Sistemas de Informação e Modelação em Ambiente

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Models for aquaculture production
and environmental effects

J. Gomes Ferreira

http://ecowin.org/

Universidade Nova de Lisboa

24 de Maio, 2019

Case studies

Using ecological models to inform management

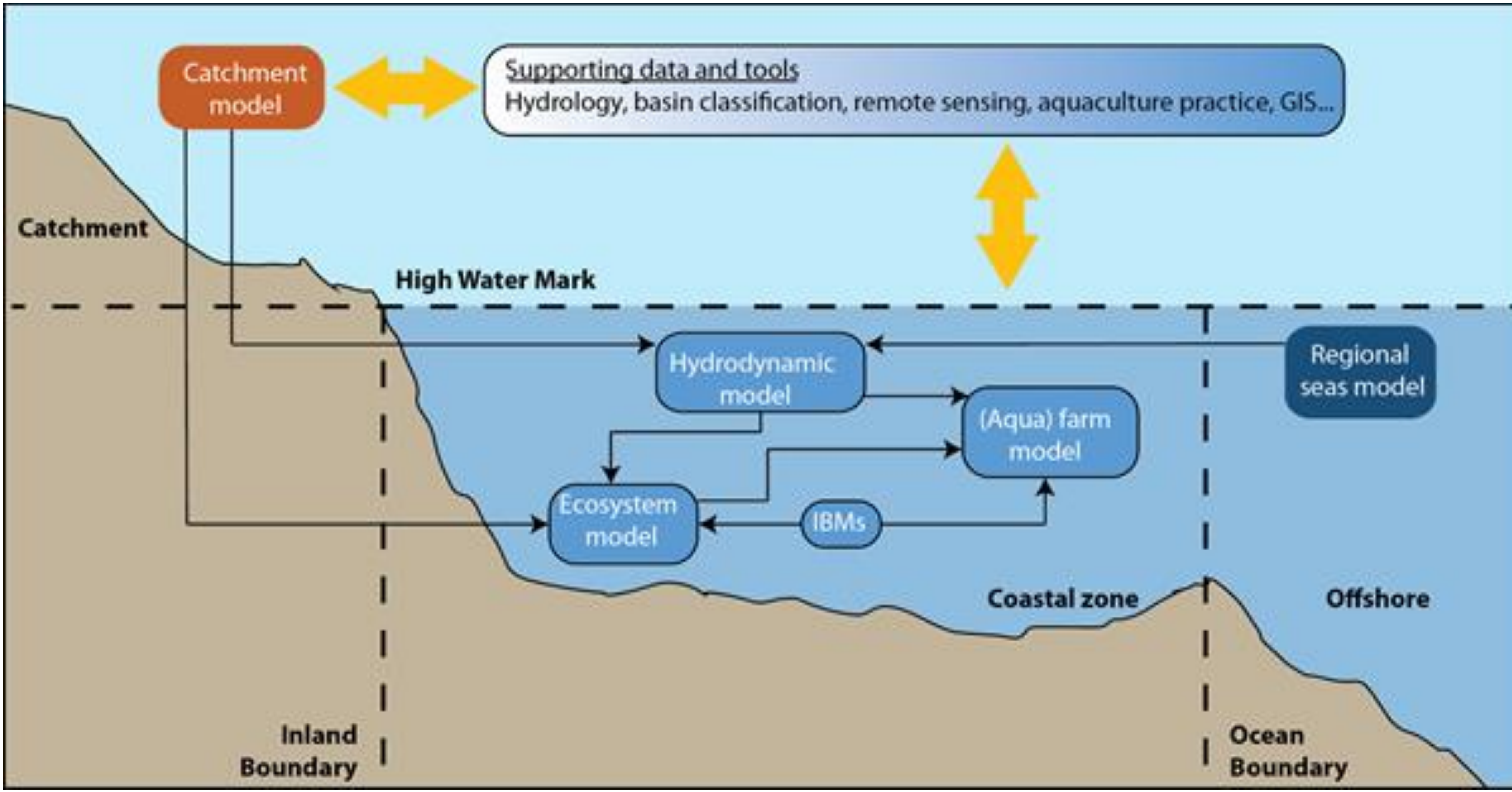
Models are developed to address questions

- Case study 1: Top-down control of nutrient loading in the West (Ireland)
- Case study 2: Future of onshore tilapia culture in the East (Thailand)

EASE - Enhanced SMILE for Lough Foyle

- The EASE project
- Hydrodynamic modelling of Lough Foyle
- Terrestrial loading and modelling
- Individual modelling of shellfish
- Ecosystem modelling for carrying capacity
- Synthesis

EcoWin.NET Lough Foyle Model
General framework for ecosystem modelling



Multi-model frameworks are complex to develop, but they make the link between catchment and coast, and have great potential for management support.

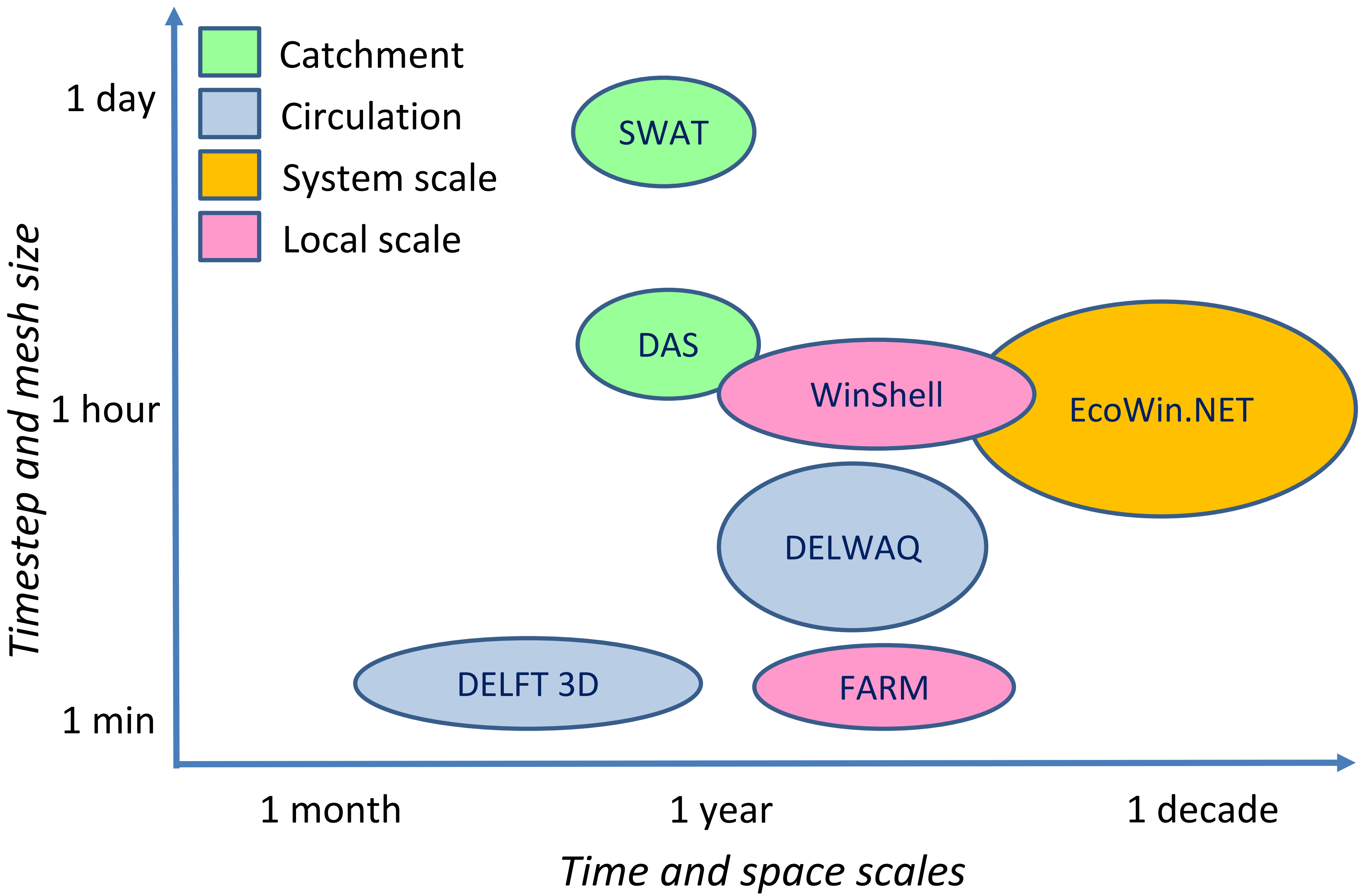
Why do we need multi-model frameworks?

Integrated catchment management needs a transdisciplinary approach

Different models address different problems, using distinct time and space scales.

The trick is to get models (cars, planes, and trains) to work together, not build Godzilla.

Models, timescales, timesteps

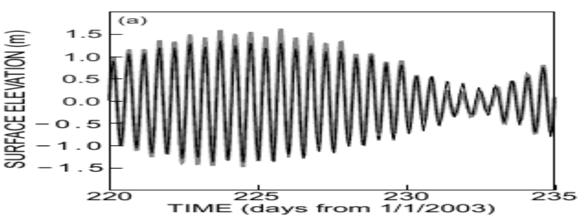


Like any endeavour, ninety percent perspiration, ten percent inspiration.

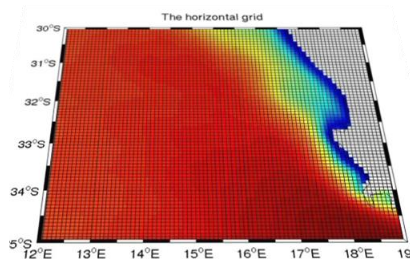
Hydrodynamic modelling for detailed circulation patterns

Delft3D - Flow

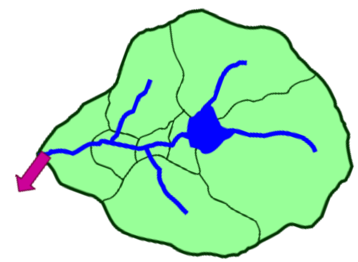
Atmospheric forcing



Tide



Flow

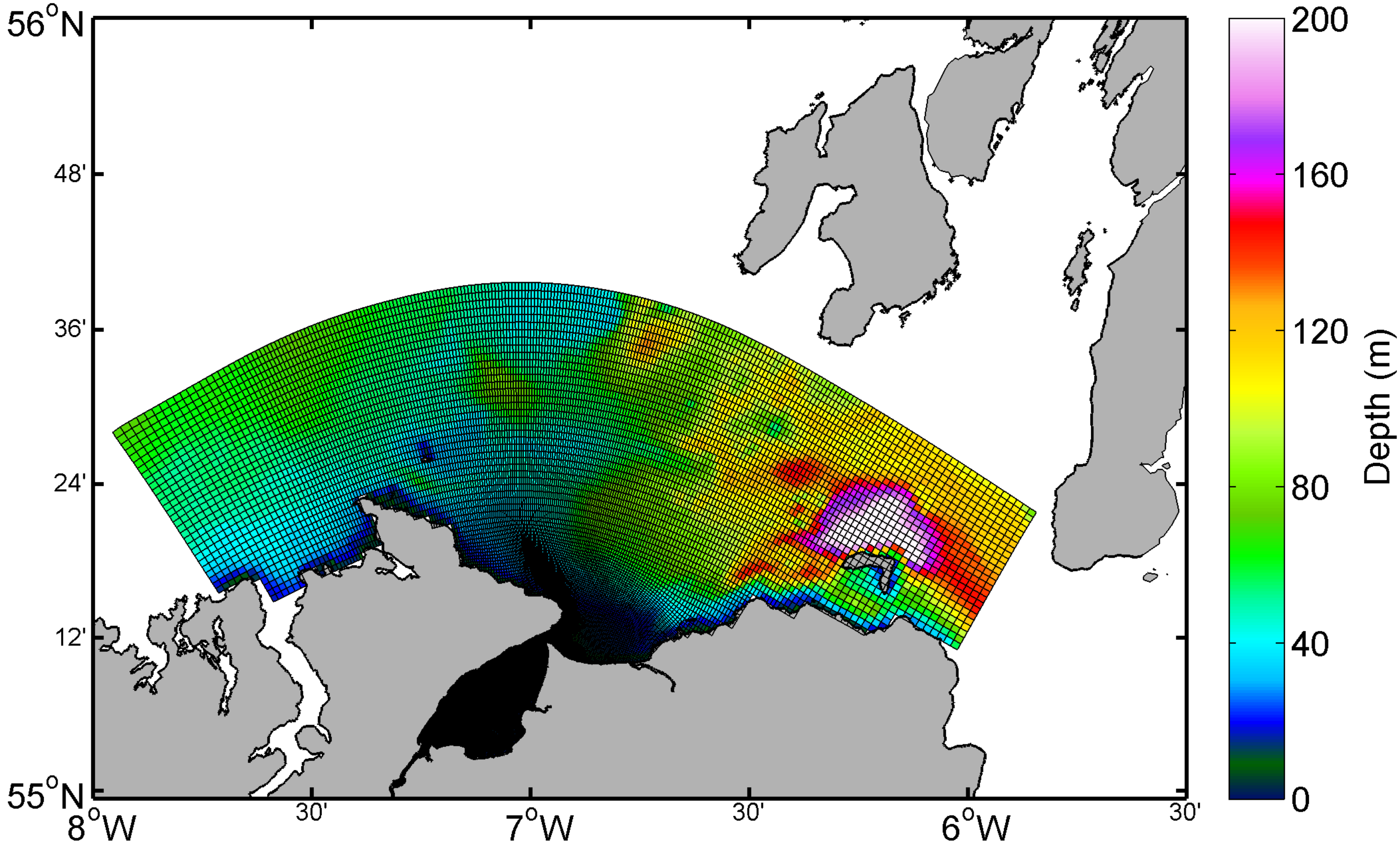


River flow

Water Quality / Ecological Modelling

Free and open source, tidal response, drying and flooding, evaporative processes, inner shelf circulation, shelf stratification.

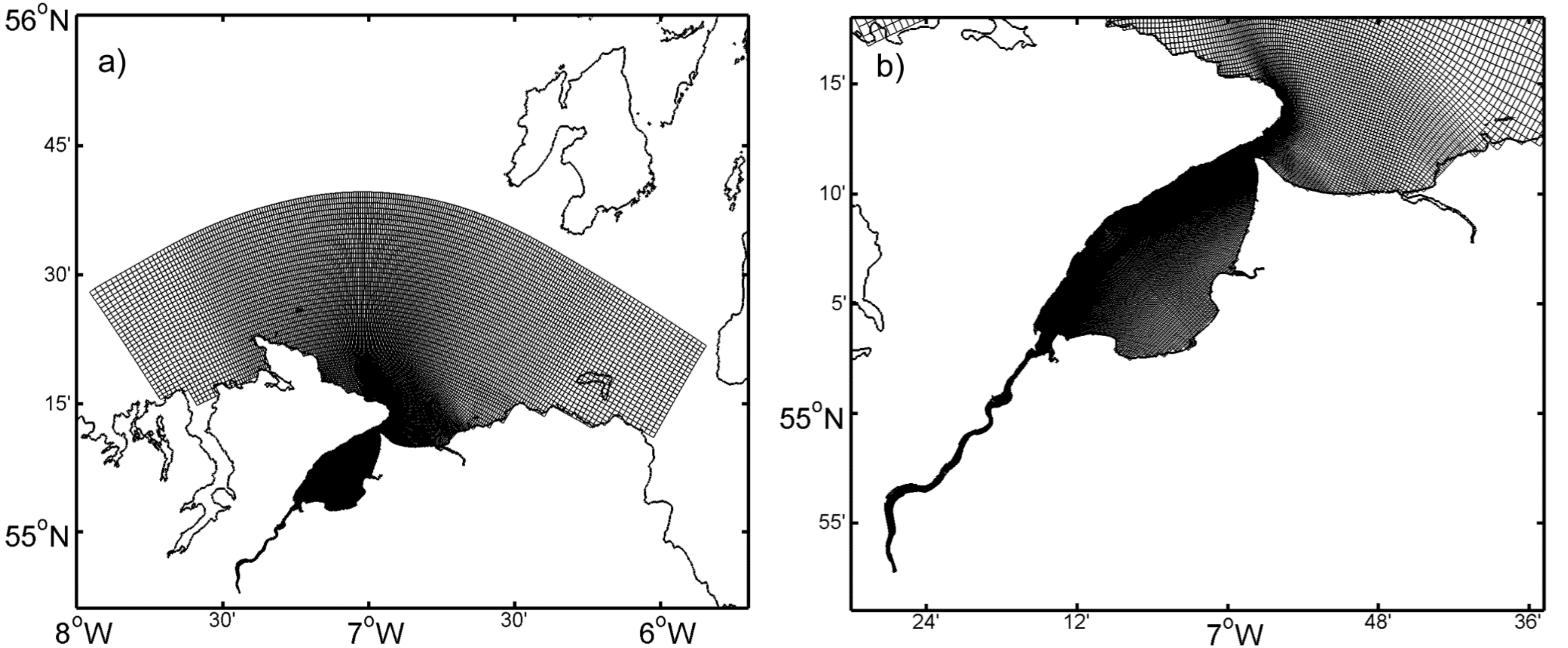
Bathymetry of the shelf



Bathymetry data supplied by the UK Hydrographic Office.

The grid design usually includes not only the domain of interest but also a wider area, because what happens *outside* a system (mesoscale) is generally important.

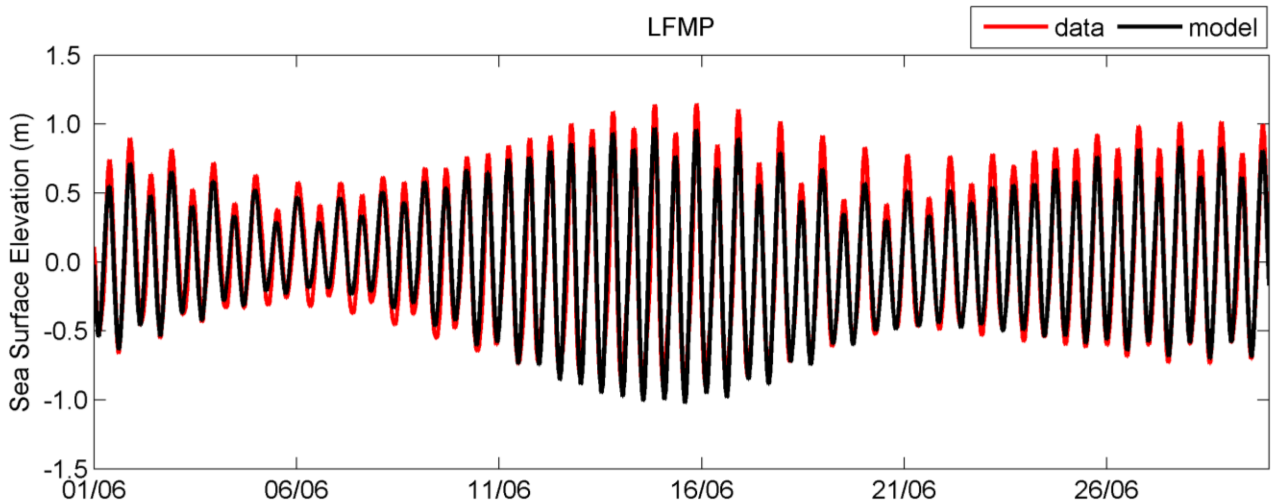
Model components - Grid

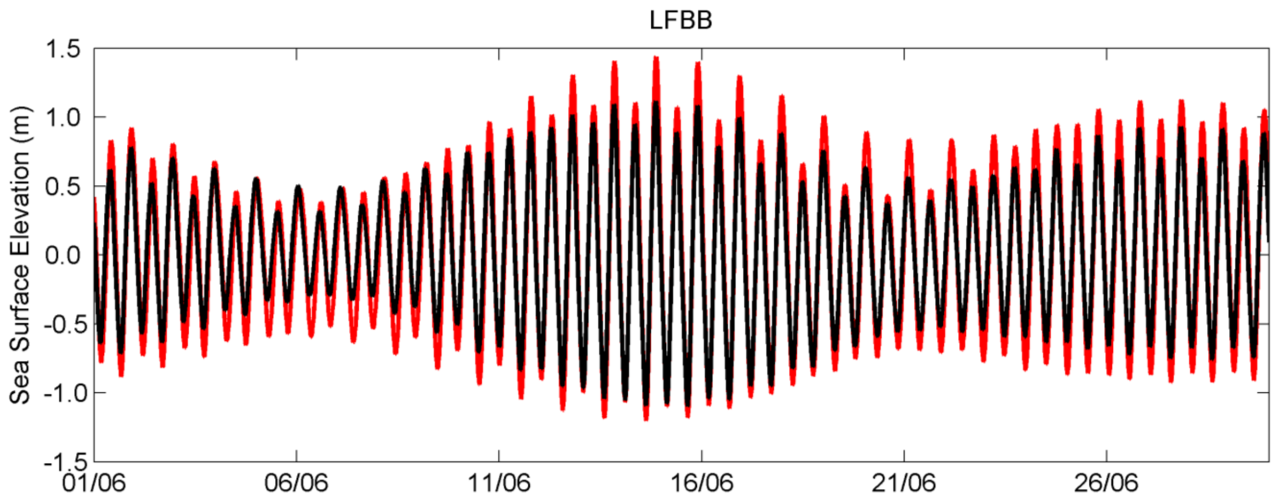


Layer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
% Depth	2	3	4	5	6	8	8	8	8	8	8	8	8	8	8

