Sistemas de Informação e Modelação em Ambiente

http://ecowin.org/sima

Models for aquaculture production
and environmental effects

J. Gomes Ferreira

http://ecowin.org/

Universidade Nova de Lisboa

17 de Maio, 2019

Models for aquaculture production and environmental effects

Lecture overview

Part I – World outlook and perspectives
60 m lecture

Part 2 – Individual models
15 m introductory lecture + 120 m modelling workshop

Part 3 – Population models
15 m lecture

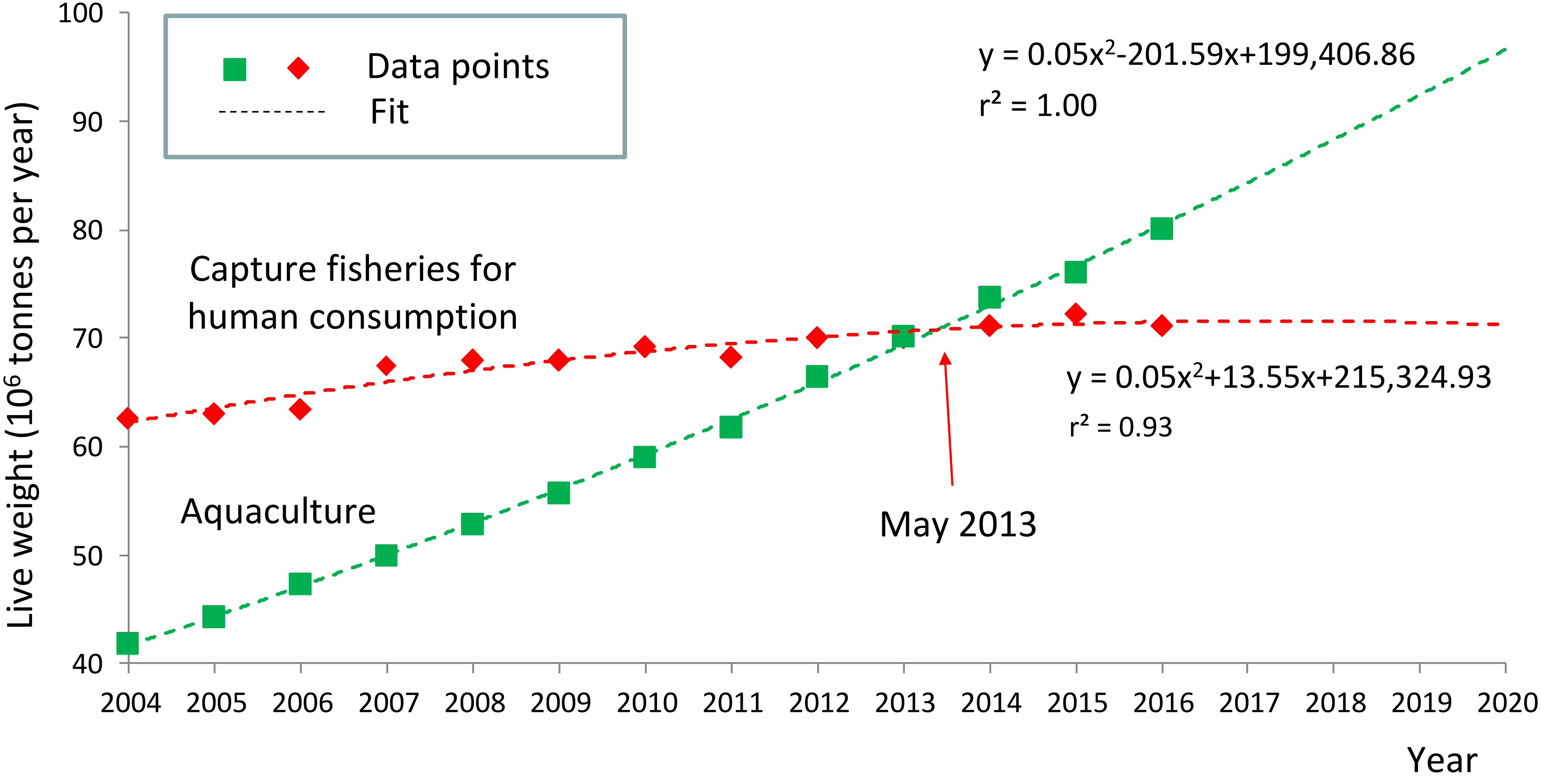
Models for aquaculture production and environmental effects

Lecture topics

Part I – World outlook and perspectives

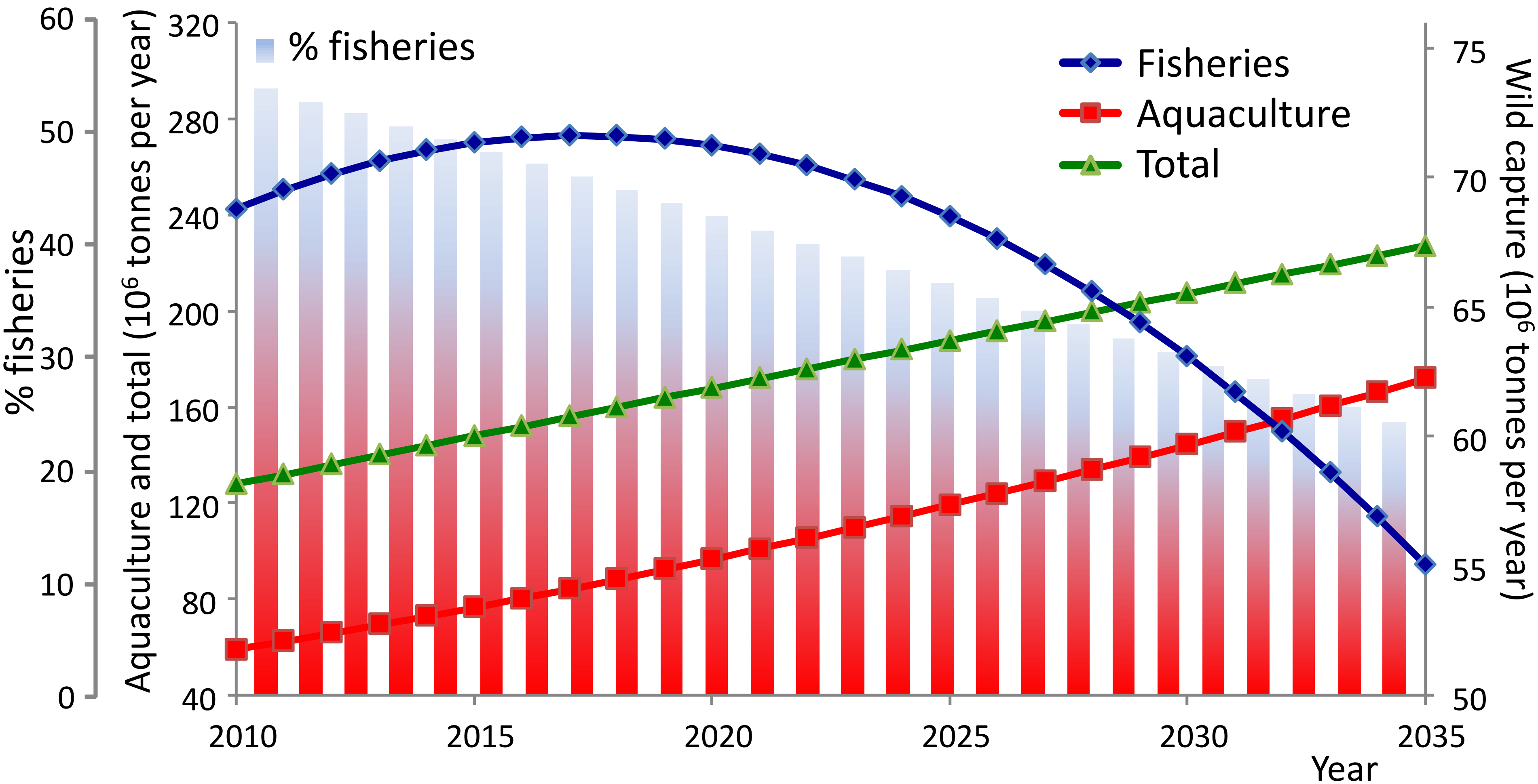
- World supply and demand
- Species, nations, and trade
- Aquaculture, the blue revolution?
- Carrying capacity and site selection
- Eutrophication and aquaculture
- Summary

Trends in fisheries and aquaculture – SOFIA 2018



Equivalent to the emergence of agriculture 10,000 years ago in the Neolithic period.

