated multi-trophic aquaculture. Analysis of production and environmental effects by means of the FARM model. Aquaculture 358-359, p. 23-34.

FARM model – IMTA layout



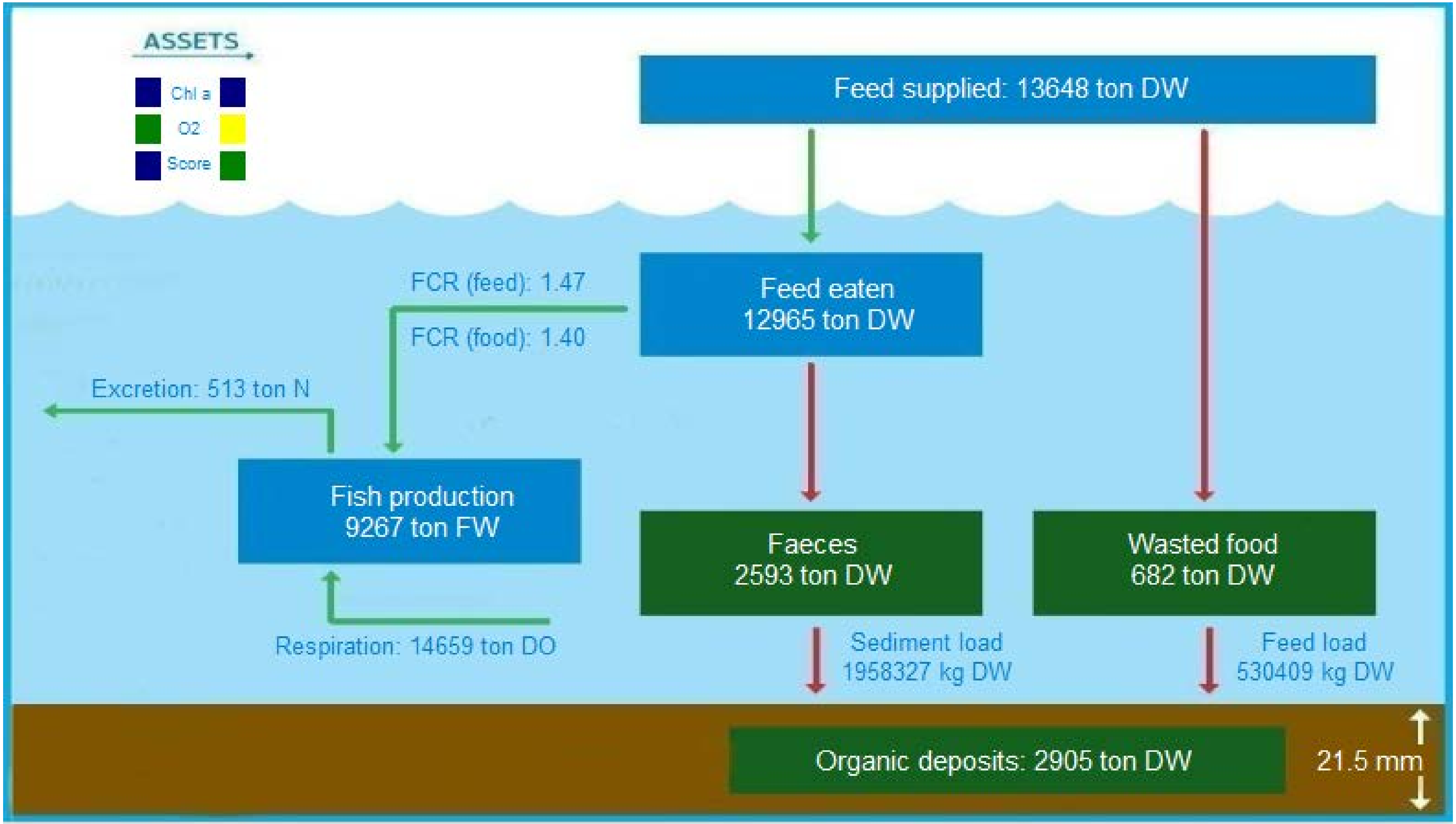
FARM simulates changes to individual weight, harvest, environment, and income.

Synthesis of FARM outputs for deposit feeders

Scenario	Mono	IMTA 1 5 fish m^{-2}	IMTA 2 20 fish m^{-2}	IMTA 3 Oysters	IMTA 4 IMTA 2 + IMTA 3	IMTA 5 IMTA4 + seaweeds
Individual weight (g)	112.2	299.8	308.9	128.7	309.1	309.1
Length (cm)	13.5	19.0	19.2	14.2	19.2	19.2
Harvest (t $cycle^{-1}$)	101.9	581.7	602.6	143.6	603.0	603.0
APP	8.5	48.5	50.2	12.0	50.3	50.3
Profit (k€) as EBITDA	2182	13179	13658	3139	13669	13669
POM removal (gC m^{-2} y^{-1})	1043	2437	2518	1191	2520	2520
Net POM loading (g C m^{-2} y^{-1})	4	409	5724	5	5874	5874
Population-equivalents (y^{-1})	5737	13484	13930	7243	14658	18500

Scenarios for monoculture (20 ind. m^{-2}), different finfish densities in IMTA, shellfish longline culture (100 ind. m^{-2}), shellfish + finfish, and seaweeds (50 ind. m^{-2}). IMTA6 (not shown) increases deposit feeders to 80 ind. m^{-2}.

FARM model – IMTA5 finfish



Mass balance for finfish culture shows POM load for feed and faeces.

Two key questions

Role of seaweed (winged kelp *Alaria esculenta*) culture

- Kelp monoculture: final individual weight of 134 g
- Increases to 175 g in IMTA5
- 22% increase in total physical product (TPP) for plants of harvestable size from 153 to 214 t cycle^{-1}
- No significant effect on DIN concentration (P_{90} decreases by 0.4 μM)

Role of suspended shellfish (Pacific oyster *C. gigas*) culture

- Oyster individual weight increases from 60.02 g to 61.65 g
- TPP from 241.9 to 243.9 t cycle^{-1}
- Increase of ratio of suspended particles to 80% makes little difference (end points are 65.7 g and 246.9 t)

Shellfish suspended culture is not enhanced by salmon culture; seaweeds do not reduce DIN significantly. This is basin-scale IMTA.

Summary

- No question, no model. What is your question?
- No model can predict the weather. The weather affects circulation (wind, freshwater flow), salinity (rainfall), food (chlorophyll depends on e.g. clouds, temperature). Ecosystem models show general patterns;
- Many different models exist. Models are simplifications of reality, but can be very useful. <u>No model does everything</u>;
- Models can (and often should) be combined, which often adds huge value to the end product.

All slides

http://ecowin.org/aulas/mega/pce/