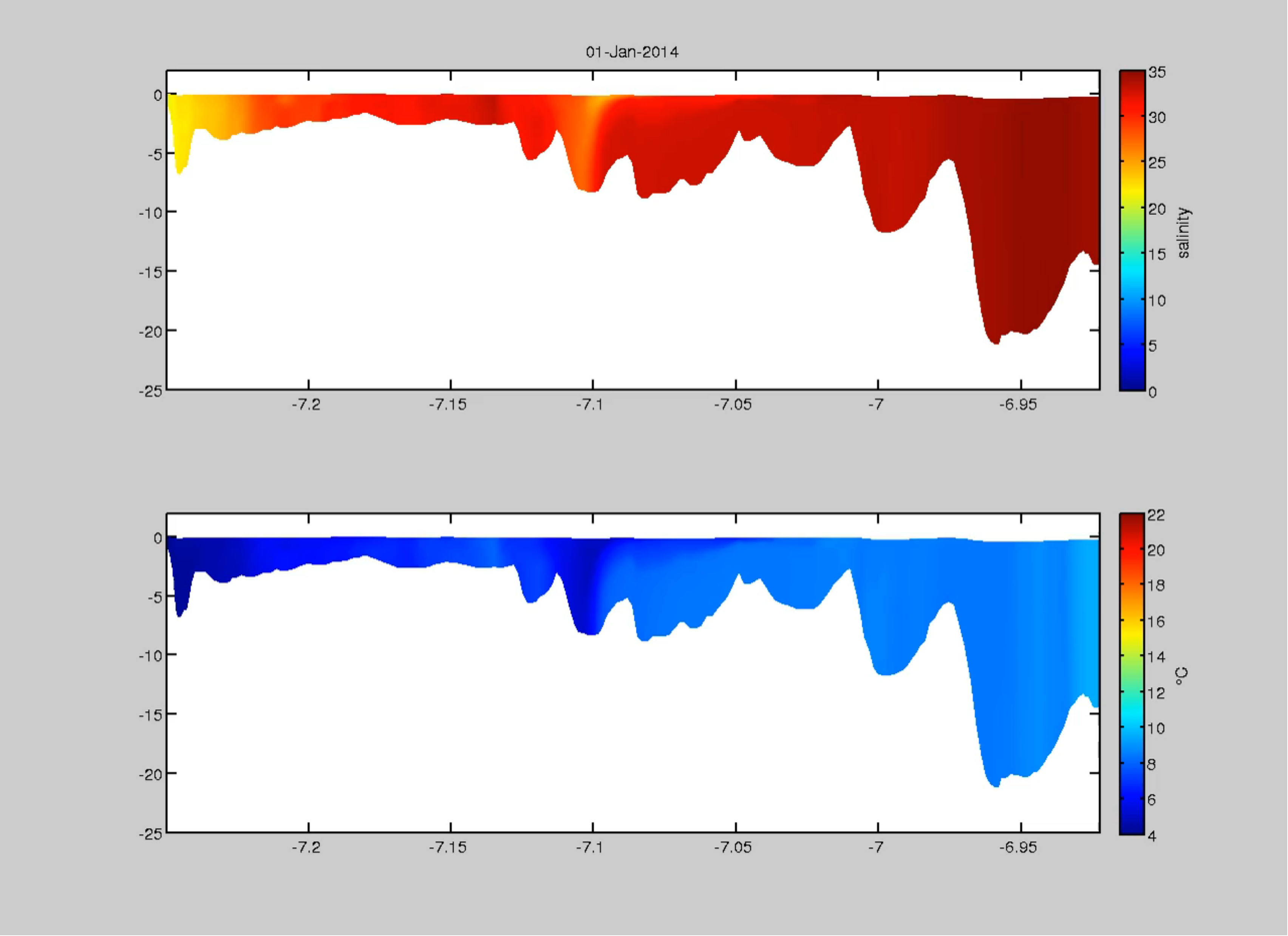
Ocean boundary conditions extracted from the FOAM model.

Model Fitness

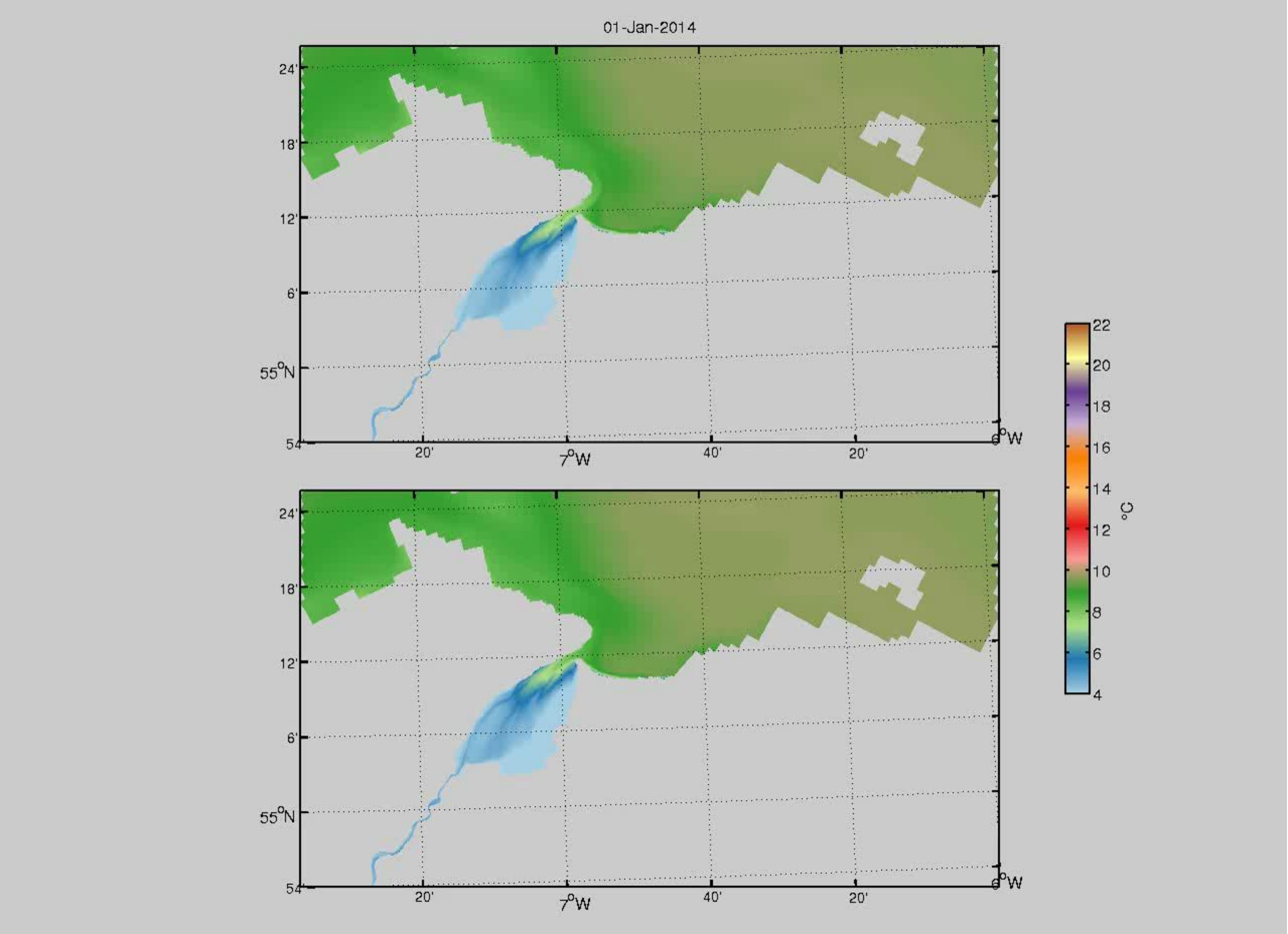




Lough Foyle – Vertical temperature profiles Delft 3D



Some Like It Hot!

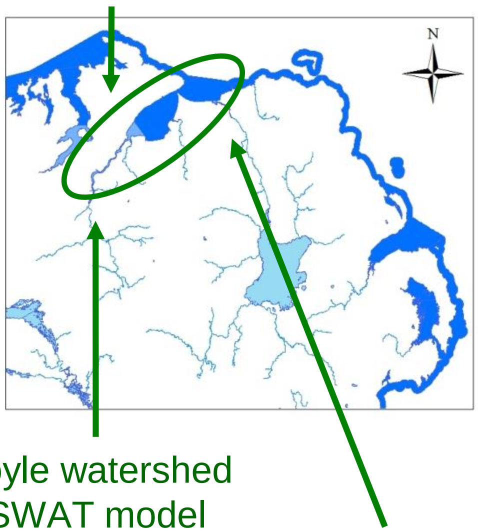


SWAT application for the Foyle catchment
General objectives

1. Estimate the terrestrial loads to Lough Foyle
   - Update the SMILE estimate for 1995
   - Loads: water, sediment, dissolved N and P, particulate organic matter (POM)
   - Sources: WWtWs, agriculture
   - Reference year: 2014
   - Time-step: daily

2. Build a modelling tool capable of apportioning sources and assessing scenarios
   - The SWAT eco-hydrological model was applied and calibrated for the Foyle watershed

Methodology



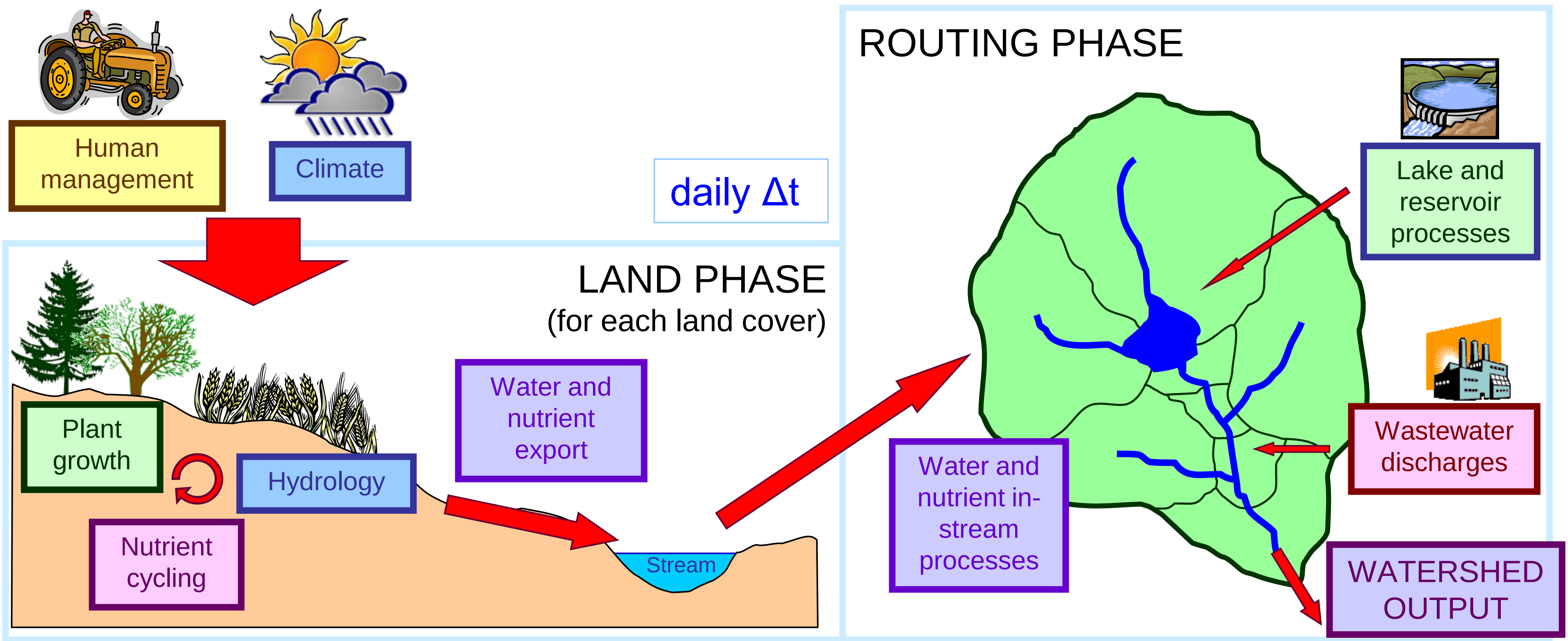
Integration of catchment modelling is critical to deal with European directives such as the Water Framework Directive.

SWAT Soil & Water Assessment Tool

What is SWAT?

- SWAT – Soil and Water Assessment Tool
  - **Management tool**: assesses the impact of land management on water, sediment and agricultural pollution

1. provides information difficult to obtain from regular water quality measurements
2. helps assign loads to sources: wastewater, land use, land management...
3. allows for scenario testing by modifying climate, population, land use...