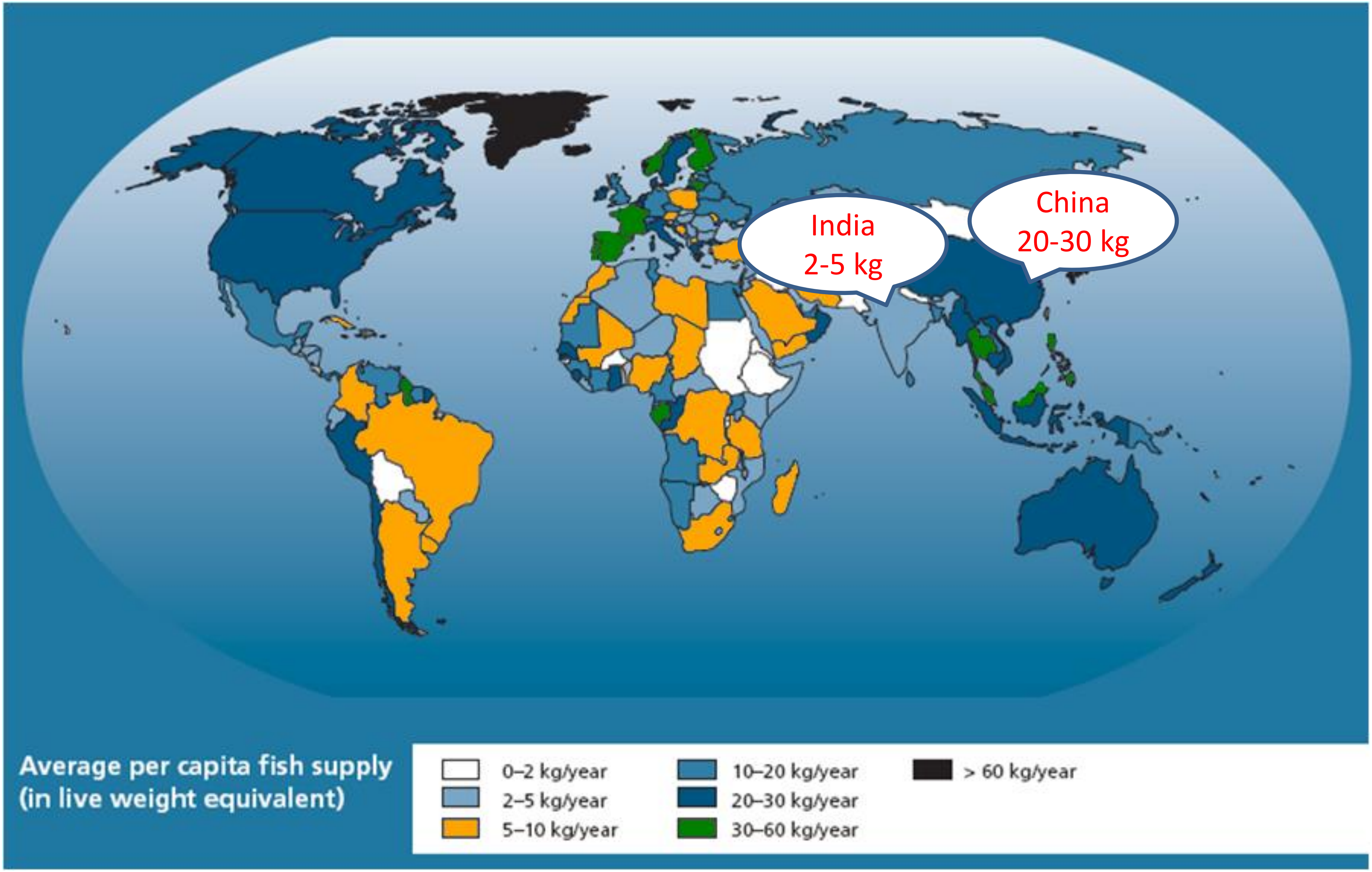
Trends in fisheries and aquaculture : 2010-2035



For projected APR growth in aquaculture and fisheries, 160 million tonnes in Sept 2018.

Fish as a food

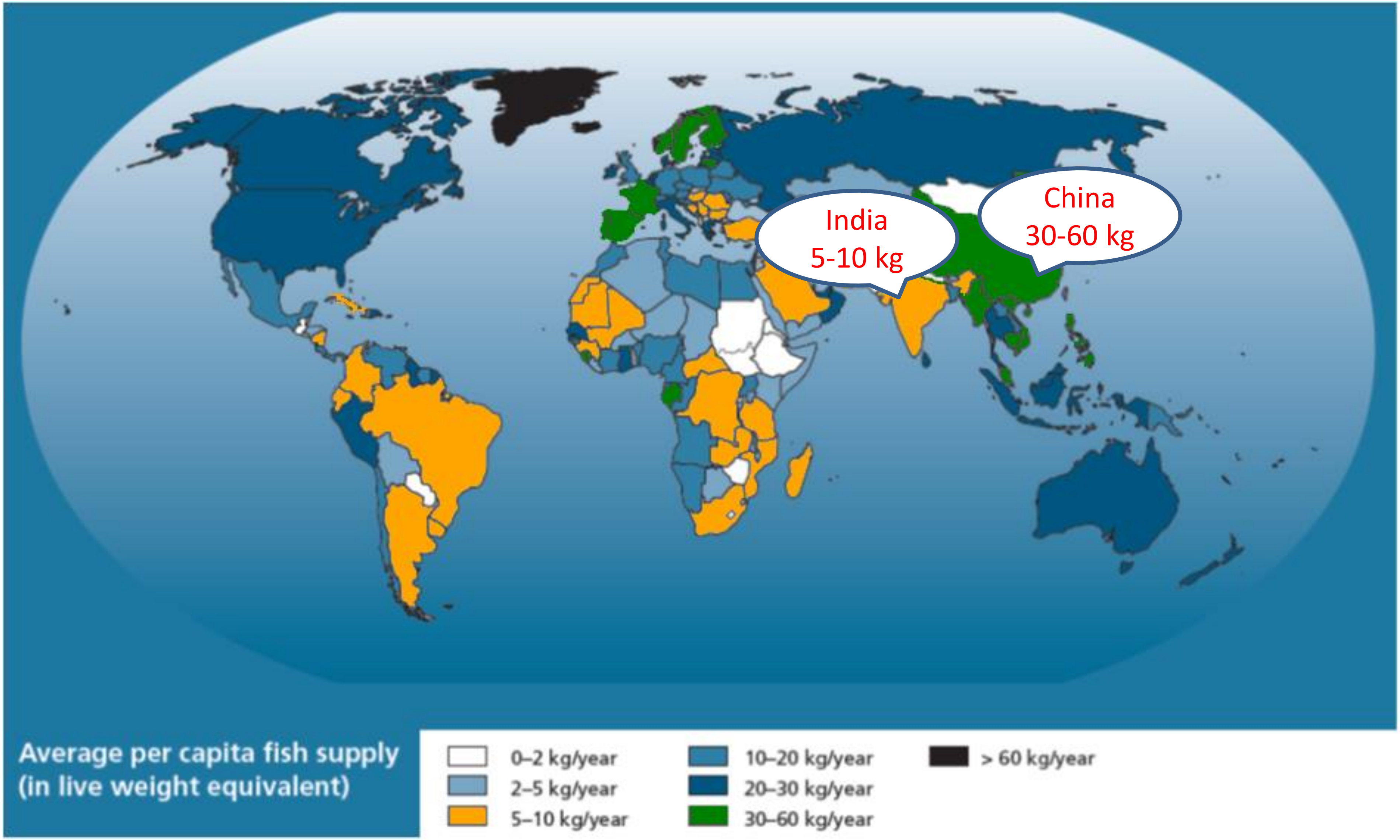
World per capita supply (average 2003-2005)



FAO, 2009. The State of World Fisheries and Aquaculture (SOFIA). Food and Agriculture Organization of the U.N.

Fish as a food

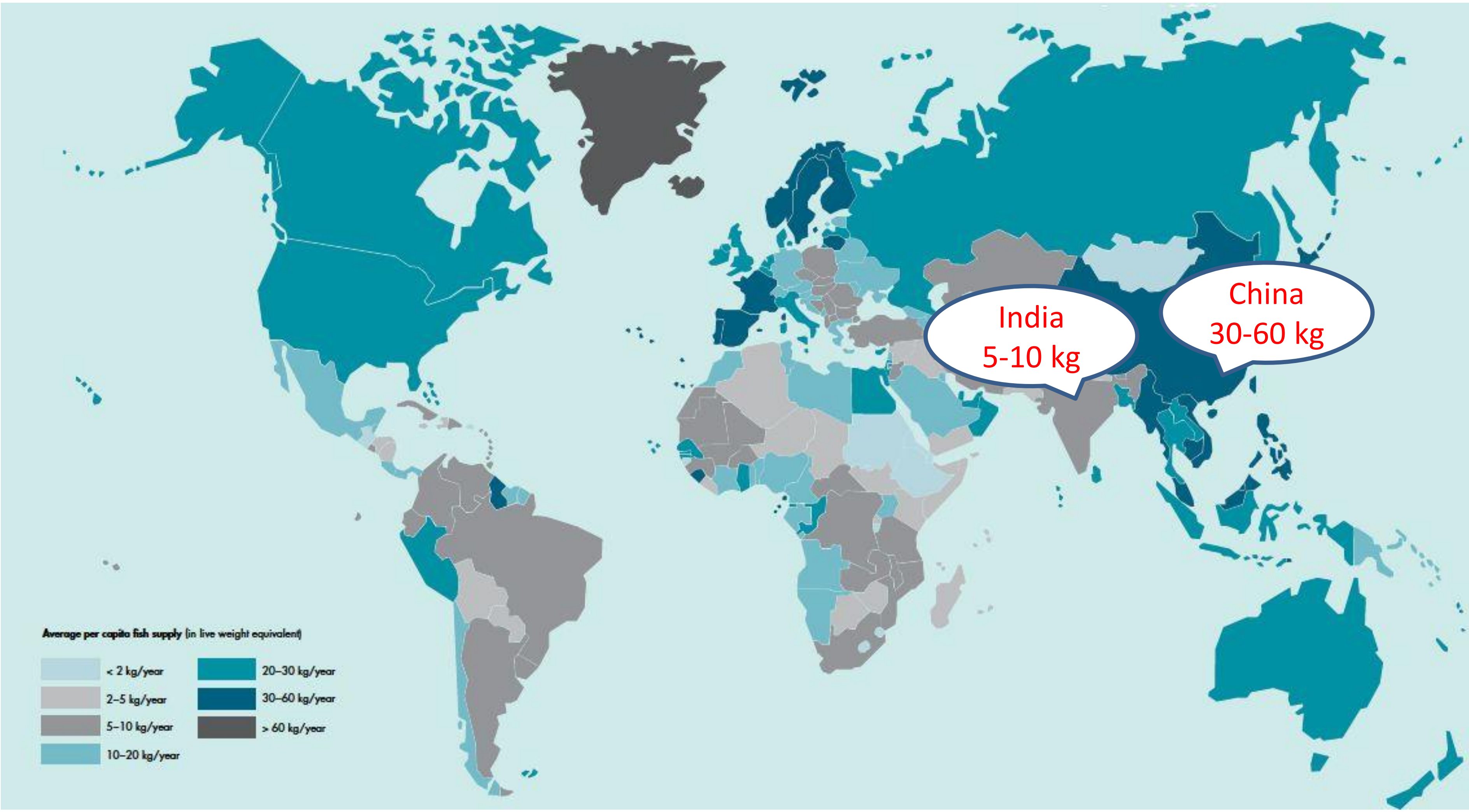
World per capita supply (average 2008-2010)



FAO, 2014. The State of World Fisheries and Aquaculture (SOFIA). Food and Agriculture Organization of the U.N.