Direct input points (WWtW, Bann) and SWAT simulation area

29 watersheds

330 HRUs

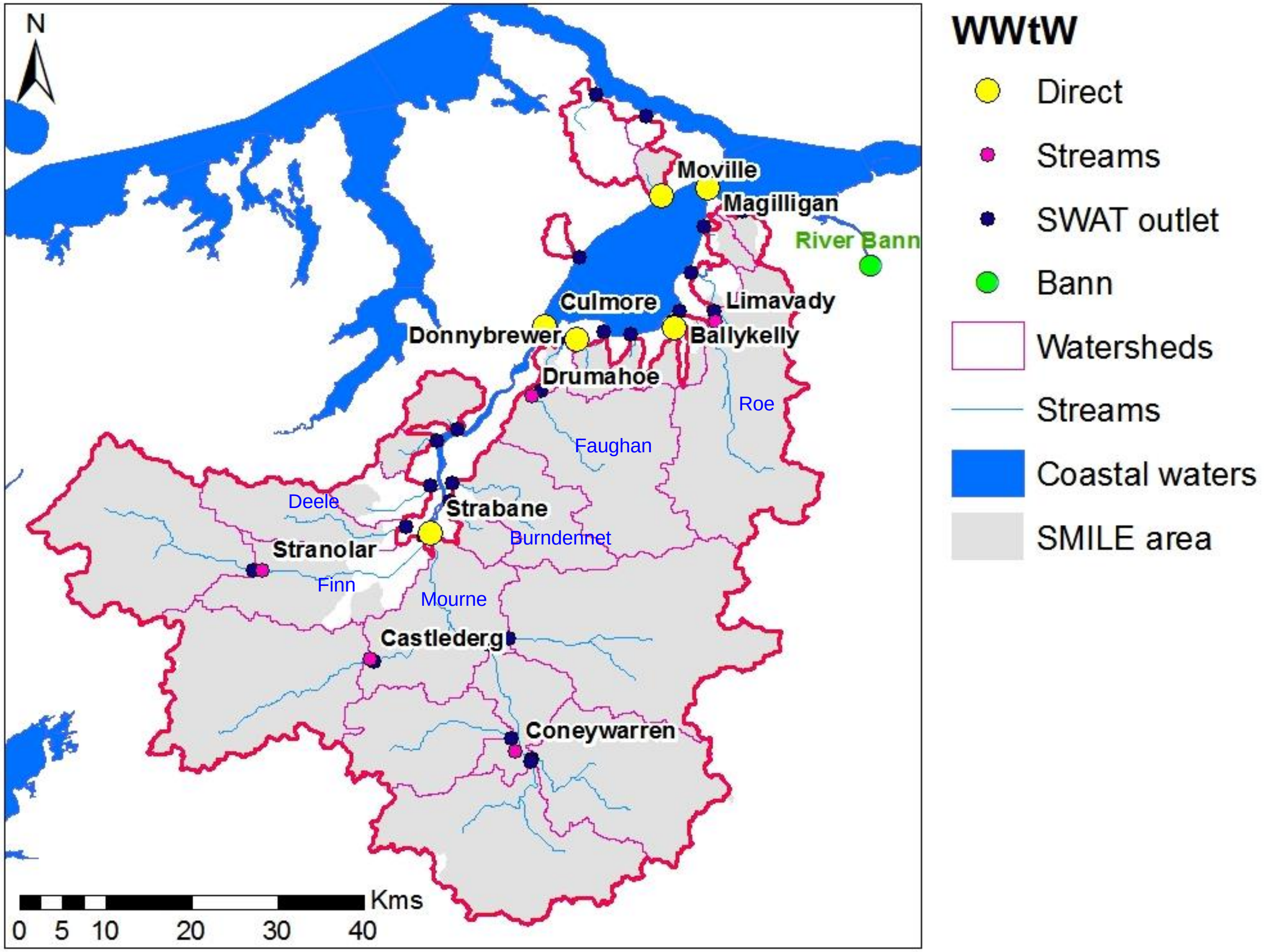
Hydrological Response Units

11 WWtW

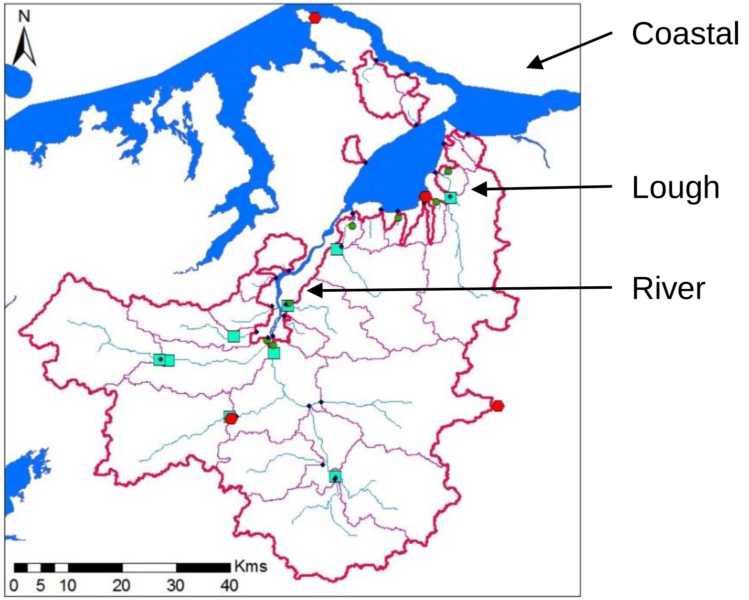
Waste Water treatment Works

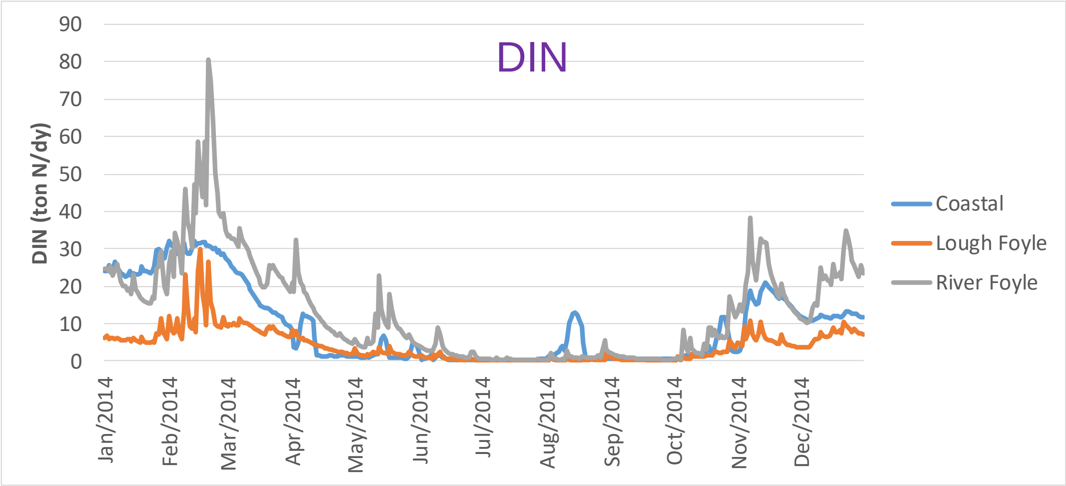
Measured loads

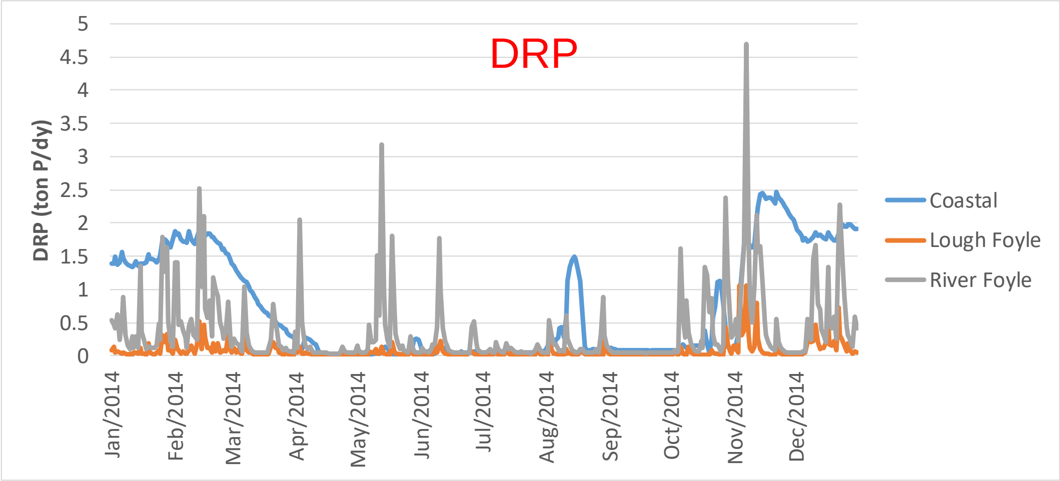
Moville: untreated



SWAT outputs
Nutrient loads in time: 2014



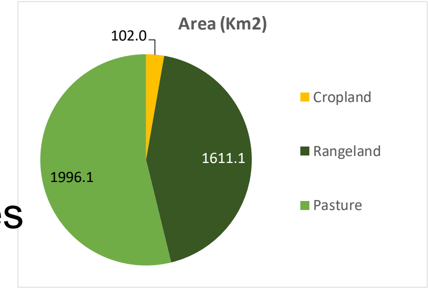


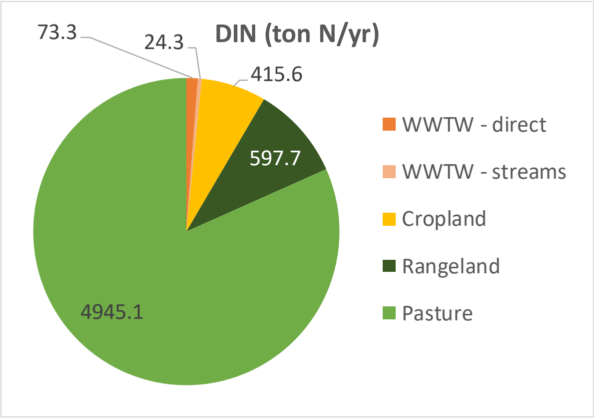


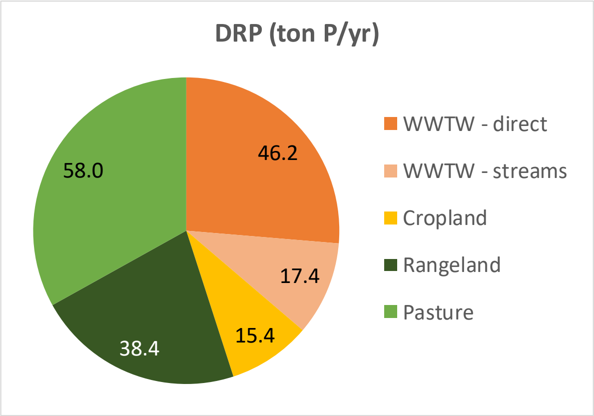
Daily loads are used to drive the nutrient input for the carrying capacity model, with simulated inputs to appropriate model boxes.

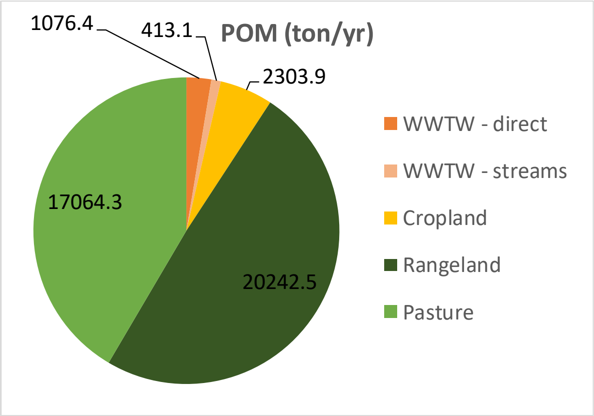
SWAT - source apportionment (Foyle only)

- Main DIN source: diffuse pasture – follows fertilizer application
- DRP sources: point-source & diffuse
  - Diffuse: low erosion rates leads to exports at “background” values
- DIN & DRP results broadly agree with Foy and Girvan, 2004
- POM sources: diffuse – follows landuse
  - Diffuse: low erosion rates leads to exports at “background” values
  - Point source: negligible exports due to WW treatment



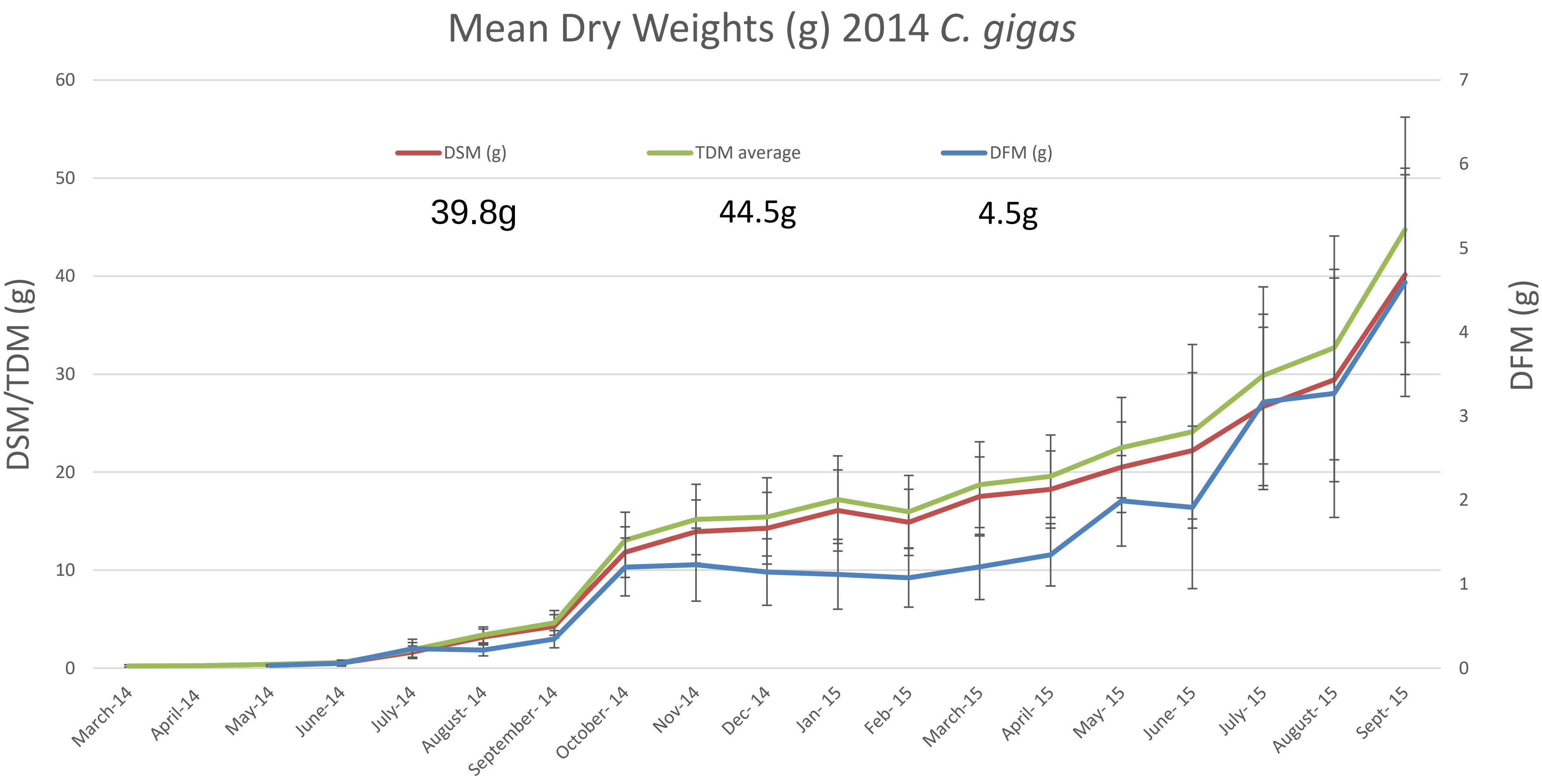




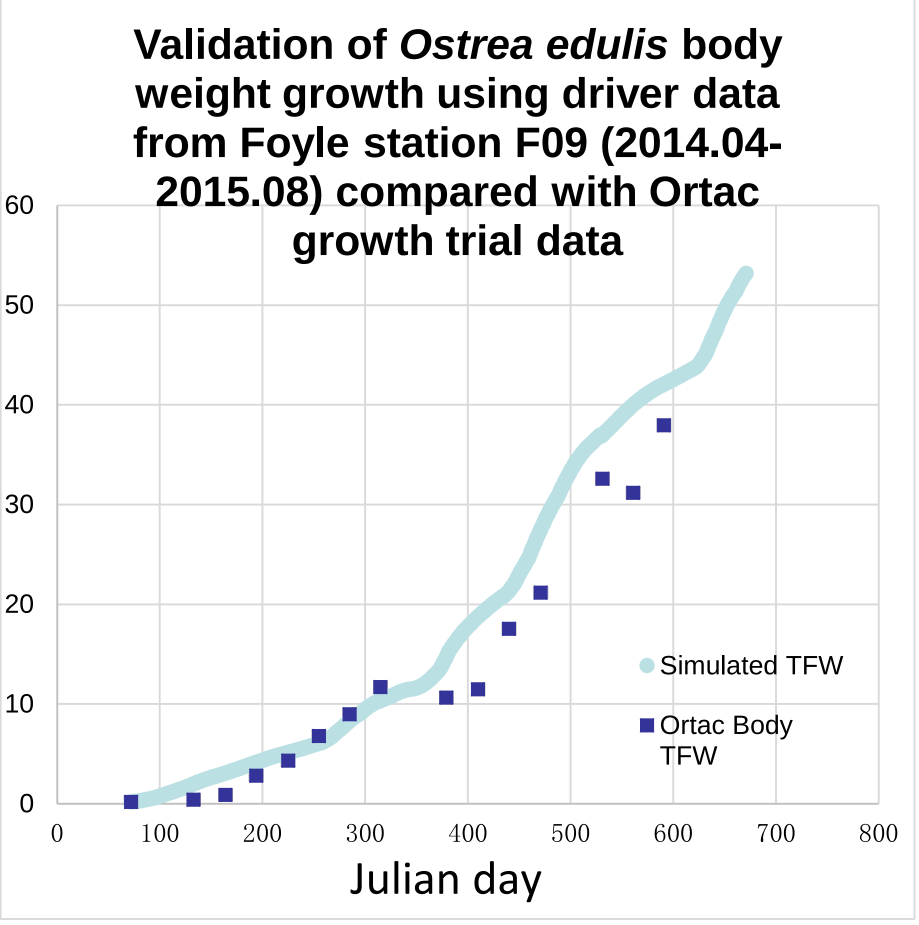


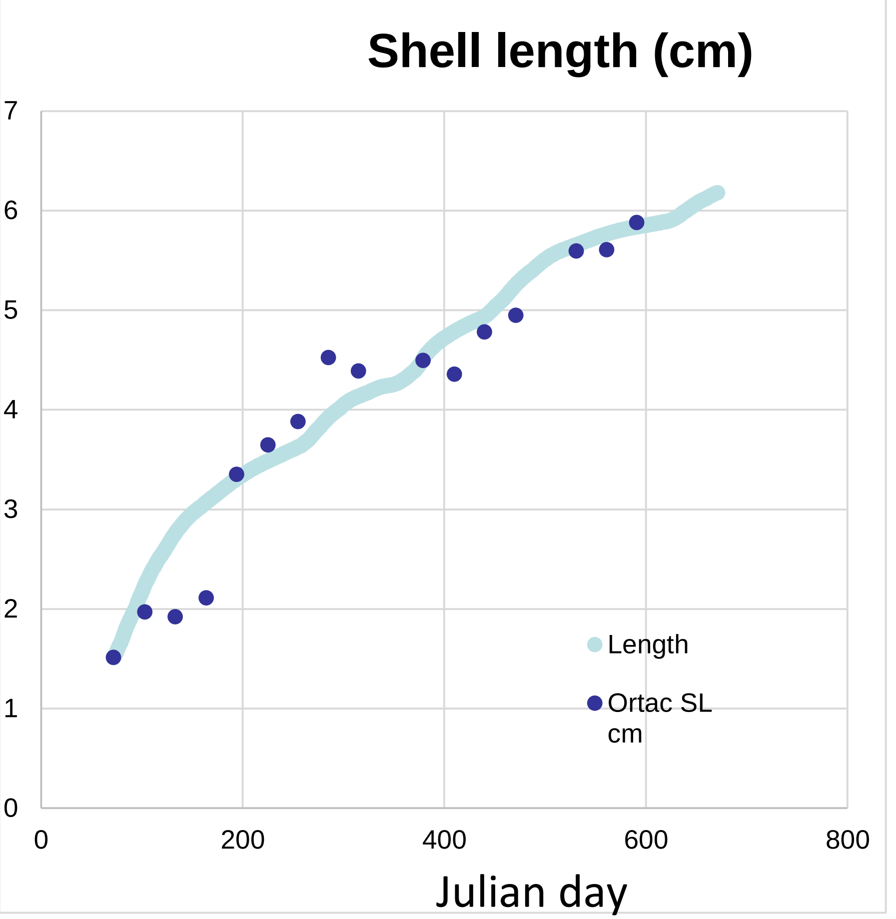
Without source apportionment, management is a black art. Source control in systems such as Lough Foyle is complex, costly, and socially challenging.

Crassostrea gigas 2014 Seed



AquaShell native oyster validation: using local Foyle environmental drivers and oyster growth trial data with Ortac system

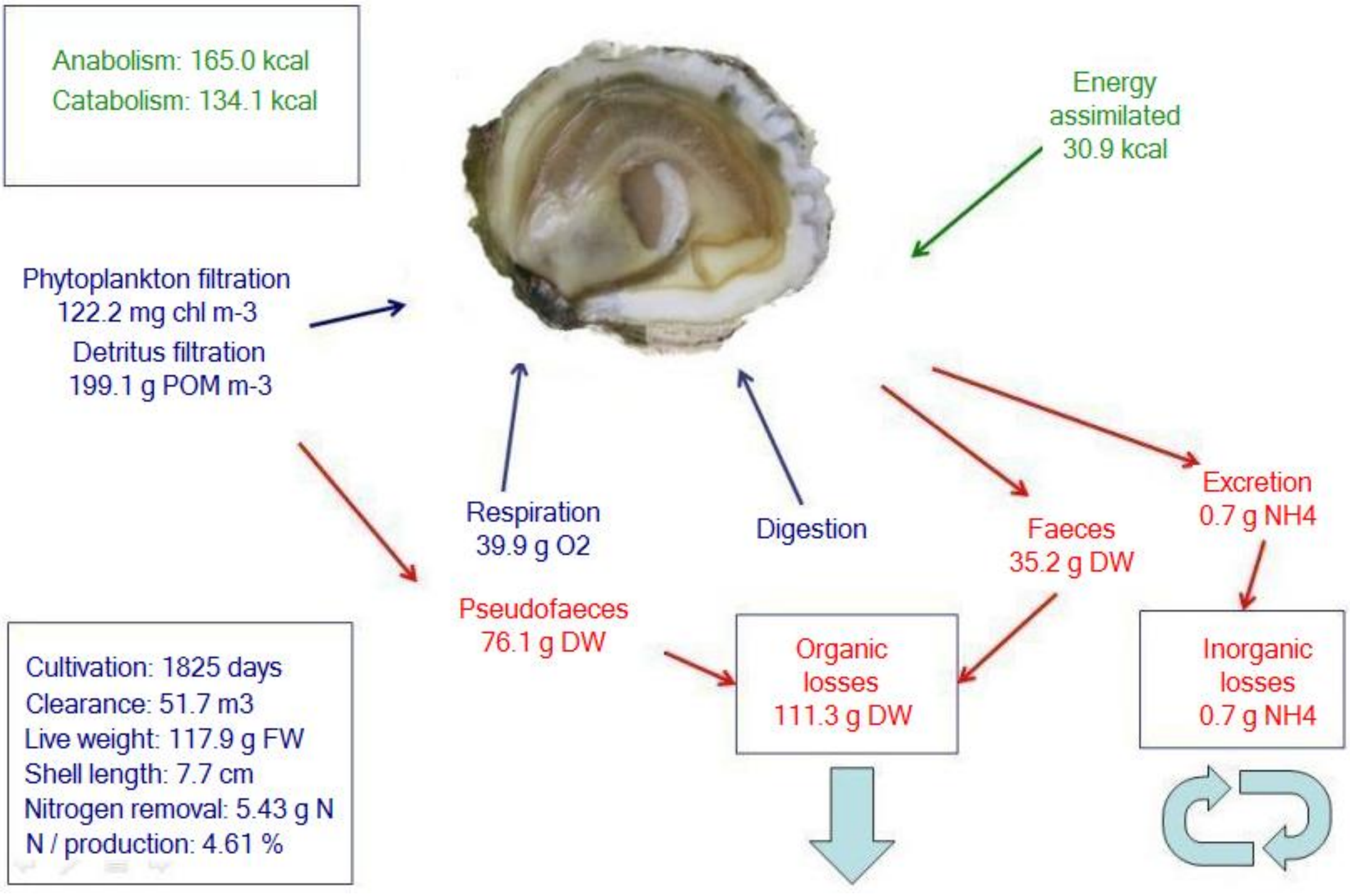




Model performance is an excellent match to Ortac growth data.

WinShell mass balance for native oyster

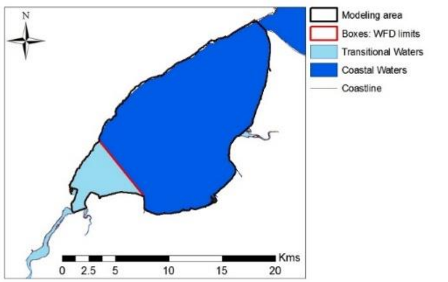
AquaShell native oyster model for the Foyle



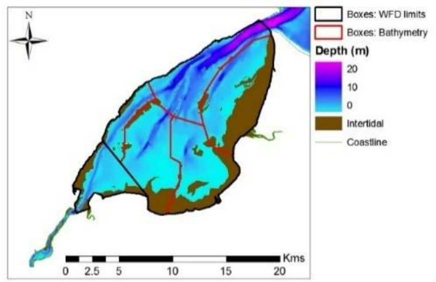
Model results are a good match to measured data; N removal seems high.

EcoWin model boxes

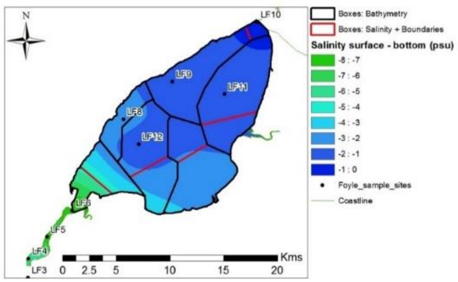
Division of Lough Foyle into simulation areas



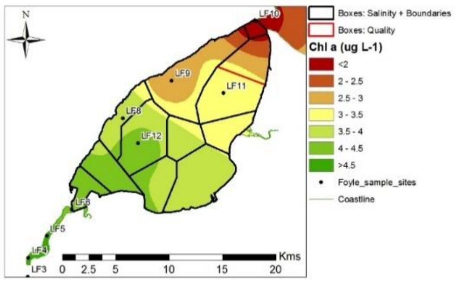
1. WFD water bodies



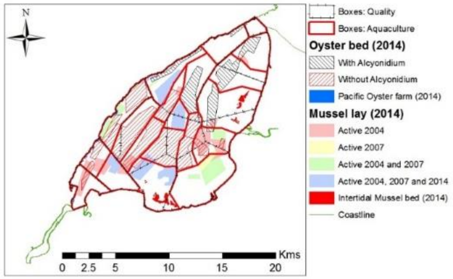
2. physical: bathymetry



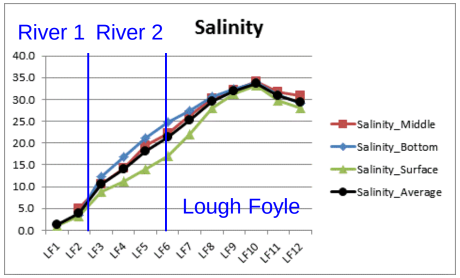
3. physical: salinity



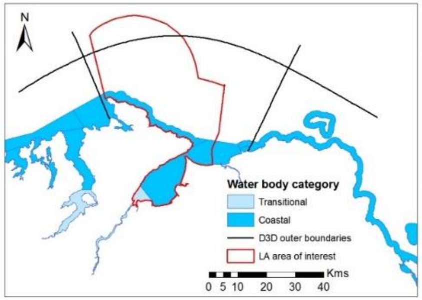
4. water quality



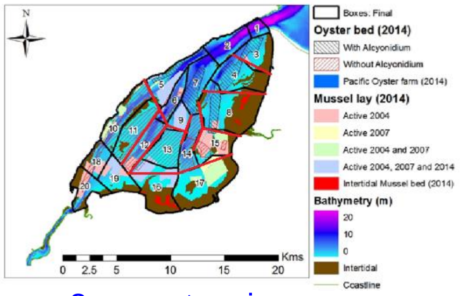
5. aquaculture



6. Foyle river: salinity gradient



7. Coastal areas: WFD water bodies + LA area

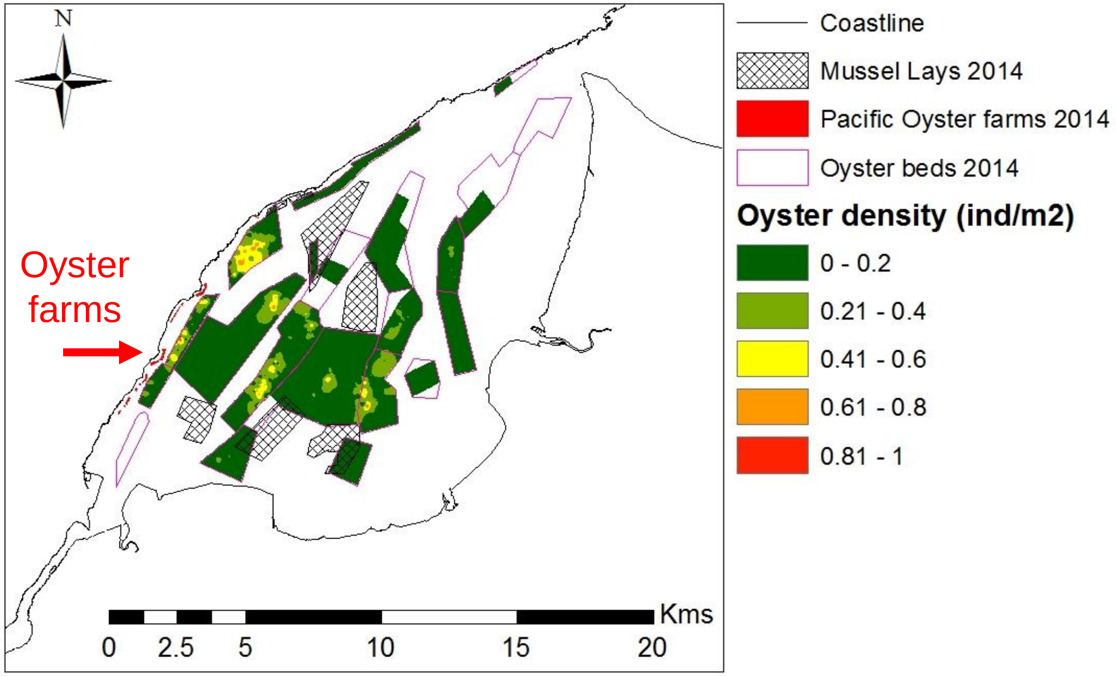


8. expert review (Loughs Agency)

Before a model is deployed in EcoWin, multicriteria analysis and stakeholder consultation is used to define simulation areas.

EcoWin application to Lough Foyle
Location and density of shellfish

- Mussel lays (subtidal)
  - 0.6 kg/m^2 (TFW) seed
- Oyster farms (intertidal)
  - 0.5 kg/m^2 (TFW) seed
- Oyster beds (subtidal):
  - 0.06 g/m^2 (TFW) seed
  - 0.1 ind/m^2 (0-1)
  - Beds: 0.02-0.3 ind/m^2
  - Oyster beds without samples: low bound (0.02 ind/m^2)

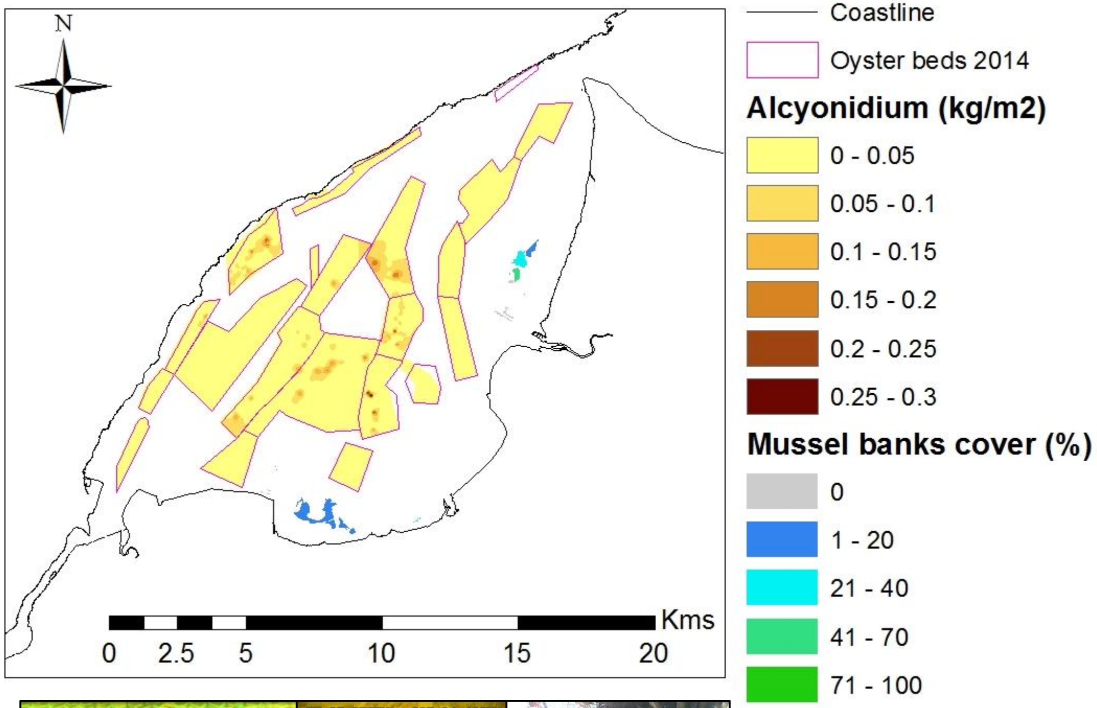


Location and density of wild species

- Mussel banks (intertidal)
  - Average density: 20.4 kg/m^2 (TFW) over life cycle
  - Cover: 16.5% (0-100%)

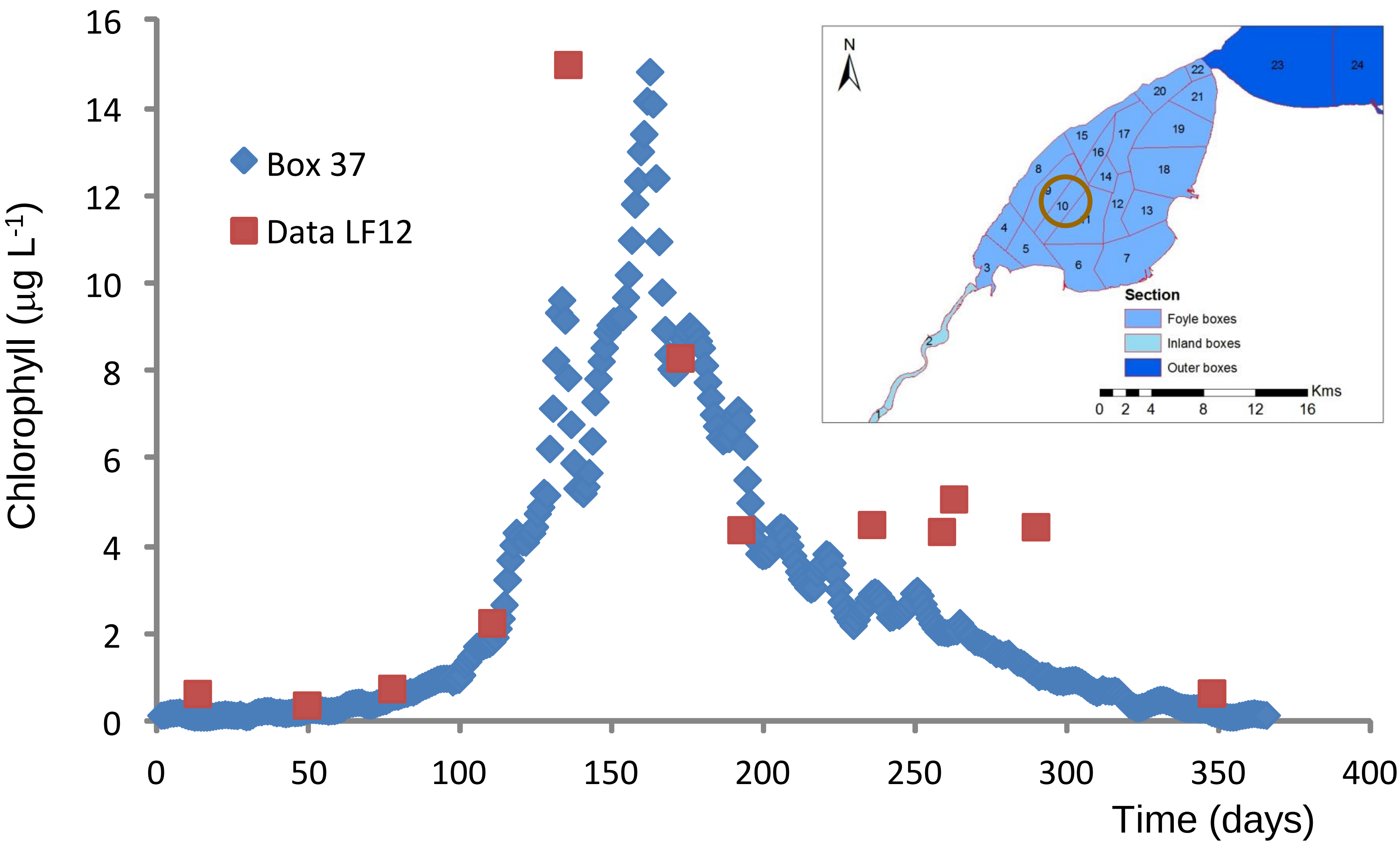
- *Alcyonidium* presence
  - Oyster beds sampled by LA in Autumn 2014
  - Density in unsampled beds estimated from Autumn 2015 data

- Subtidal filtration rates
  - Preliminary estimate
  - Oysters: 1 L/m^2.h
  - *Alcyonidium*: 28 L/m^2.h



EcoWin.NET model - EASE

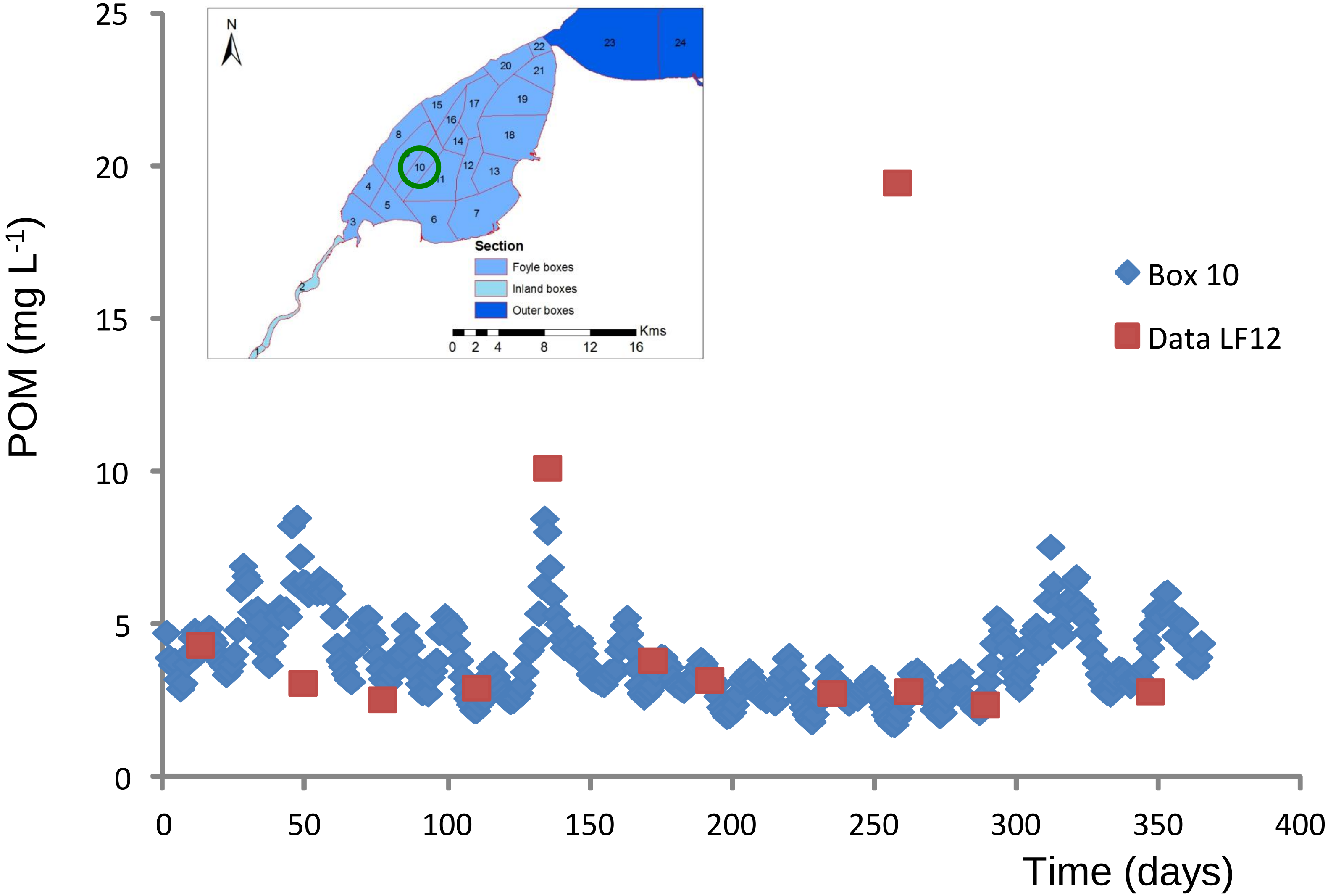
Water quality validation – chlorophyll (Model Year 2)



Bottom chlorophyll at some stations (and dates) is higher than in surface samples.

EcoWin.NET model - EASE

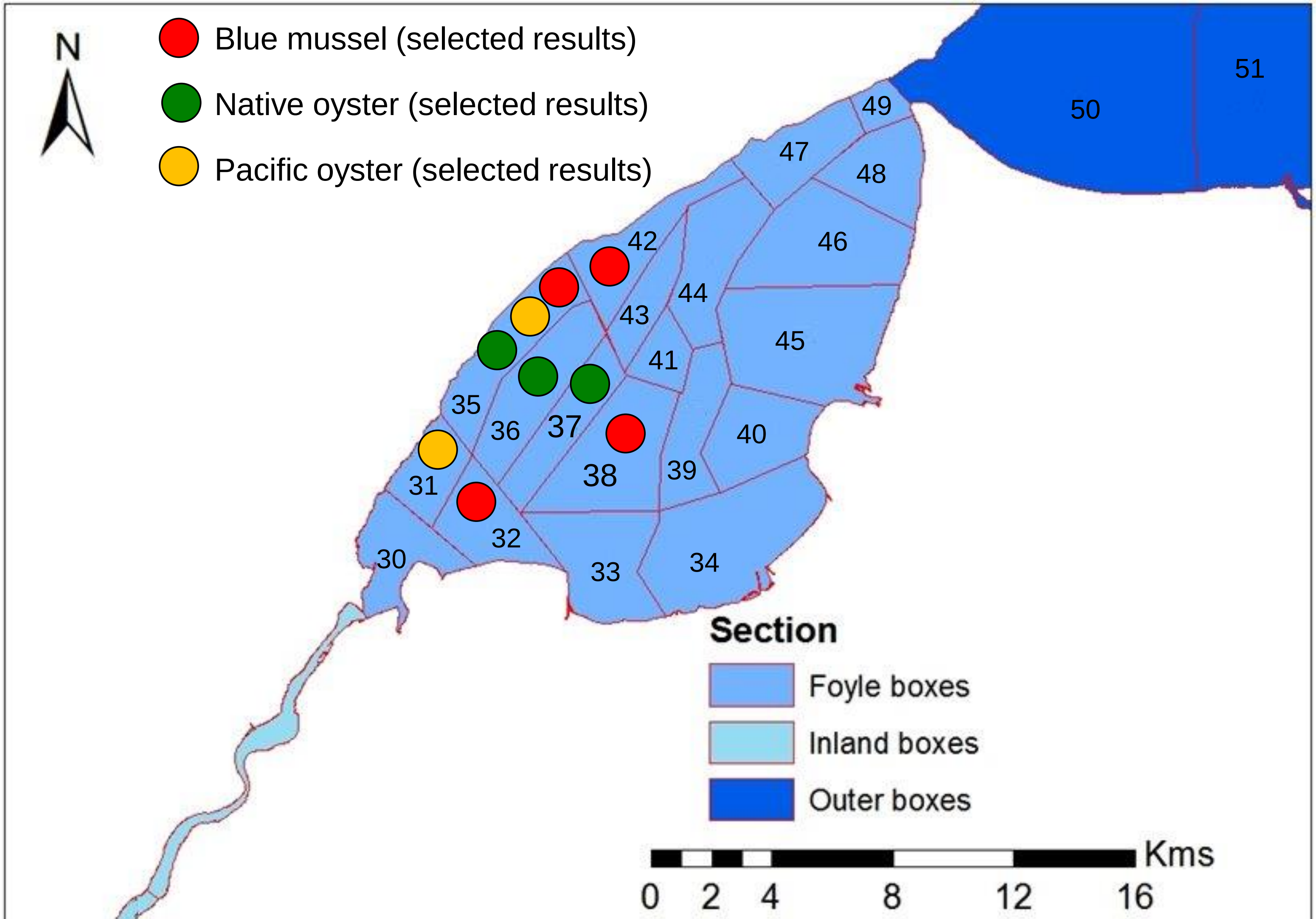
Water quality validation – POM (Model Year 2)



Model calibration focused on optimising shellfish growth drivers, with an emphasis on salinity, temperature, chlorophyll, and POM.

EcoWin.NET

Lower boxes are assigned for shellfish culture



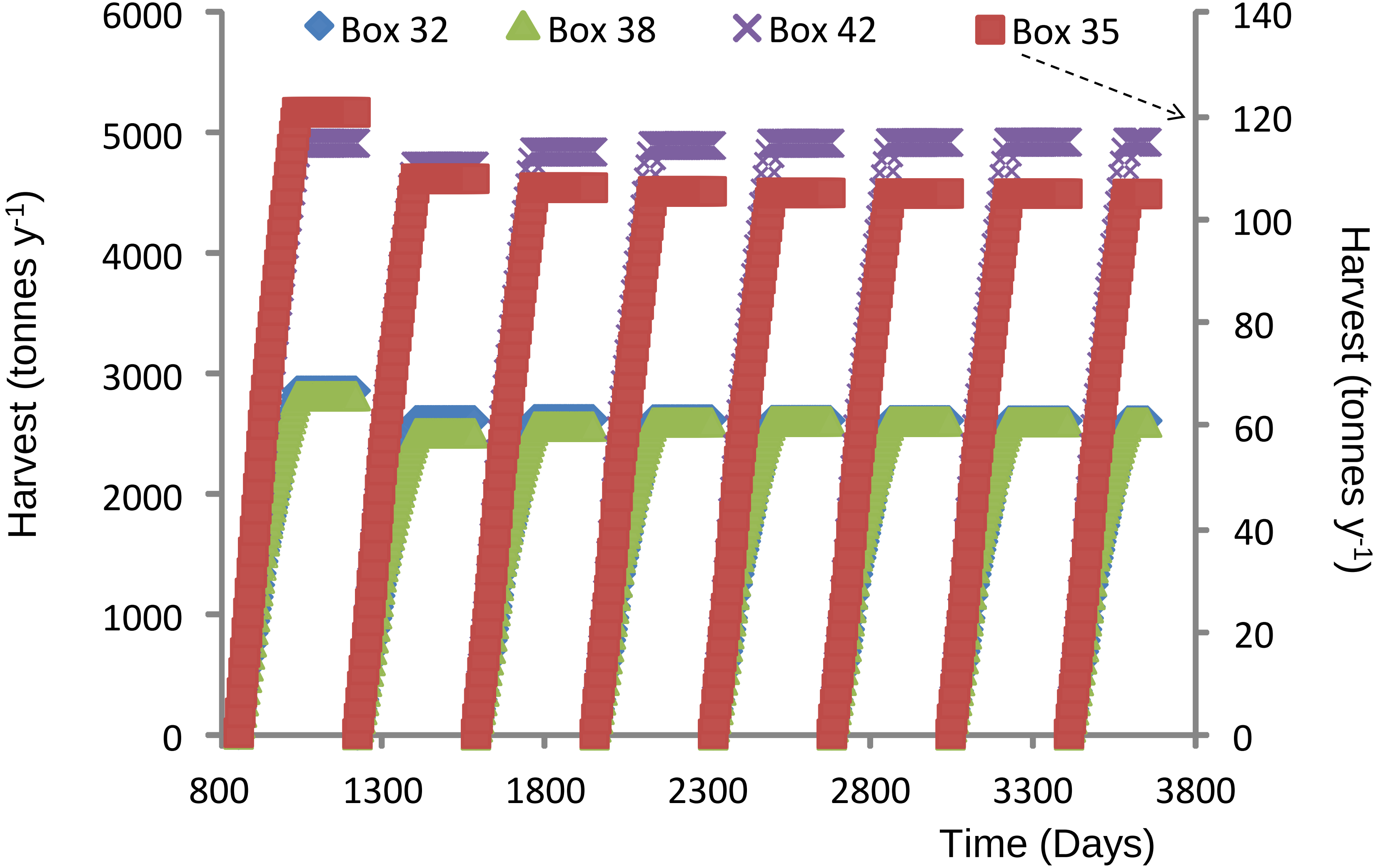
Yields vary substantially among boxes. The following slides show a subset for each species, with all objects active.