Fish as a food

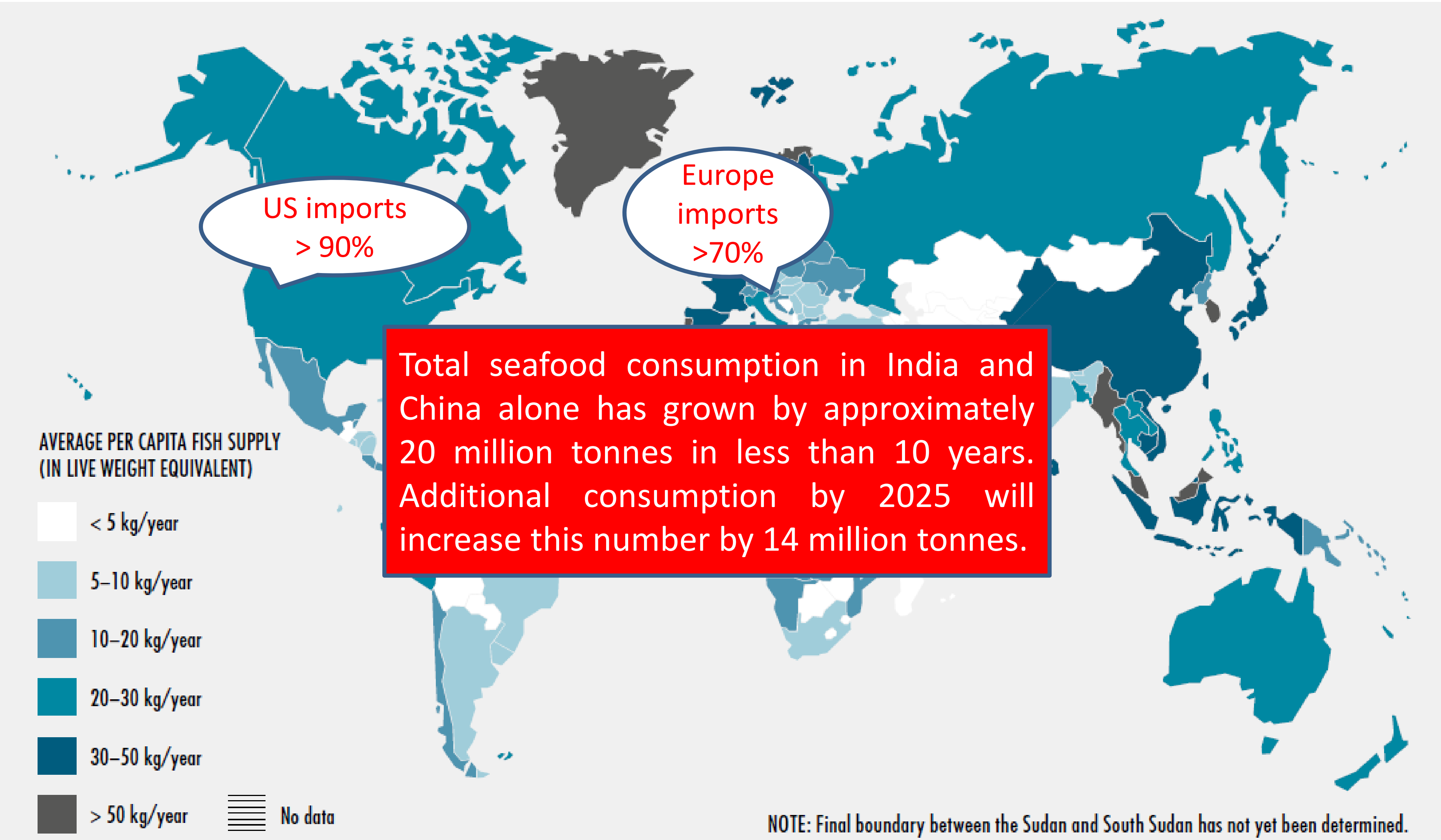
World per capita supply (average 2011-2013)



FAO, 2016. The State of World Fisheries and Aquaculture (SOFIA). Food and Agriculture Organization of the U.N.

Fish as a food

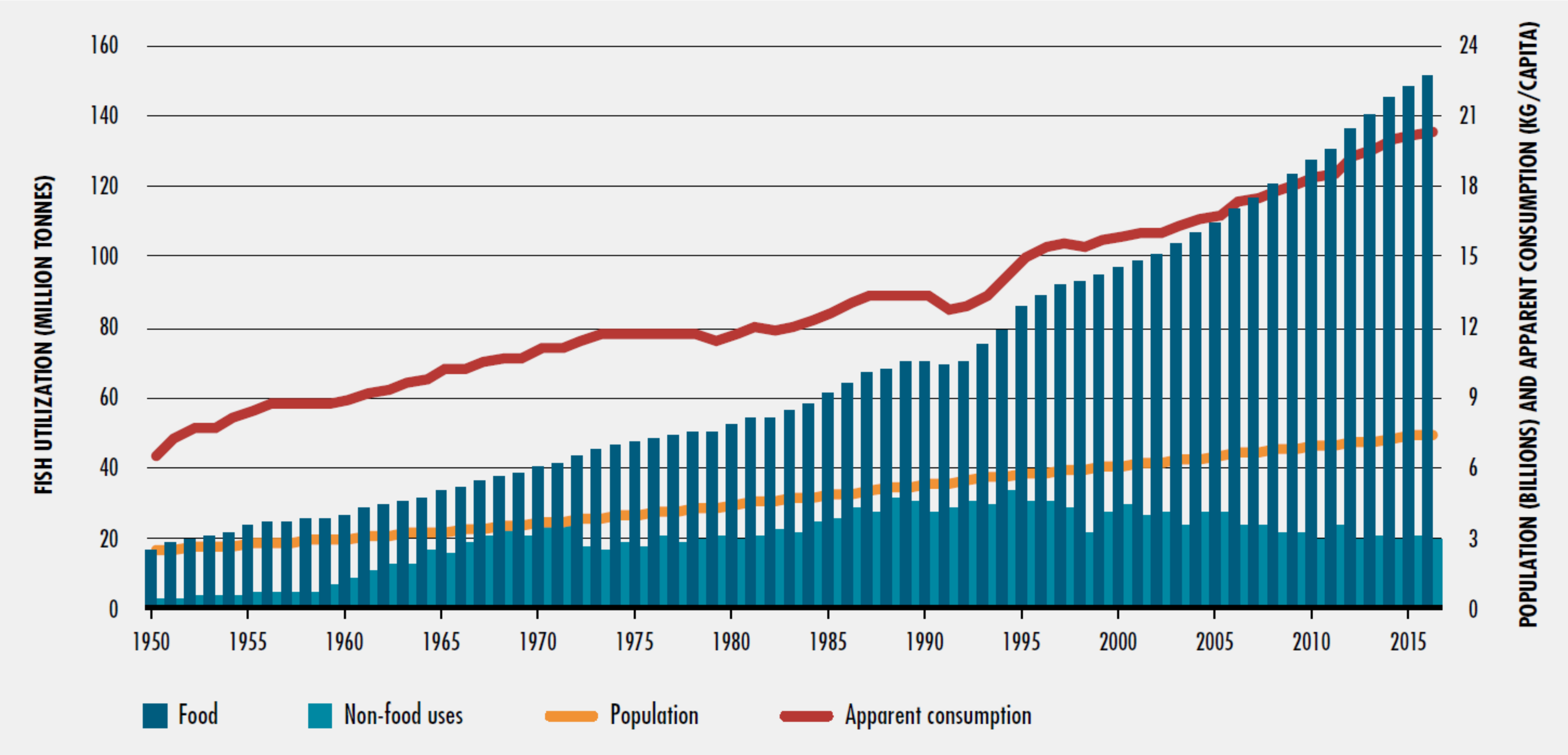
World per capita supply (average 2013-2015)



Total seafood consumption in India and China alone has grown by approximately 20 million tonnes in less than 10 years. Additional consumption by 2025 will increase this number by 14 million tonnes.

FAO, 2018. The State of World Fisheries and Aquaculture (SOFIA). Food and Agriculture Organization of the U.N.

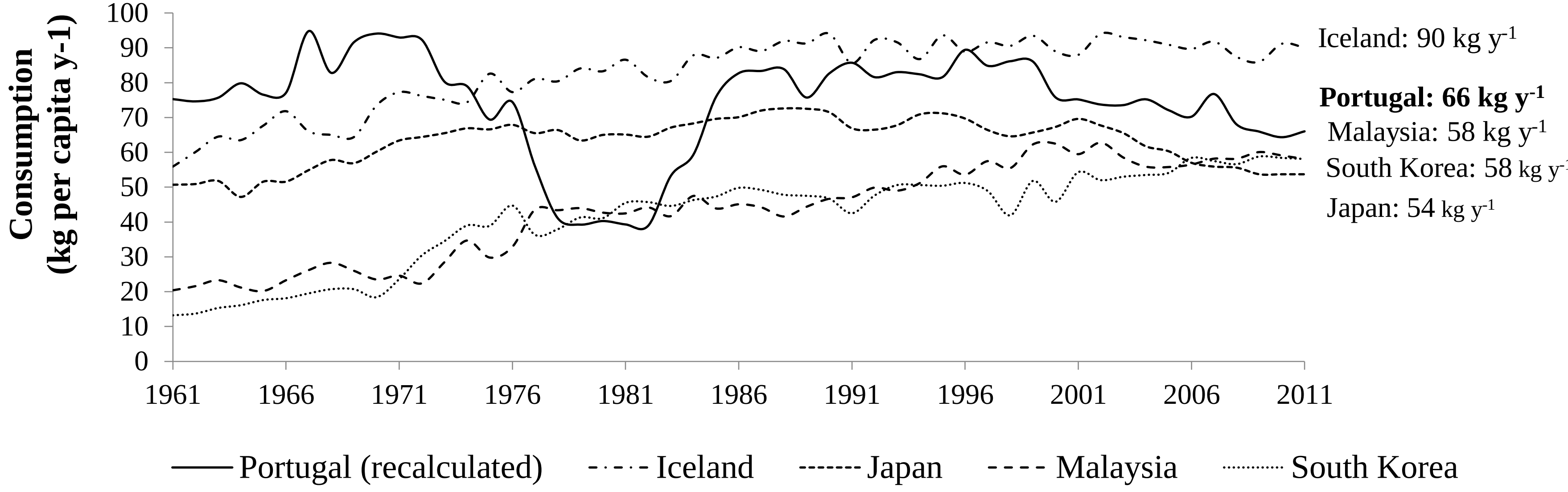
The state of world fisheries and aquaculture SOFIA 2018 (FAO)



FAO, 2018. The State of World Fisheries and Aquaculture (SOFIA). Food and Agriculture Organization of the U.N.

Balance of supply and demand. Non-food uses continue to decrease.

Improvements to production estimates

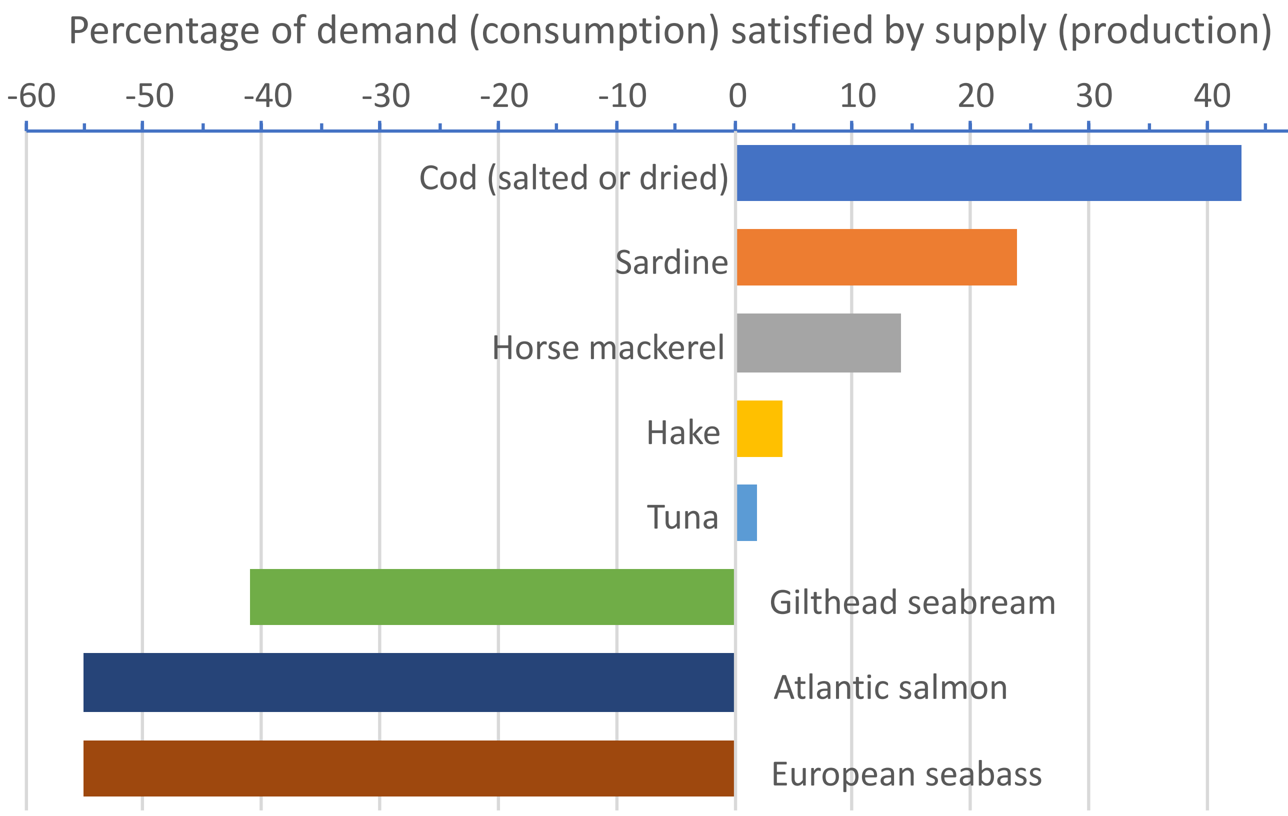


Countries with the highest *per capita* seafood consumption. Weight for Portugal is displayed using the corrected live weight for cod products.

Processing of aquatic products has an impact in *per capita* consumption volumes. In this case study, consumption in Portugal increases by 16%, from 57 kg to 66 kg per capita

Processing of seafood products has an impact on seafood consumption estimates.

Mass balance estimates for supply and demand Data for Portugal



Farmed products display the highest discrepancies, which can indicate an underestimation of production data. The opposite occurs for wild-caught species, which can indicate an oversupply.

Aquaculture in Europe

Sustainability and legislation

Environmental, legal, and social pressures

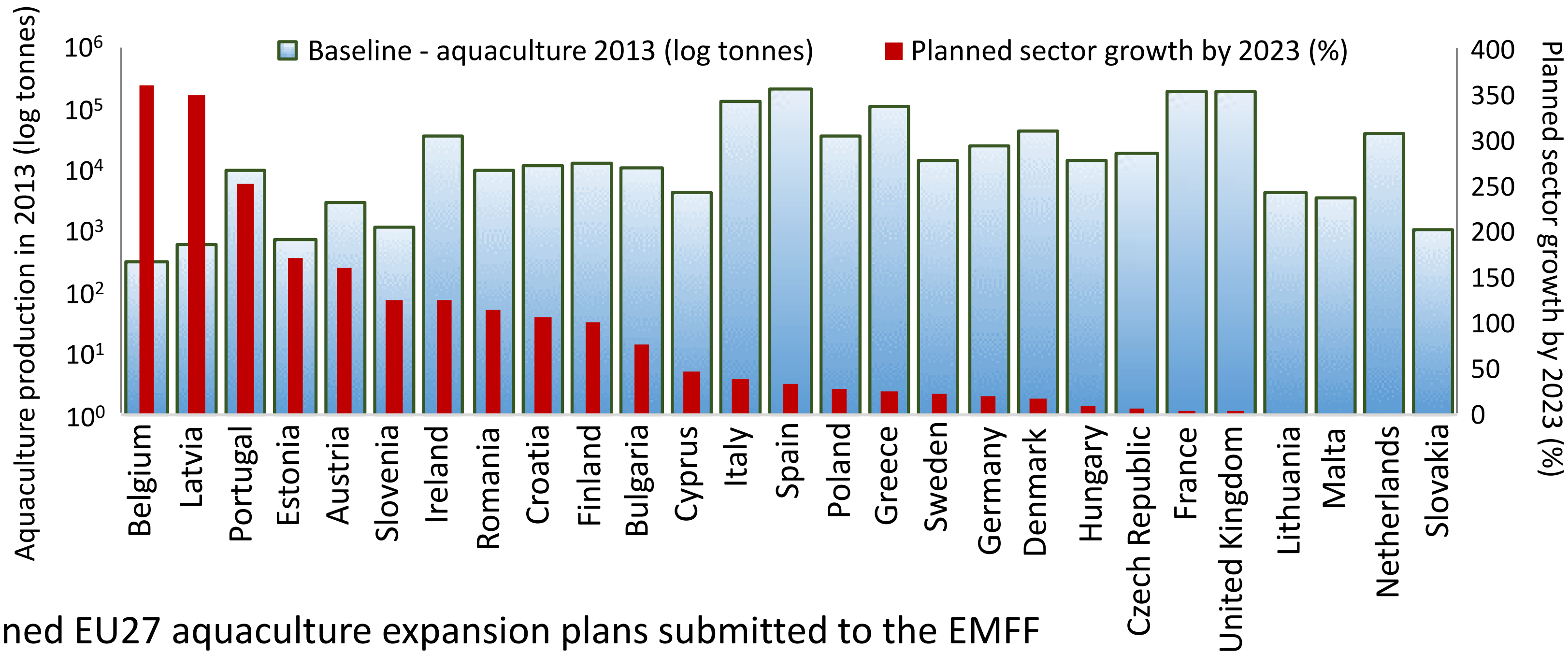
- Aquaculture is the most heavily regulated food production sector in Europe (Varadi, 2010)
- Competition for space, access to capital, availability of special services, limited authorised veterinary products (Varadi, 2010)
- Water Framework Directive (2000/60/EC) – no reference to aquaculture. Benthic biodiversity, fish (in transitional waters); Good Ecological Status in Europe by 2015
- Marine Strategy Framework Directive (2008/56/EC) – Fish and Shellfish Quality Descriptor (QD3). Aquaculture is seen only as a pressure. Good Environmental Status by 2020
- Many other parts of the world don't come close to the EU regulatory panorama

In all likelihood Europe will add value over volume.