EcoWin.NET shellfish model
Harvest yields for Year 9 (tonnes)

Box	Blue mussel	Native oyster	Pacific oyster
30	-	1.87	-
31	-	3.96	1009.53
32	2742.90	2.50	-
33	101.29	-	-
34	99.72	1.52	-
35	108.93	13.31	936.42
36	291.73	14.28	-
37	58.83	4.97	-
38	2777.59	-	-
39	97.06	6.78	-
40	-	4.24	-
41	3003.21	-	-
42	5053.06	0.22	-
43	1364.02	0.62	-
44	160.54	0.10	-
45	-	0.36	-
46	-	0.95	-
48	-	0.03	-
49	-	-	-
Total	15859	56	1946

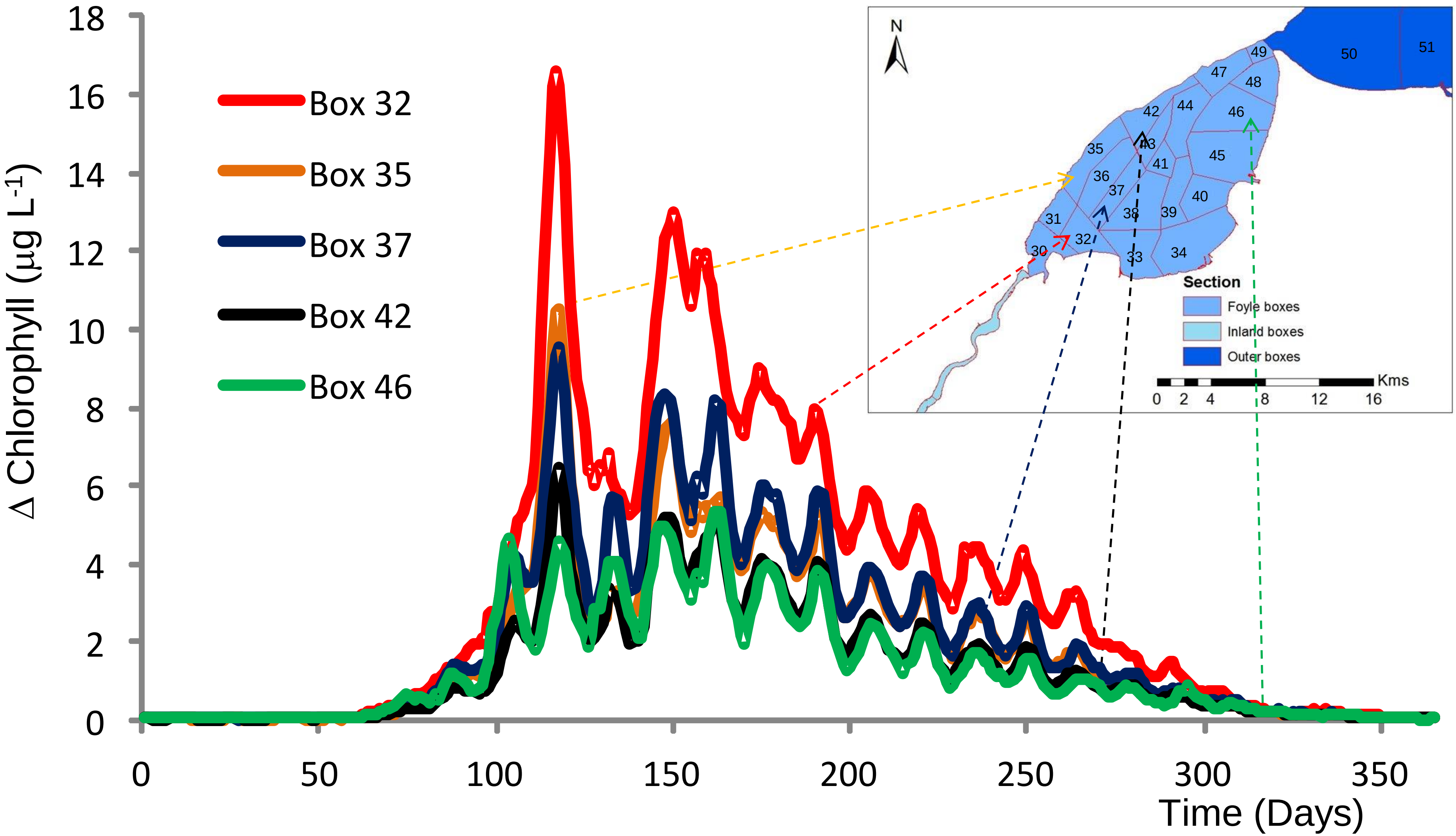
Production of native oysters in some boxes (e.g. 32, 42, 43) is strongly limited by blue mussel culture. Wild species are also important.

EcoWin.NET Lough Foyle Model
Blue mussel harvest over time – standard model



Blue mussel spin-up is very fast and harvest stabilizes.

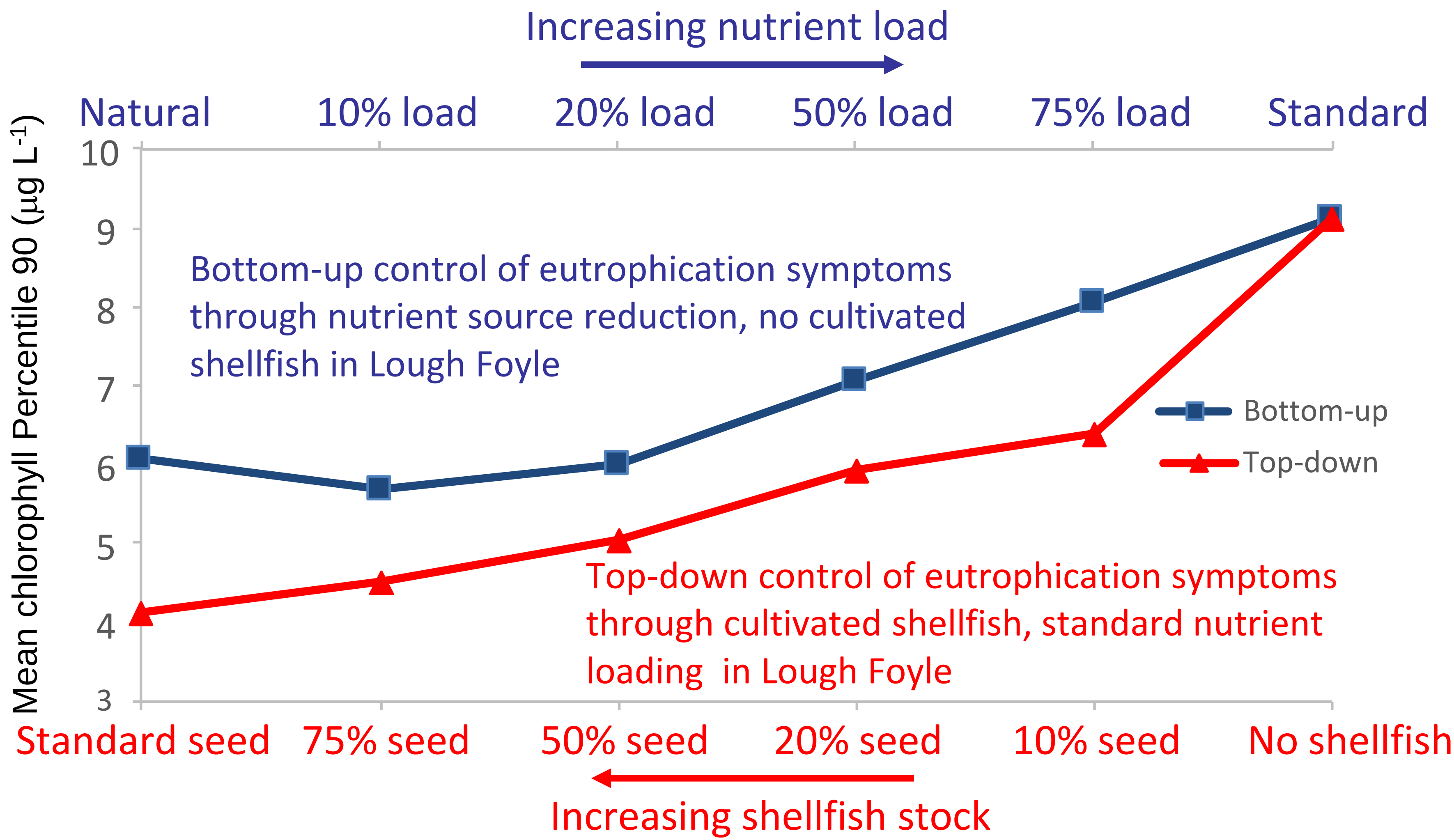
EcoWin.NET Lough Foyle Model
Phytoplankton drawdown – standard model, Year 9



The strongest drawdown is in the central and upper parts of the lough, where both native oyster (*O. edulis*) and blue mussel (*M. edulis*) are grown.

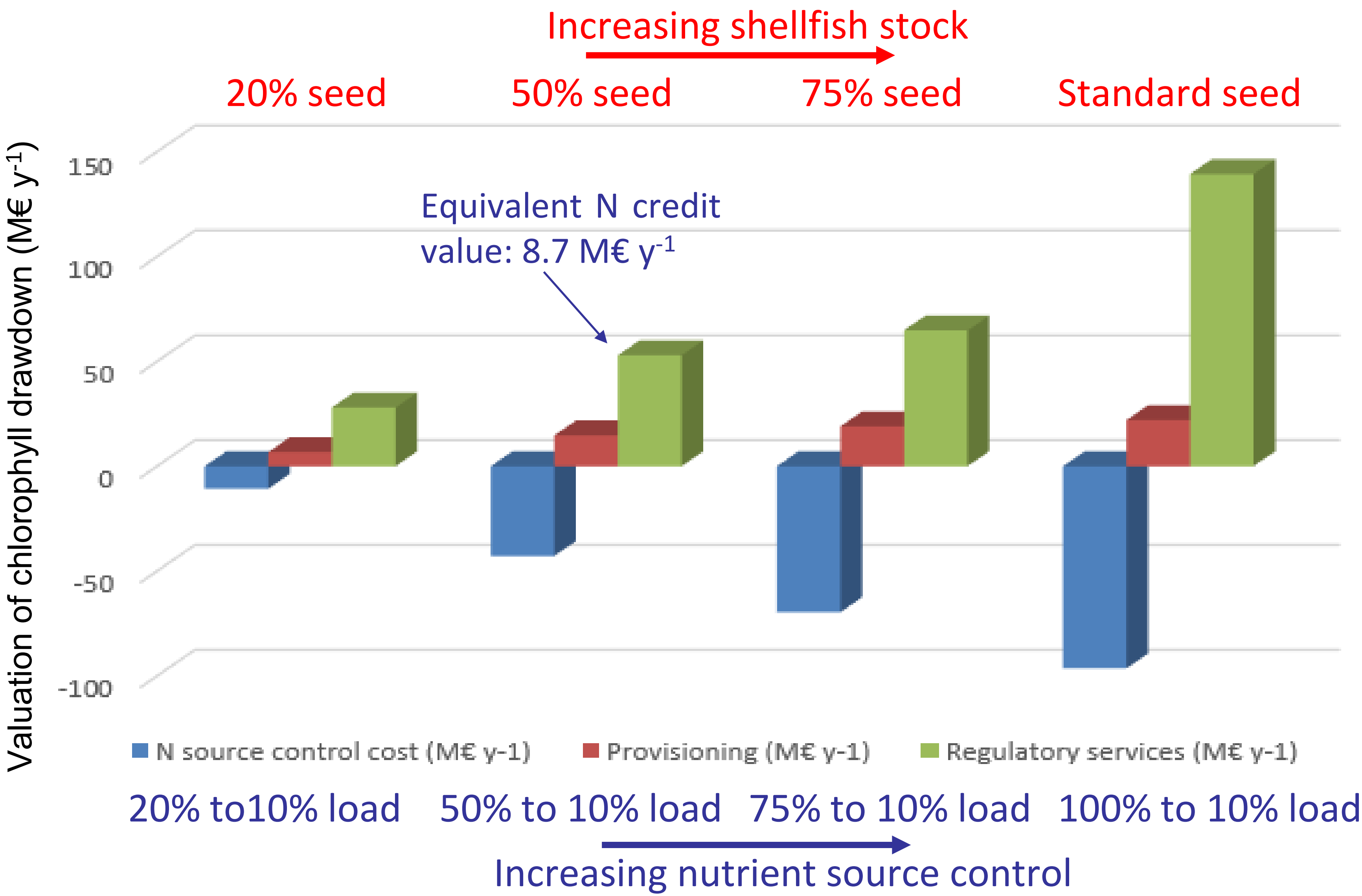
EcoWin.NET Lough Foyle Model

Chlorophyll drawdown with bottom-up and top-down control



Shellfish culture outperforms source control in controlling eutrophication symptoms, and provides an additional provisioning service.

EcoWin.NET Lough Foyle Model
Valuation of shellfish ecosystem services



The value of the regulatory service of chlorophyll removal by shellfish is far higher than the value estimated through direct nutrient removal.

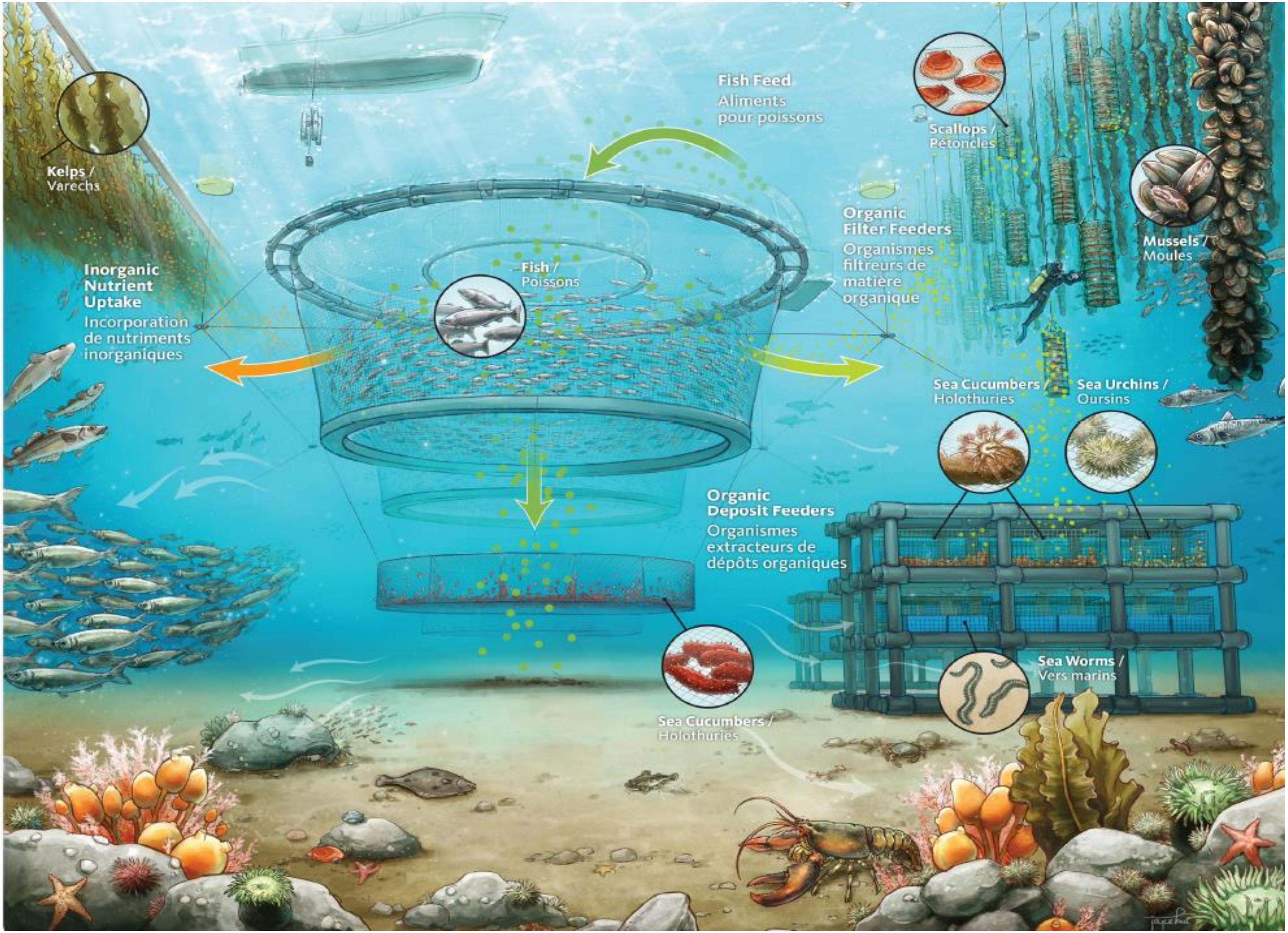
Synthesis

- A full ecological model was set up for the Foyle, integrated both at the catchment and shelf sea scales;
- There is no silver bullet: different models work within a framework but have standalone capabilities;
- In a system where some areas have elevated chlorophyll peaks, and where production is driven by diffuse sources of nutrients, shellfish culture is key for eutrophication management;
- EASE supports the EU Water Framework Directive (WFD), Marine Strategy (MSFD), and Habitats directives.
- Potential uses include licensing, restoration, risk assessment, climate change analysis;
- A model framework of this kind is a powerful toolset, and outputs may be combined with local-scale models such as FARM.

Integrated Multi-Trophic Aquaculture: Panacea or Hype?

- Aquaculture description and modeling framework
- Finfish and shrimp individual growth models
- Simulation of growth in ponds
- Production, environmental externalities and IMTA
- Upscaling to the Kingdom of Thailand

Conceptual diagram for IMTA

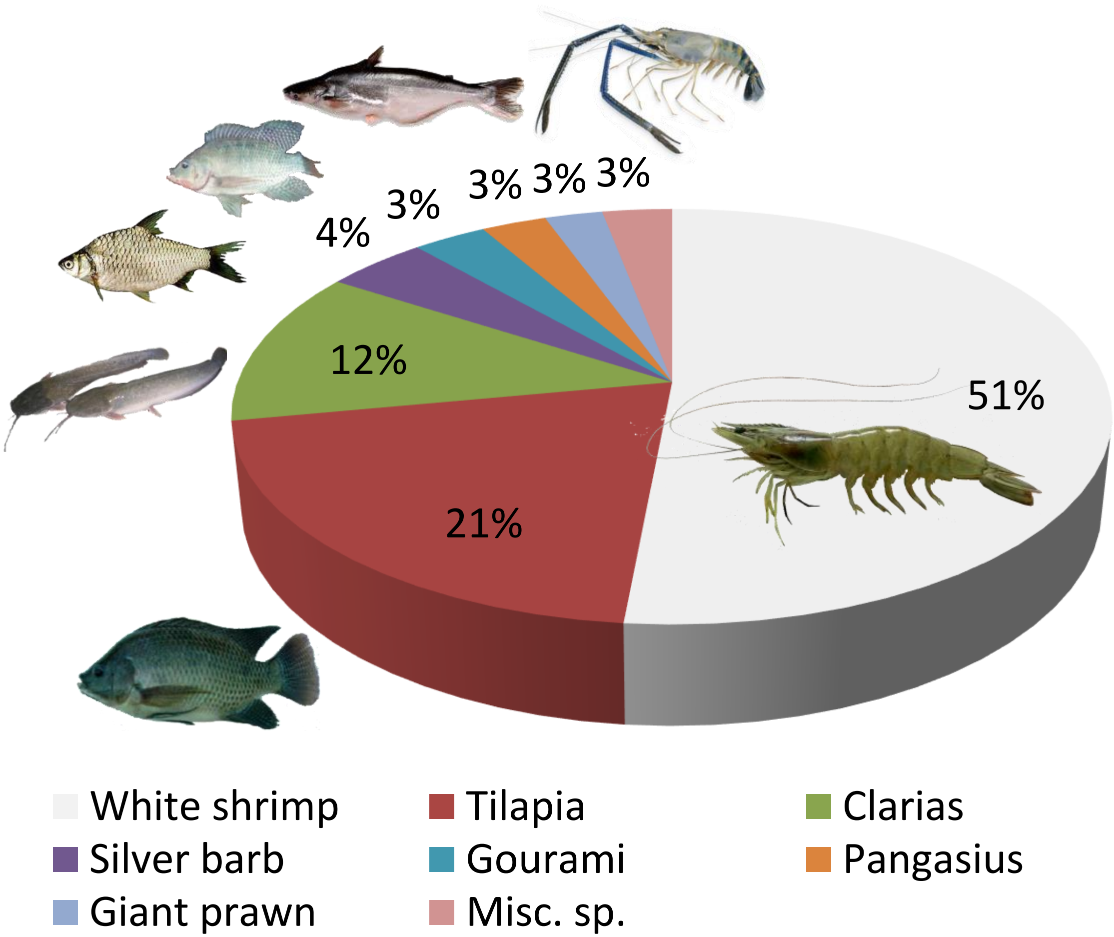


Integration
Southeast Asia and China

- 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.

Species production from aquaculture
Data for Thailand, 2009



Species	Tons y^{-1}
Tilapia	221 042
Clarias	130 064
Silver barb	47 231
Gourami	34 220
Pangasius	30 200
Giant prawn	26 785
Misc. sp.	32 338
Total inland	**521 880**
White shrimp	**553 899**

White shrimp production is approximately the same as the total for inland aquaculture.

Source: Department of Fisheries Thailand

Export of aquaculture products from Thailand

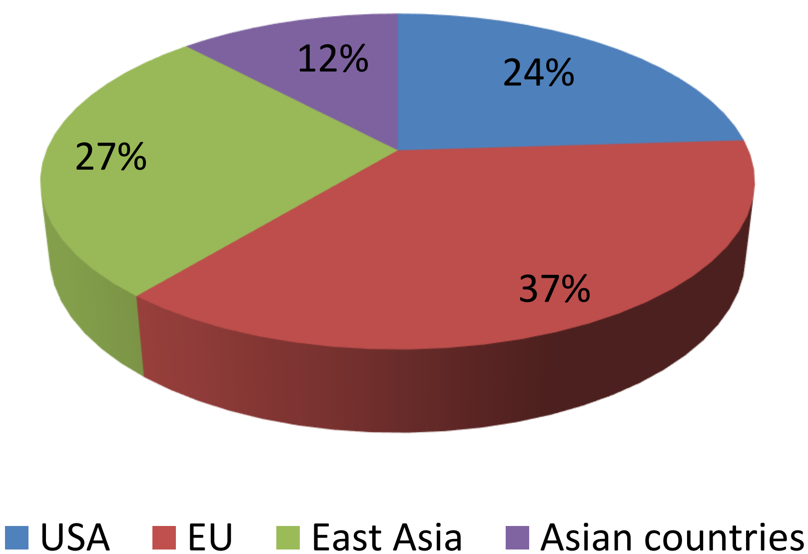
Inland total and white shrimp

Inland

33 454 tons y^{-1}

1 421 M baht y^{-1}

33.25 M euro y^{-1}

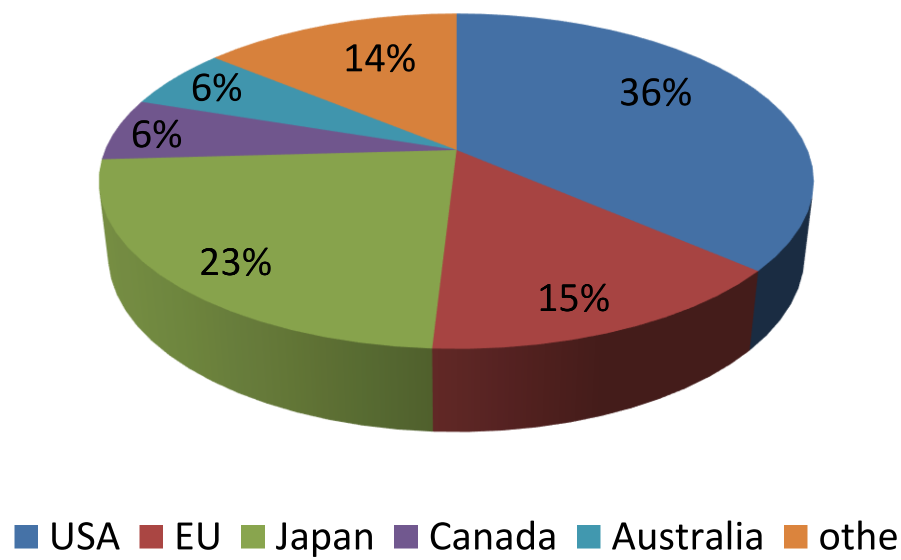


White shrimp

311 322 tons y^{-1}

78 920 M baht y^{-1}

1 846.65 M euro y^{-1}



White shrimp (*Litopenaeus vannamei*) is a high value product. During 2003-2009, export was ten times more than inland export, and income was fifty-five times higher.

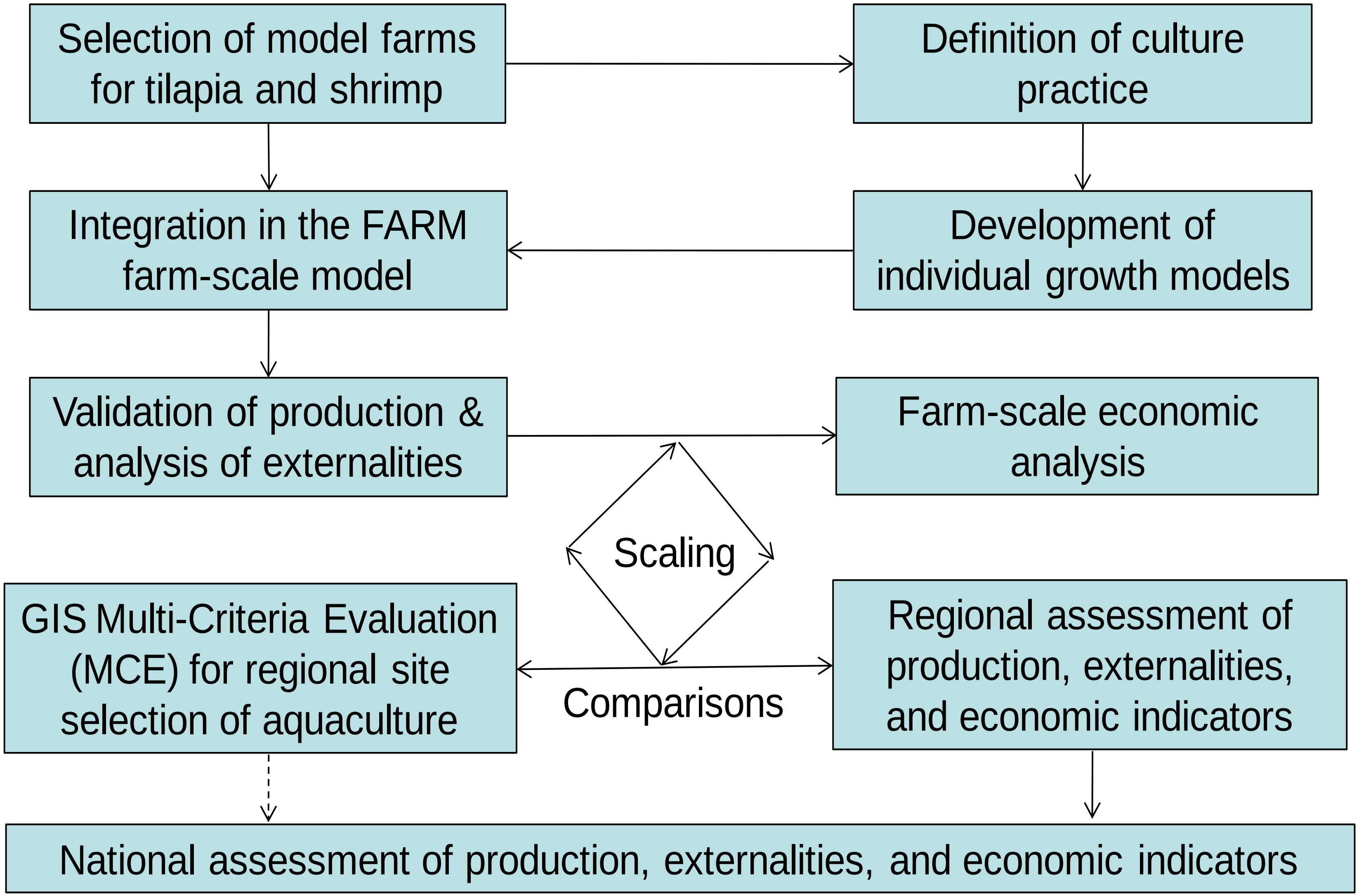
Source: Department of Fisheries Thailand


Nile tilapia
Central Thailand


Nile tilapia
Central Thailand

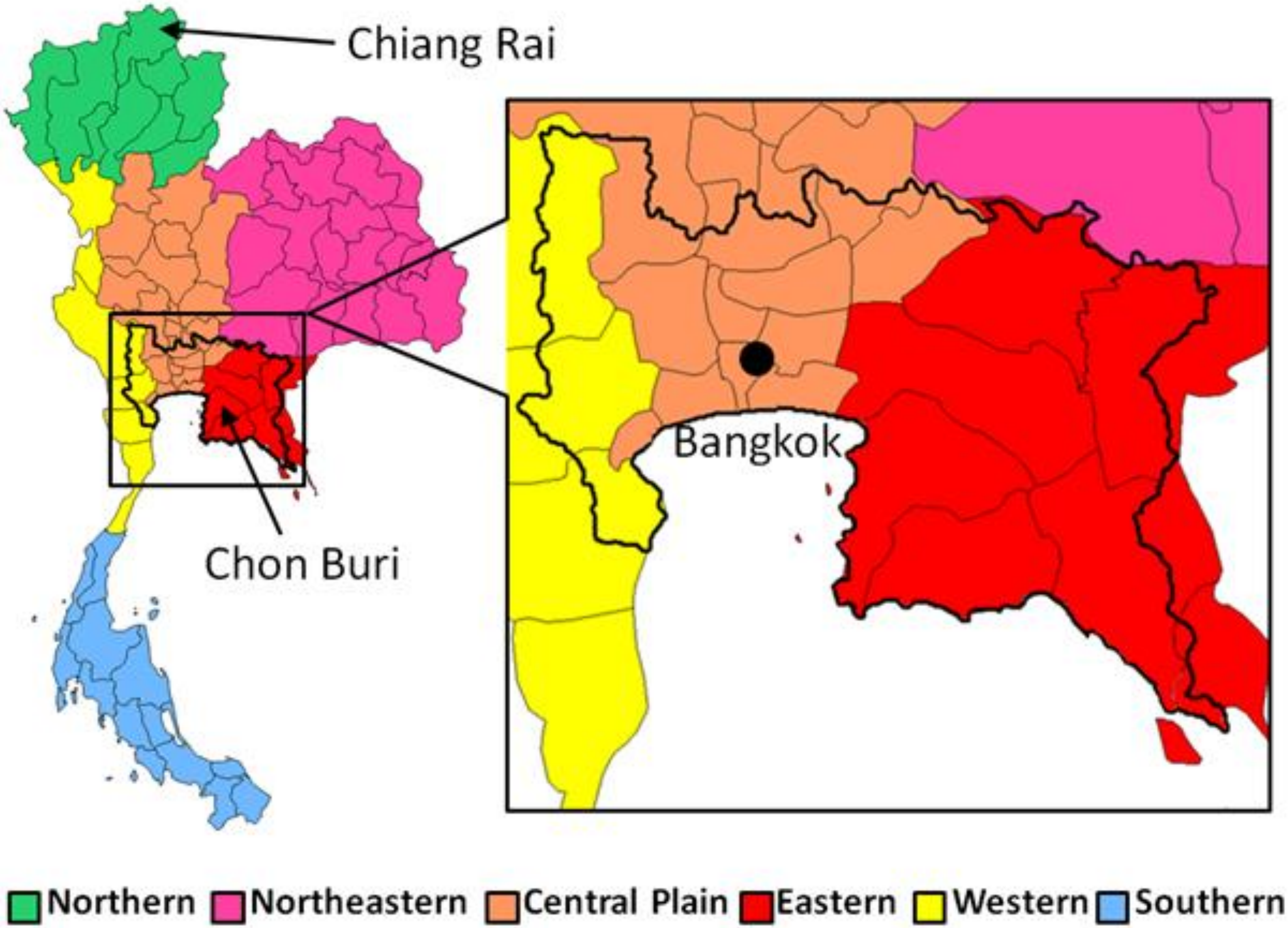
Modelling framework

Field and experimental data combined with various models



A combination of models helps address different aspects of sustainability.

Study areas in Thailand



Tilapia in NW Thailand, IMTA in Western Thailand.

FARM setup for Chiangrai pond culture

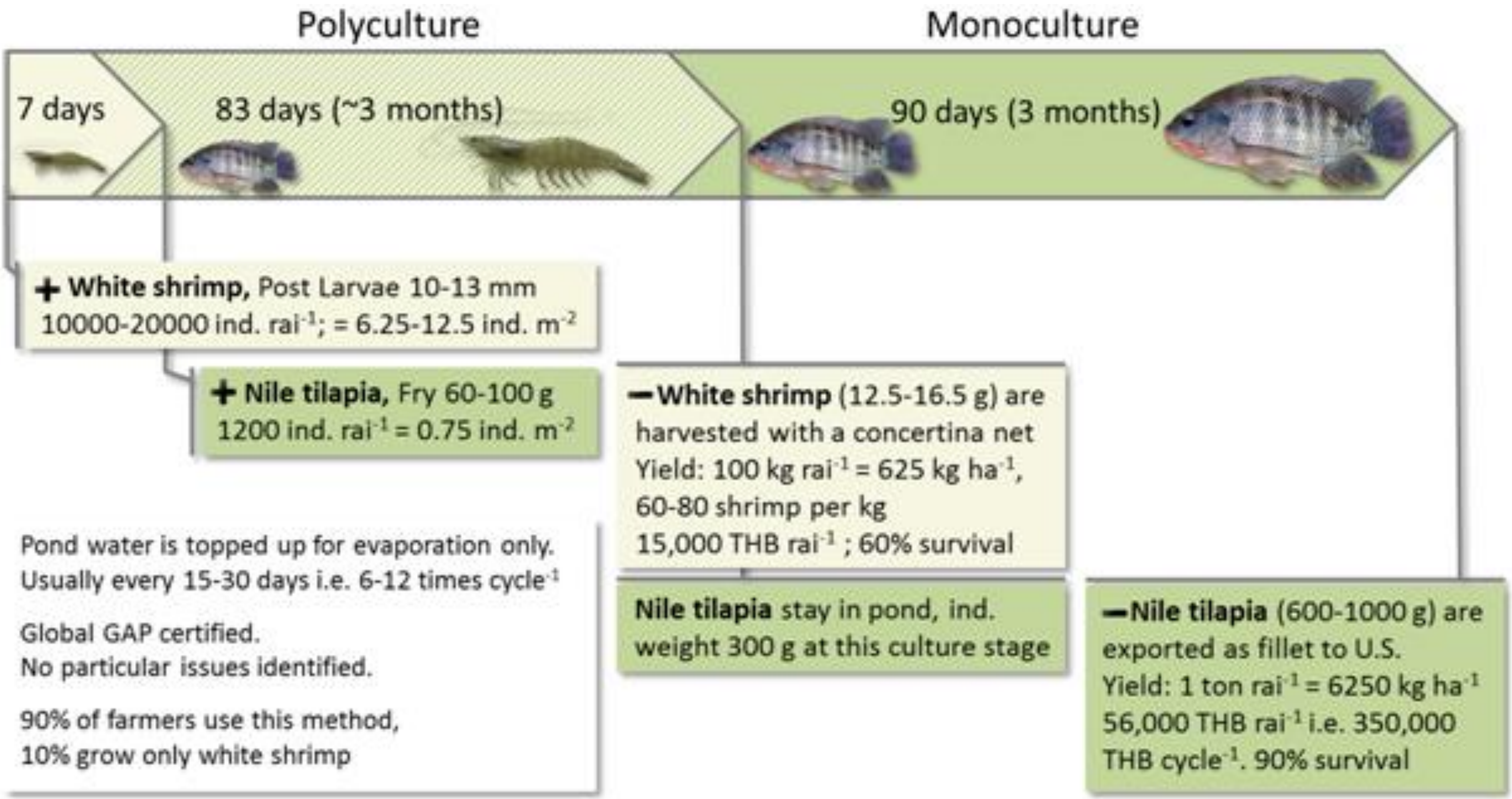
Tilapia, *Oreochromis niloticus*

Cholburee, Thailand

Integrated culture of tilapia and shrimp

Shrimp go in for one week, then the tilapia are added and eat the *Azolla*.

IMTA culture practice



Put the shrimp in first so the tilapia don’t eat them.

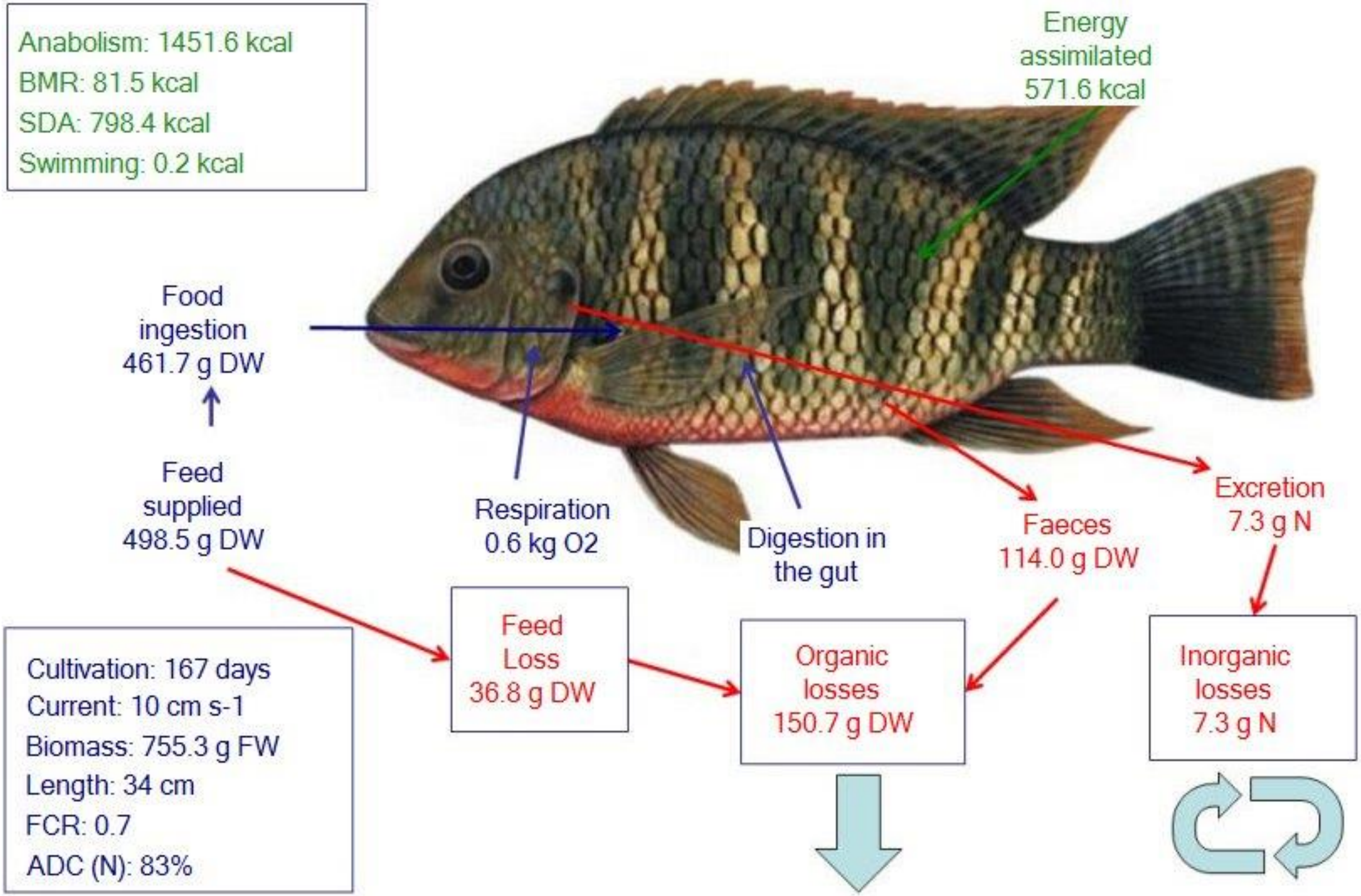
Blinded by the light

Luring the shrimp with an energy-efficient 220 V bulb

Shrimp are lured at night and captured in concertina nets.