Aquaculture production in Europe (2017)

Data from Eurostat obtained using web services.

Aquaculture plans for European countries



Planned EU27 aquaculture expansion plans submitted to the EMFF

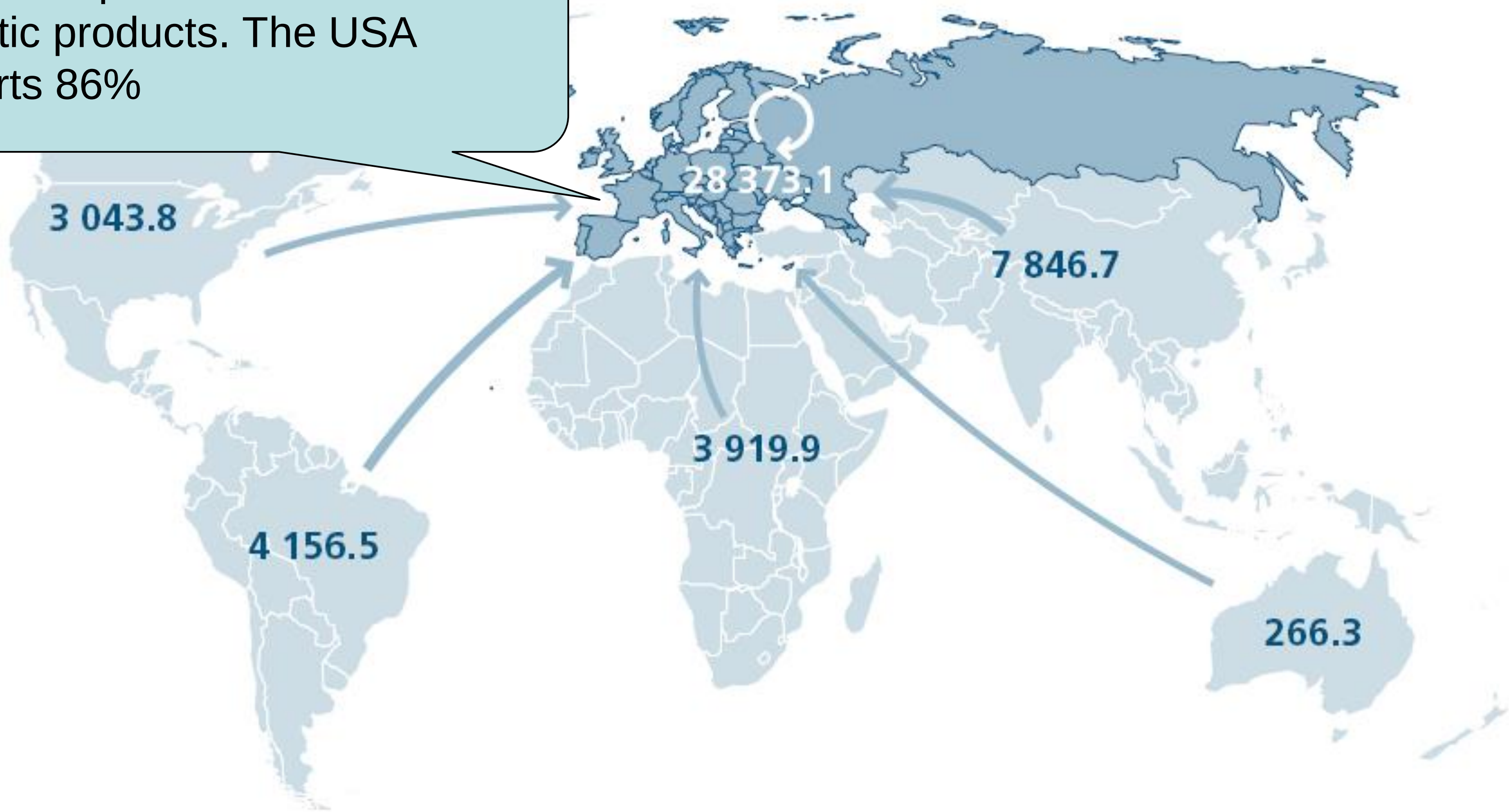
EU farmed seafood production is planned to grow by 23% between 2013 and 2023. Despite this, national plans lack information on areas such as environmental issues, species to be cultivated, as well as regulatory and business factors.

Sustainable sector growth requires adequate planning for environmental, market, and regulatory issues. It also requires integration with fisheries policy.

Imports to Europe

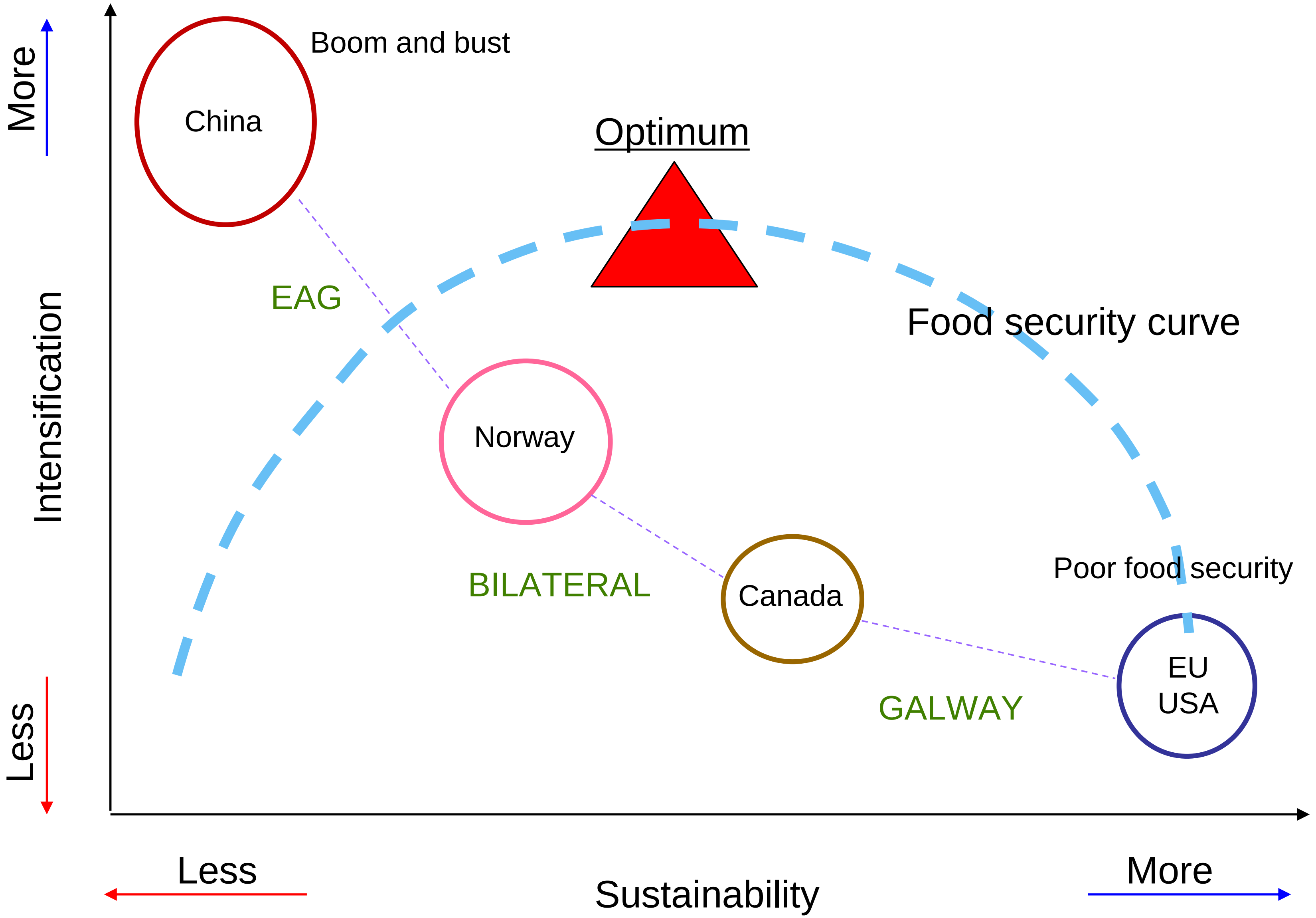
All numbers in millions of USD (SOFIA 2012)

Europe imports 74% of its aquatic products. The USA imports 86%



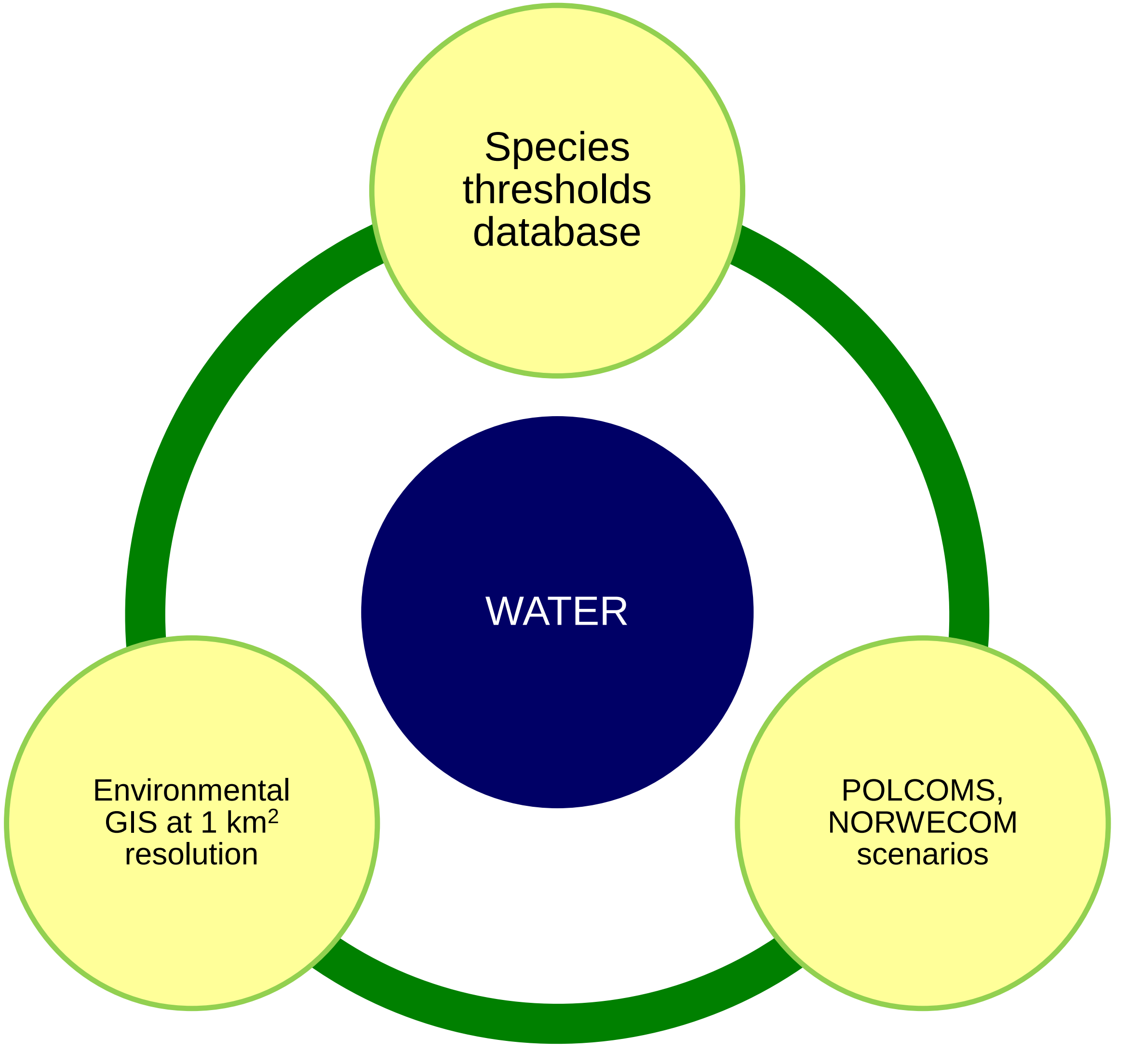
If European consumption was at the level of Portugal (57.4 kg y^{-1} per capita) an extra 27 million tonnes of fish products would be required annually.

Eco-intensification and world aquaculture



China, 2015: 1.3 X 10^6 t y^{-1} of marine finfish and 15.7 X 10^6 t y^{-1} of freshwater fish. Norway produces 1.4 X 10^6 t y^{-1} of marine fish.

WATER – Where can Aquaculture Thrive in Europe
Online Aquaculture-Environment platform



WATER uses current speed, temperature, chlorophyll, and oxygen, together with depth, significant wave height, distance to port, etc.

Maritime and Environmental Thresholds for Aquaculture (META)

META Home Search List References AquaStats About Contact

List.

List META thresholds.

Choose the species you want to grow, then hit search to see all the environmental thresholds that apply.

Select species

Atlantic salmon

Find thresholds

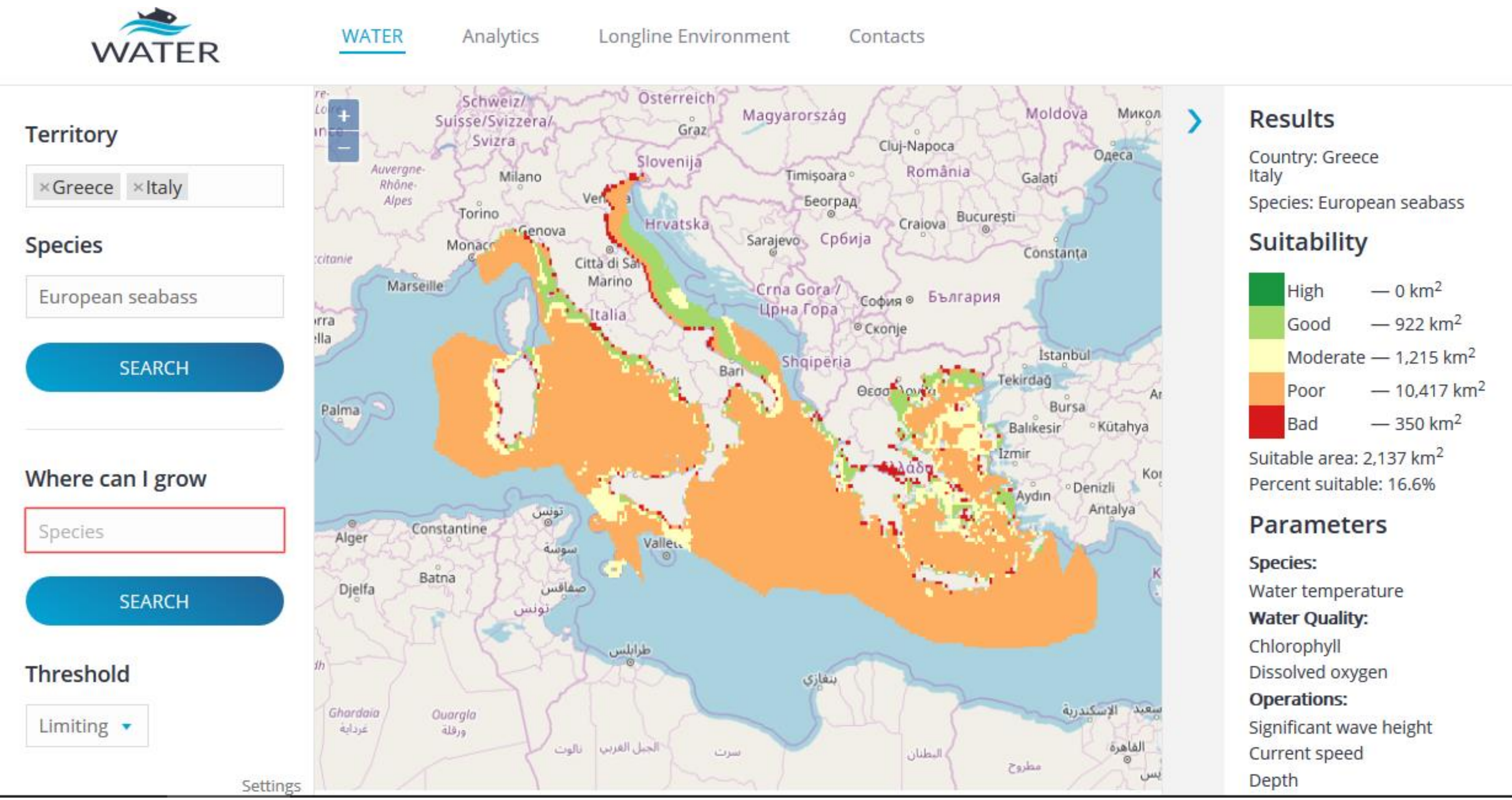
Genus	Species	English (UK)	English (US)	French	Spanish	Italian	Portuguese	Mandarin
Salmo	salar	Atlantic salmon	Atlantic salmon	Saumon Atlantique	Salmón del Atlántico	Salmone atlantico	Salmão do Atlântico	大西洋鲑

The table below lists 11 environmental thresholds for Atlantic salmon

Parameter	Units	Low threshold	High threshold	Optimal low	Optimal high	Aquaculture low	Aquaculture high
Water temperature	oC	2	22	10	16	N/A	N/A
Salinity	psu	0	35	8	28	N/A	N/A
pH		5	9	6.5	8.5	N/A	N/A
Total Ammonia Nitrogen (TAN)	mg L-1	0	N/A	N/A	2	N/A	N/A
Ammonia	mg L-1	0	0.28	N/A	0.035	N/A	N/A
Nitrite	mg L-1	0	0.6	N/A	0.06	N/A	N/A
Nitrate	mg L-1	0	300	N/A	100	N/A	N/A
Dissolved oxygen	mg L-1	5	13	9	11	N/A	N/A
Suspended solids	mg L-1	N/A	75	N/A	10	N/A	N/A
Carbon dioxide	mg L-1	7	20	N/A	N/A	N/A	N/A
Cultivation depth	m	0	210	N/A	N/A	N/A	N/A