Individual mass balance for Nile tilapia cultivation

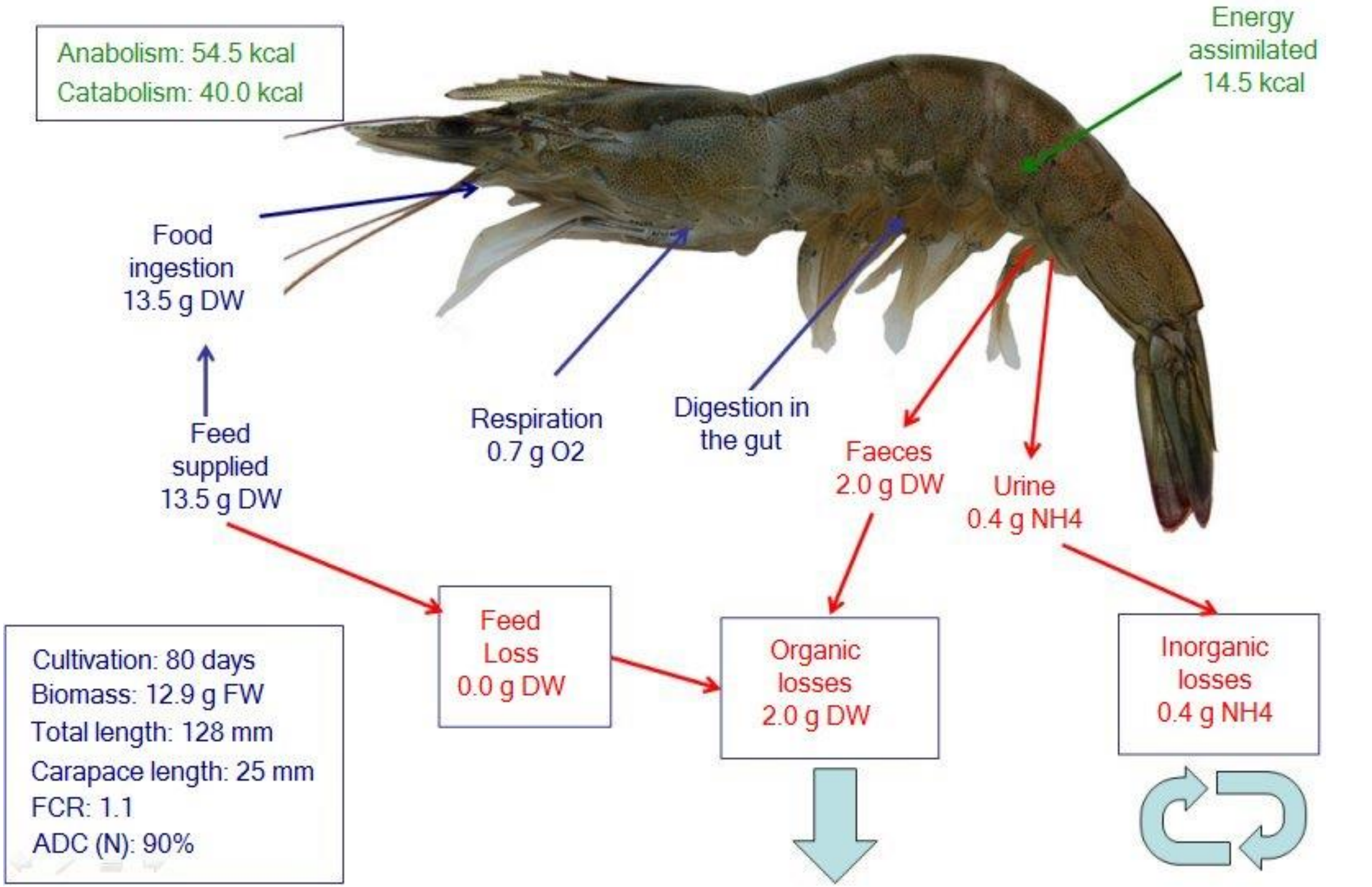
Final weight: 755 g, AquaFish model



Average individual weight for three ponds (8 rai) in Chiangrai is 713±59 g.

Individual mass balance for white shrimp cultivation

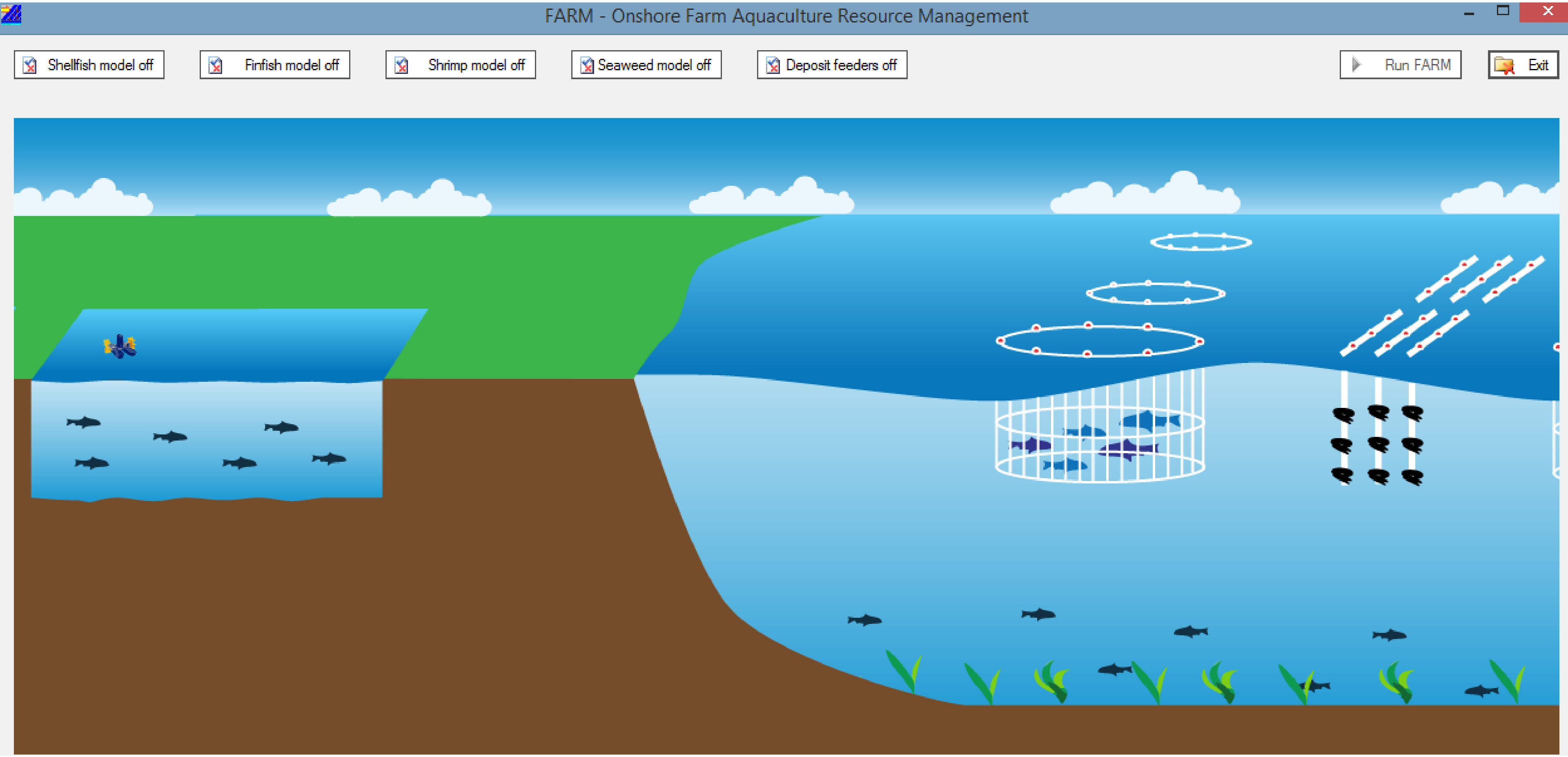
Final weight: 12.8 g, AquaShrimp model



White shrimp (*Litopenaeus vannamei*) weight in ponds varies between 10-25 g.

FARM model

Application to Integrated Multi-Trophic Aquaculture (IMTA)



FARM model for finfish, shellfish, or seaweed monoculture, and IMTA.

Ferreira et al, 2014. Analysis of production and environmental effects of Nile tilapia and white shrimp culture in Thailand. Aquaculture, http://dx.doi.org/10.1016/j.aquaculture.2014.08.042.

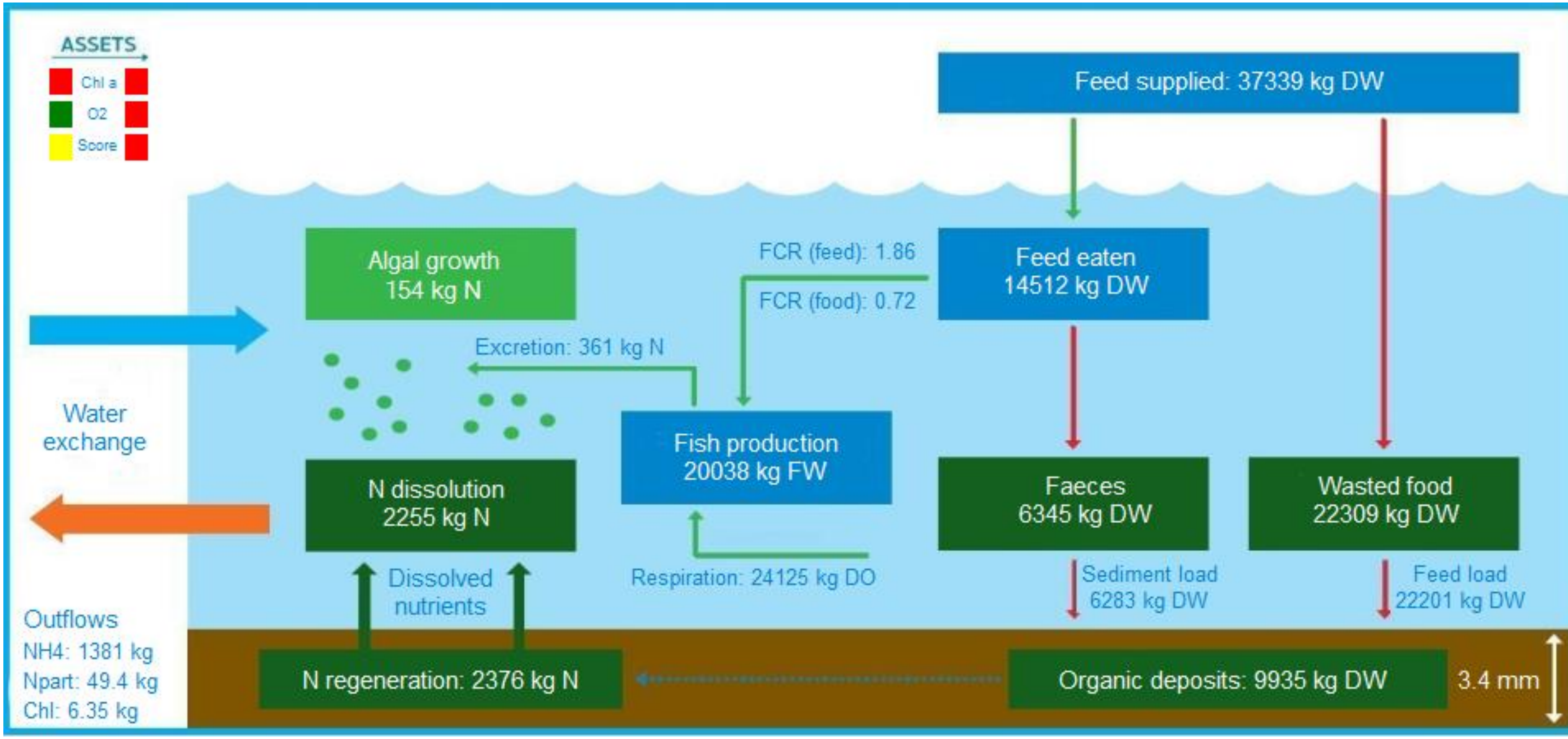
Production and environmental effects of pond culture of Nile tilapia (*O. niloticus*) in monoculture - Chiangrai

Variable	FARM - tilapia Monoculture	Data - tilapia monoculture
Model inputs		
Seeding density	3.13 fish per m^2 2 rai (3200 m^2) ponds	
Seeding density (kg FW)	801.3	800
Model outputs		
Production		
Total (TPP) (kg TFW)	5115.6	5400
Feed Conversion Ratio (FCR)	1.80	1.69
Environmental externalities		
Outflow of NH_4^+ (kg N)	224.5	-
Outflow of chlorophyll (kg chl)	1.27	-
Profit and loss		
Total income = Aquaculture products ($)	**8747.69**	**9234**
Total expenditure ($)	**7659.50**	**7388.28**
Feed cost ($)	6276.77	6324
Seed cost ($)	969.25	967.7
Energy cost ($)	413.48	96.58
Farm Profit = Income-Expenditure ($)	**1088.19**	**1845.72**

FARM model: results per pond; recorded data: average of three ponds.

FARM model for culture of finfish

Mass balance for pond culture of Nile tilapia in Chiangrai

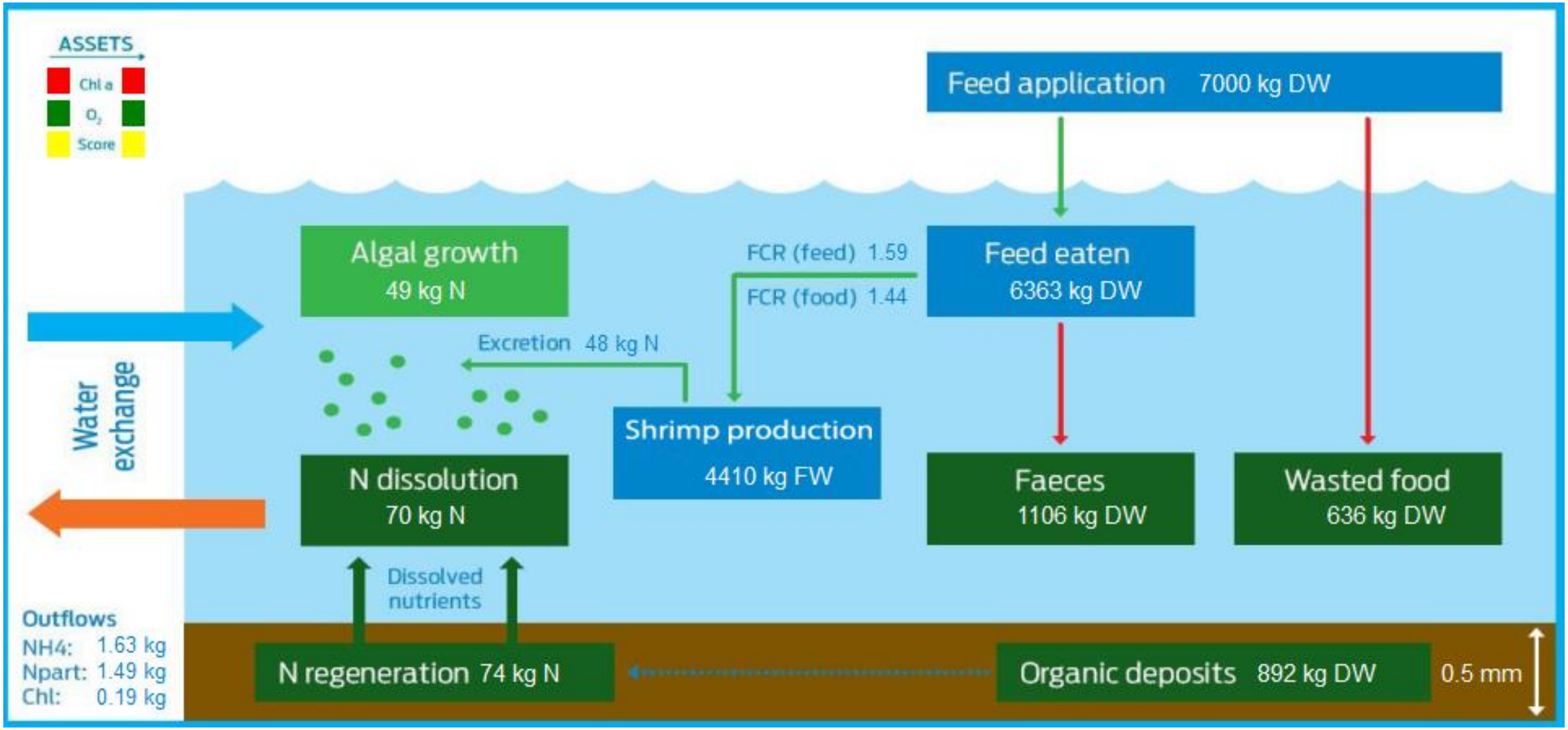


Mass balance for tilapia pond culture (4 ponds, 8 rai total area,167 day cycle, starting day 206, seed weight 80 g, harvest weight >650 g). Yield of 5009.4 kg per pond (recorded data - average: 5400 kg and FCR 1.69).

Ferreira et al, 2015. Aquaculture, 447, 23-36.

FARM model for shrimp monoculture

Mass balance for pond culture of white shrimp in Chanthaburi



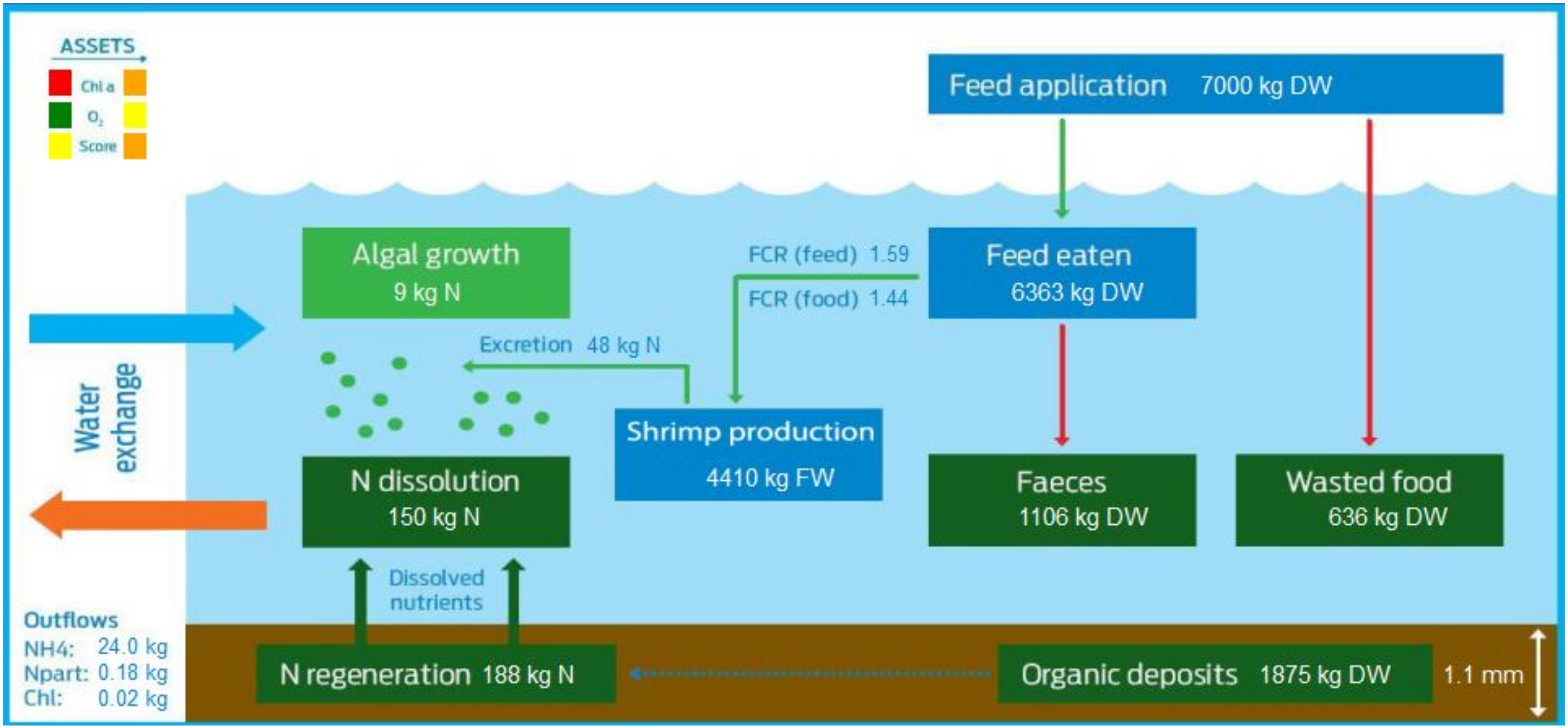
Mass balance for shrimp pond culture (1 pond, 2.5 rai area, 81 day cycle, density 80 ind. m^{-2}, starting day 1, seed weight 0.002 g, harvest weight >16 g). Yield of 4409.8 kg per pond (recorded data: 4000 kg, FCR 1.32).

Ferreira et al, 2015. Aquaculture, 447, 23-36.

FARM model for integrated multi-trophic aquaculture

Mass balance for co-cultivation of tilapia and white shrimp

Simulation for 81 days (one shrimp cycle)



Tilapia increase sedimentation of organics and diagenesis, but significantly reduce algal growth through filtration, and therefore chlorophyll emissions. There is an additional crop of about 1 ton of tilapia (400 g weight) in this 2.5 rai farm.

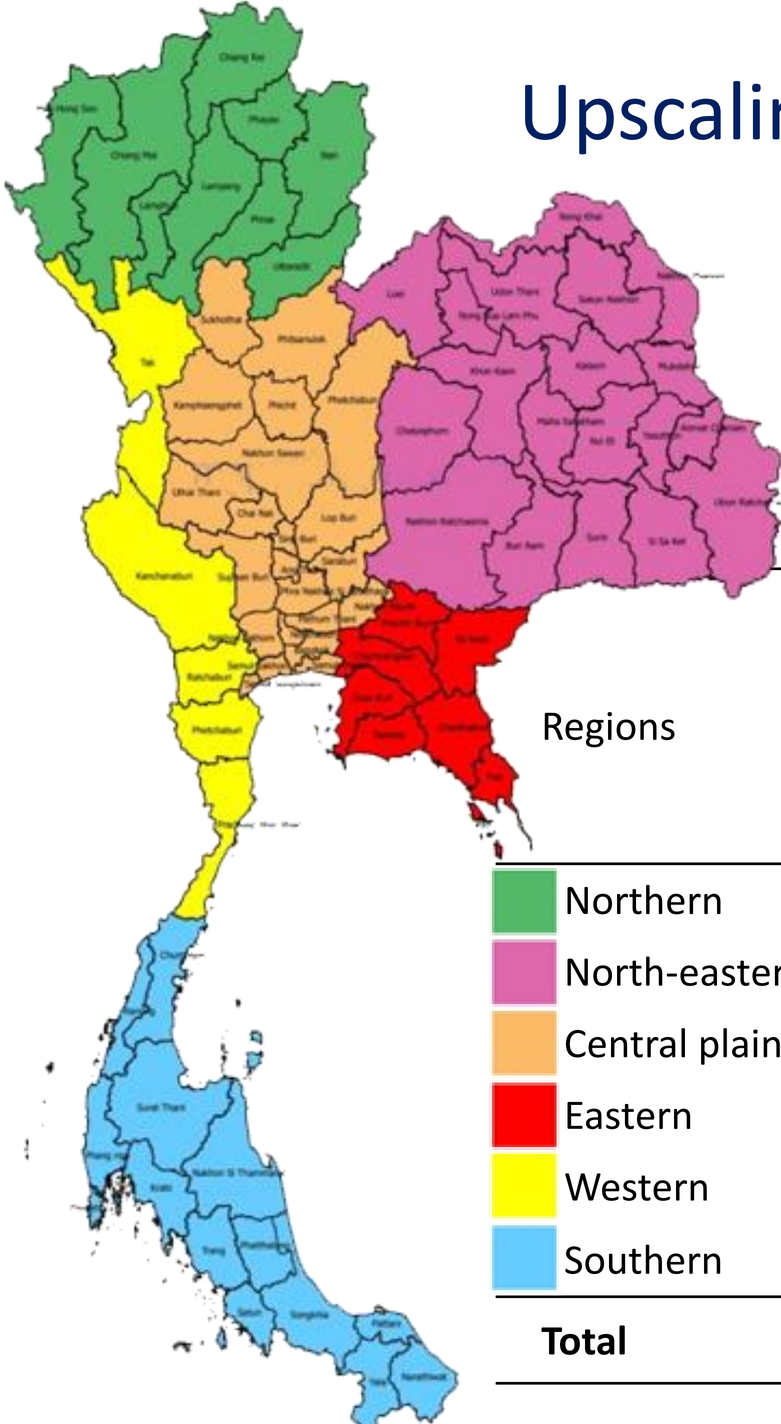
Tilapia Culture Economic Indicators:

Chiangrai province per rai (1600 m^2)

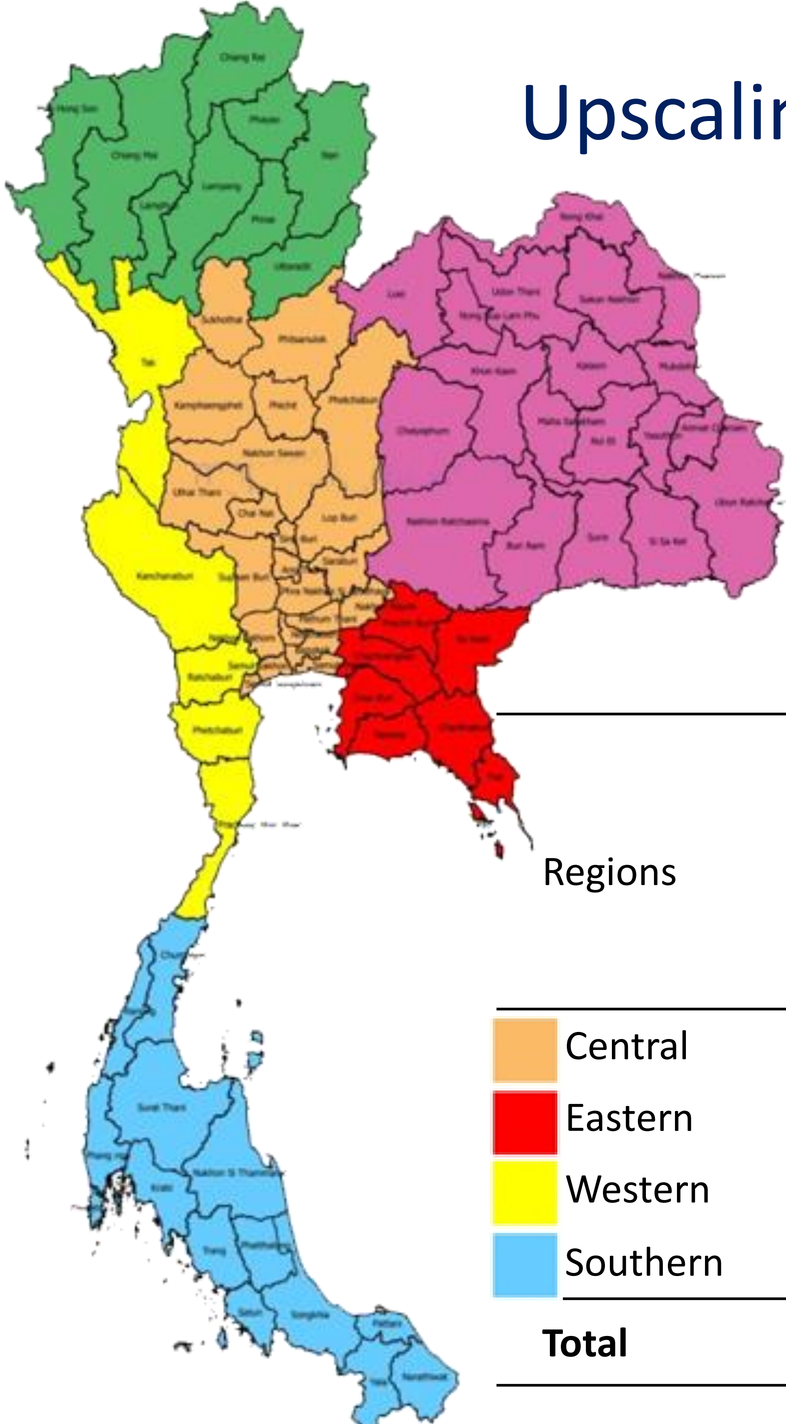
Economic Indicators	USD
Labour (Household)	82.8
Labour (Seasonal)	54
Total Labour	136.56
Total Expenditures	2 274.35
Total Revenue (income)	3 064.32

Upscaling to the Kingdom of Thailand

Production and environment



Regions	Aquaculture production	Primary production	Environmental externalities due to outflows		
			Ammonia	Chlorophyll *a*	PEQ
	$t\ y^{-1}$	$t\ N\ y^{-1}$	$t\ N\ y^{-1}$	$kg\ chl\ y^{-1}$	
Northern	36 004	718	126	125	38 187
North-eastern	42 981	857	150	149	45 587
Central plain	16 500	329	58	57	17 501
Eastern	32 957	657	115	115	34 956
Western	21 296	425	75	74	22 587
Southern	8 556	171	30	30	9 075
Total	**158 293**	**3 156**	**554**	**550**	**167 893**



Upscaling to the Kingdom of Thailand

Production and environment

Regions	Aquaculture production	Primary production	Environmental externalities due to outflows		
			Ammonia	Chlorophyll *a*	PEQ
	$t\ y^{-1}$	$t\ N\ y^{-1}$	$t\ N\ y^{-1}$	$kg\ chl\ y^{-1}$	
Central	170 975	1 641	36	6 642	10 774
Eastern	41 143	395	9	1 598	2 593
Western	43 063	413	9	1 673	2 714
Southern	298 718	2 867	62	11 605	18 824
Total	**553 899**	**5 316**	**115**	**21 518**	**34 904**

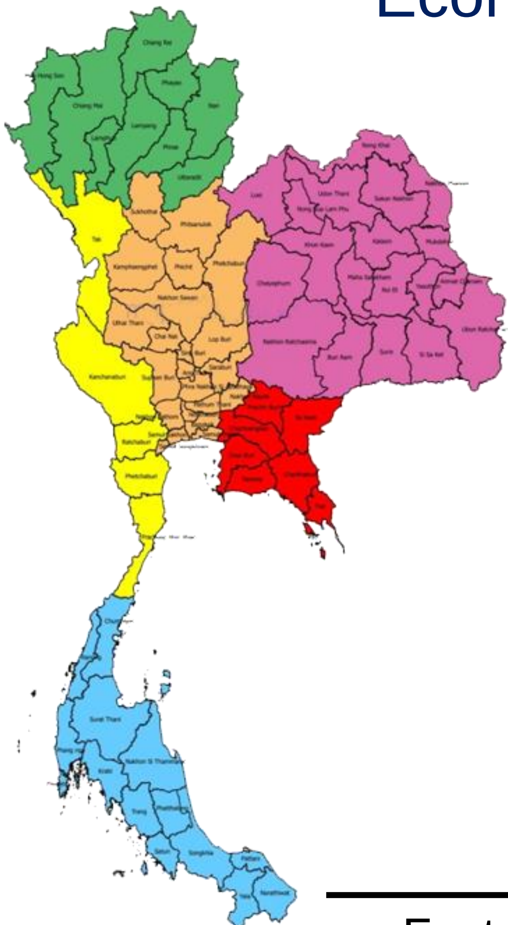
Fate of nutrients and chlorophyll

- Part of the water is stocked in other ponds for natural water quality improvement and then re-used in aquaculture;
- Part of the water is used in agri-aqua, e.g. rice cultivation;
- Some water is drained into rivers and canals.

Thailand has a tight coupling between agriculture and aquaculture, so much of the waste is recycled either within the aqua-system or in agriculture.

Upscaling to the Kingdom of Thailand

Economic analysis for Nile tilapia



Direct economic indicators

	Millions USD
Total revenue	253.27
Total expenditure	187.98
Labour income for 500 000 people	10.40 (5.5%)
Direct job creation	400,000-650,000

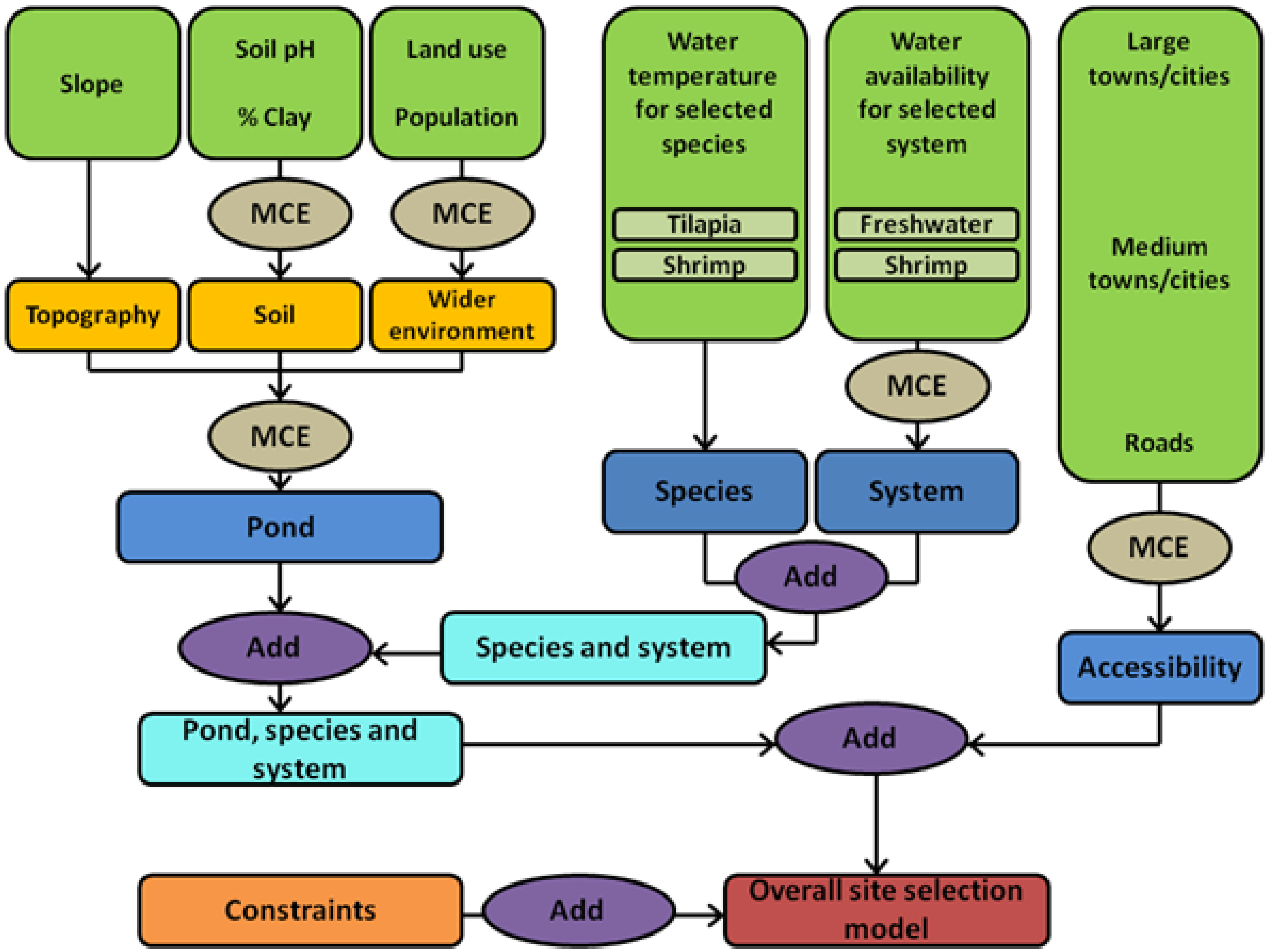
Indirect/induced economic impacts

	Value added to revenue	Jobs created from revenue	Costs of internalization
Factors	VAD ratio: 0.38	64 per million USD	10^6 USD
Value	96.24 M USD	16 209	21.1

Economic data from Thailand, based on DOF and FAO.

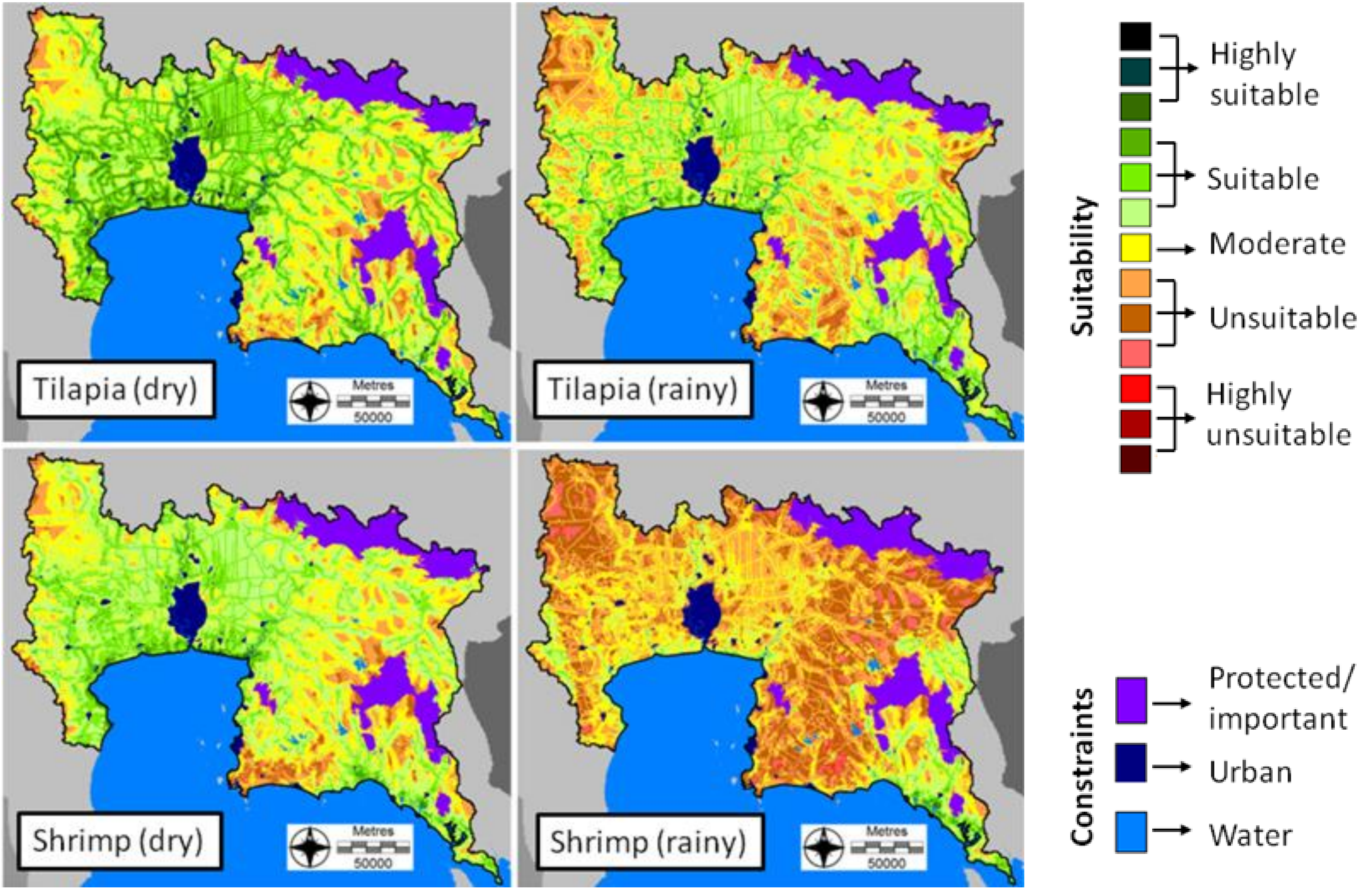
Cost of negative externalities assuming 1/3 of PEQ = 6% of production income.

Structure of site suitability model



MCE based on slope, pH, land use, water temperature, water availability, towns and roads.

Site suitability analysis for pond culture in Thailand



MCE based on slope, pH, land use, water temperature, water availability, towns and roads.

Synthesis

- Models such as FARM are valuable for analysis of environmental effects and different culture scenarios;
- IMTA of tilapia with shrimp helps reduce some negative externalities of shrimp culture, but adds to others;
- Chlorophyll outflow from shrimp farming is forty times greater than from tilapia cultivation;
- Dynamic modelling can be combined with spatial data to provide global estimates of production and environmental effects—this allows a more integrated economic valuation;
- In tilapia monoculture, nitrogen emissions equate to 170,000 PEQ, but a substantial part is recycled in agri-aqua;
- Estimated gross profit from tilapia is about 65 million USD per year;
- The potential total cost of reducing externalities (20.1×10^6 USD) would lower profit by at least one third.

http://ecowin.org/sima

Course synthesis

- We have reviewed a wide range of ecological modelling techniques, from simple to complex
- You have learnt how models can contribute to ecosystem management, with an emphasis on aquatic systems
- Many of the concepts (use of nutrients, primary production, predator-prey, animal physiology etc) apply equally well in freshwater and even terrestrial ecosystems
- You have developed models and demonstrated an understanding of the different components of a model and their interactions
- You've understood the relevance of reading SCI papers to inform your work
- Hopefully, you've had some fun along the way

All slides

http://ecowin.org/sima