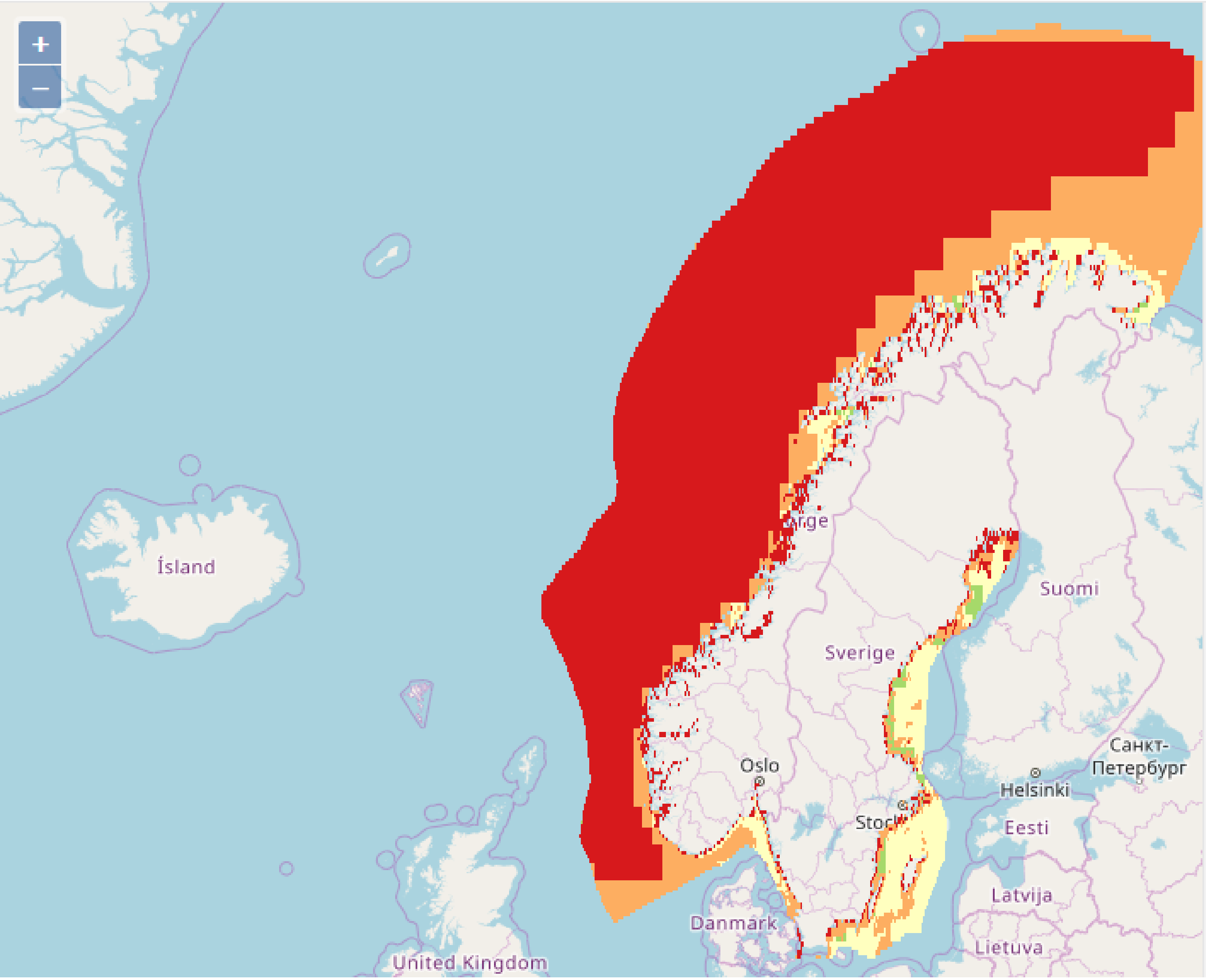
A web-driven database makes it easy to retrieve species thresholds. META includes 47 cultivated species.

WATER – Seabass in the Italian and Greek EEZ



WATER allows a choice of thresholds (optimal or limiting) based on the META database. This output is for limiting conditions.

WATER – Rainbow trout in the Swedish and Norwegian EEZ



Results

Country: Norway
Sweden

Species: Rainbow trout

Suitability

High	—	0 km^2
Good	—	217 km^2
Moderate	—	2,323 km^2
Poor	—	5,259 km^2
Bad	—	19,649 km^2

Suitable area: 2,540 km^2

Percent suitable: 9.3%

Parameters

Species:

Water temperature

Water Quality:

Chlorophyll

Dissolved oxygen

Operations:

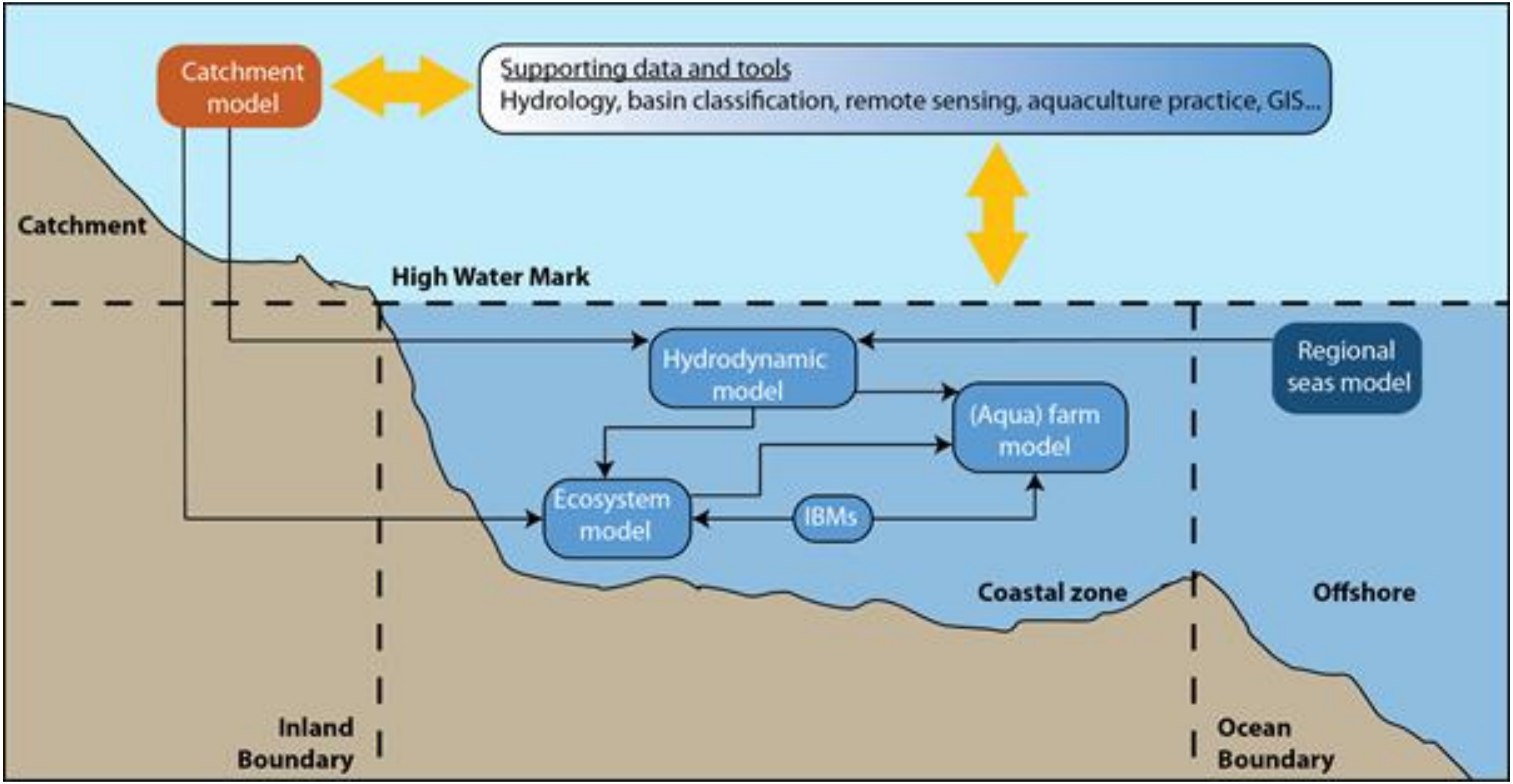
Significant wave height

Current speed

Depth

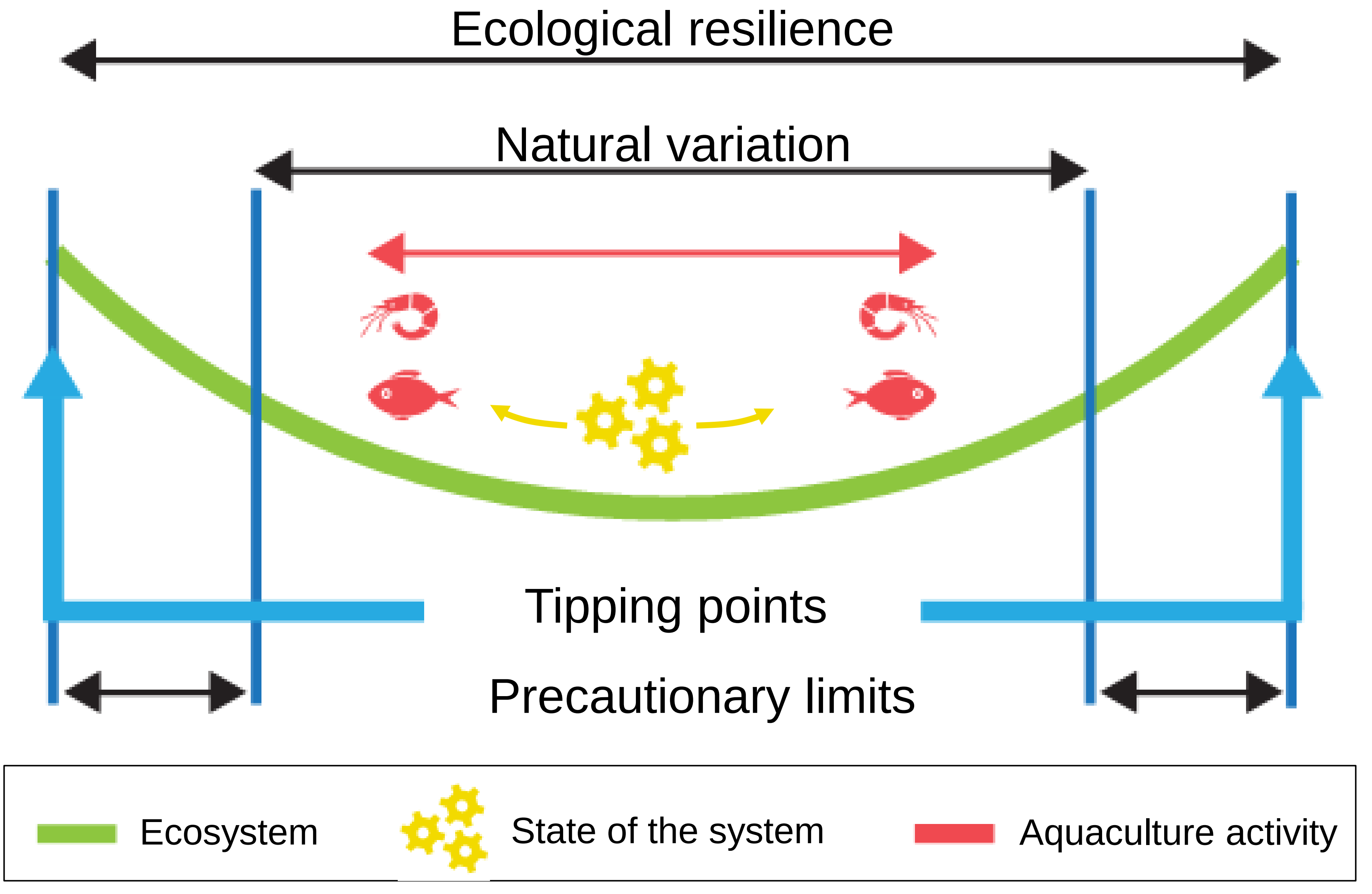
This search uses the limits for suitability, rather than optimal values. This provides a broader area.

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.

Sustainability criteria: foundation in classical ecology



Filgueira et al., 2013. Aquaculture Environment Interactions 4, 117-133.

Chiangrai pond culture, Thailand

Tilapia*, Oreochromis niloticus*

Shrimp culture in open waters

Gulf of California, Sonora, Mexico

Almost all the world production of 3 million tonnes takes place in land-based ponds.

Integrated Multi-Trophic Aquaculture

Vancouver Island, Canada

Scallop lanterns as part of an IMTA setup that includes sablefish, kelp, and sea cucumbers.

Nori in Fujian, China - *Porphyra yezoensis*

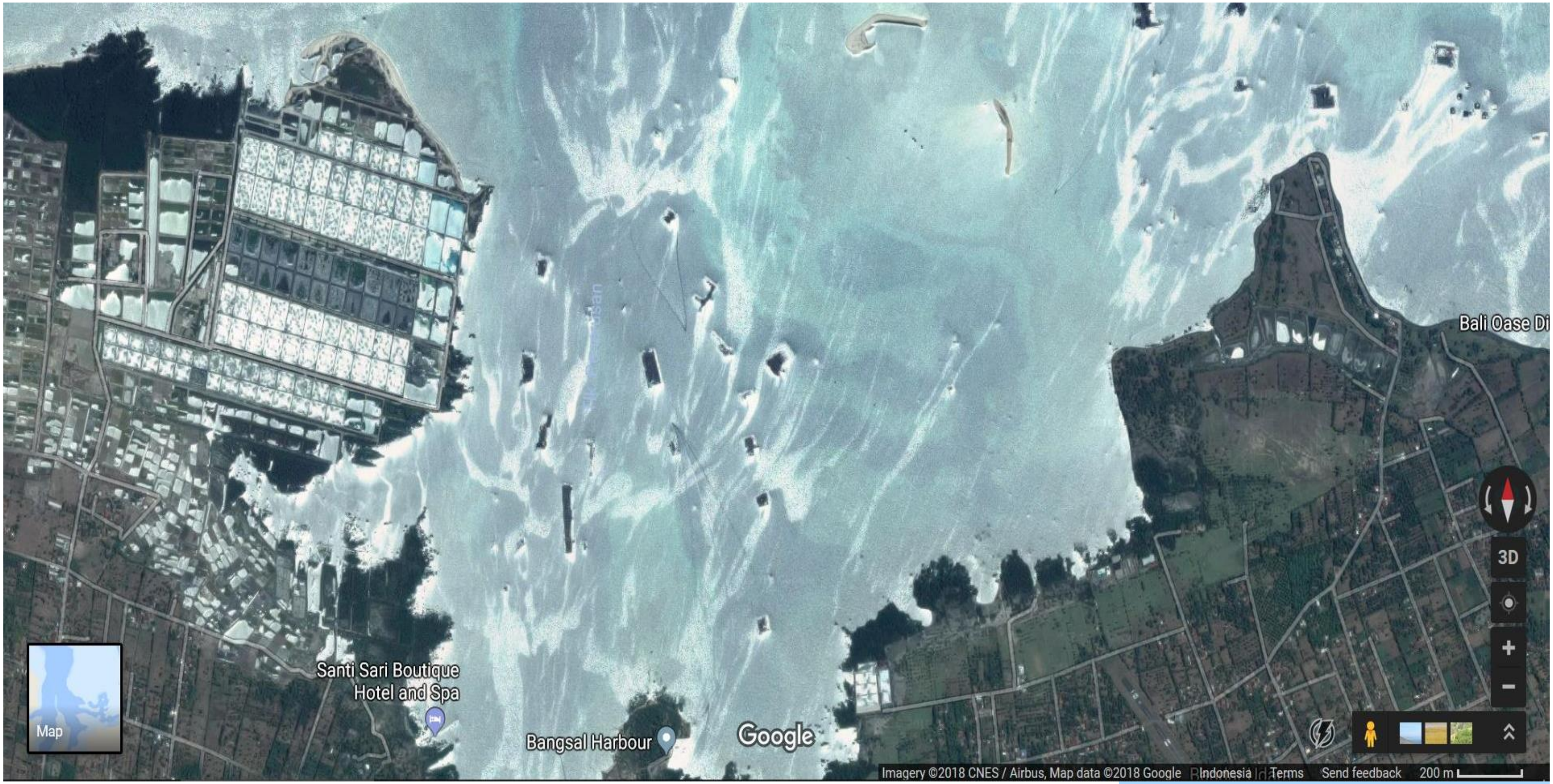
Worldwide production of 600,000 tonnes, feeds demand for Sushi.

Tilapia cage culture

Laguna de Bay, Philippines

Overstocking and slow water turnover can lead to excess organic material.

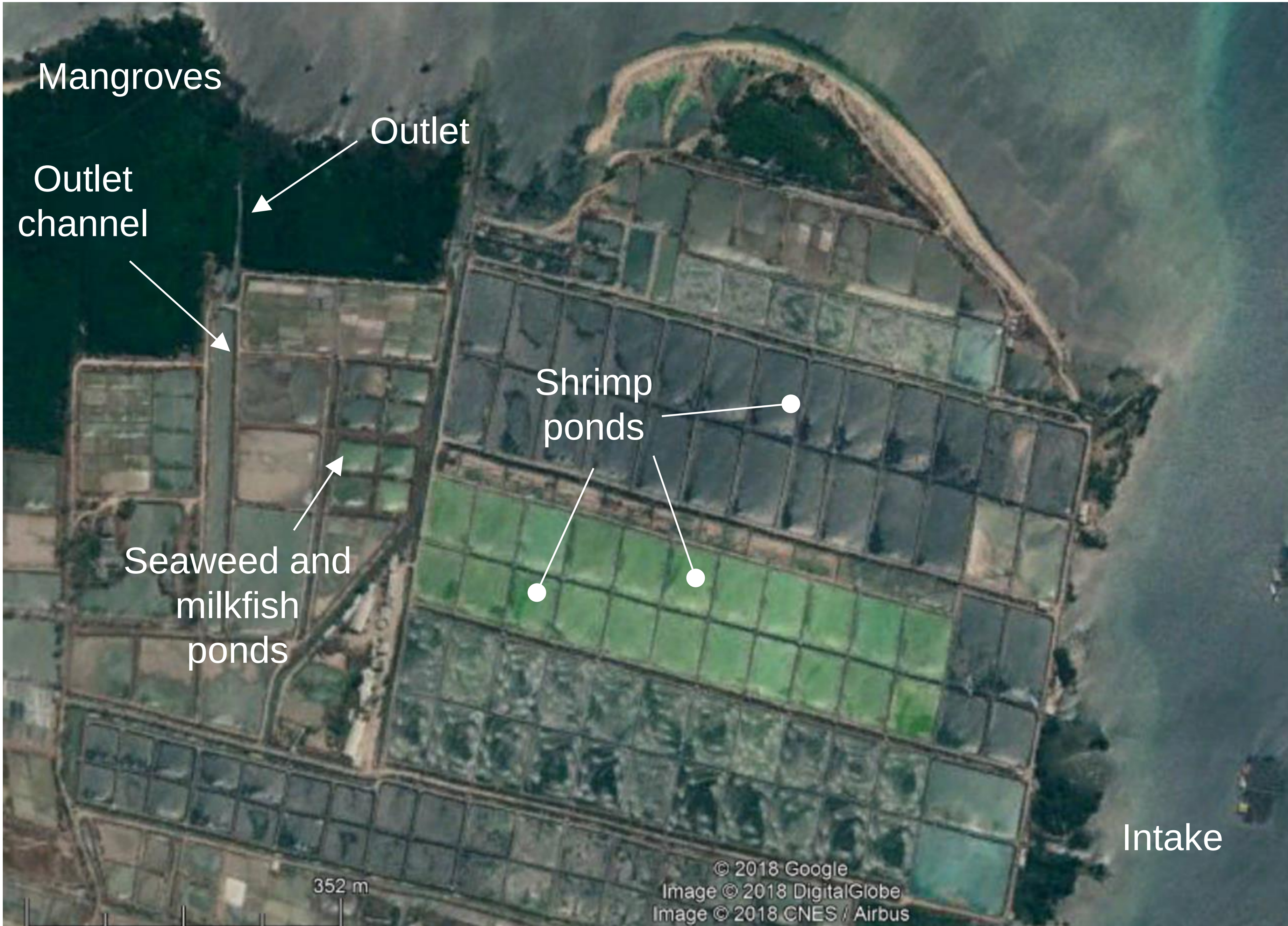
Aquaculture in developing countries
Study site in the Pemuteran region of north Bali



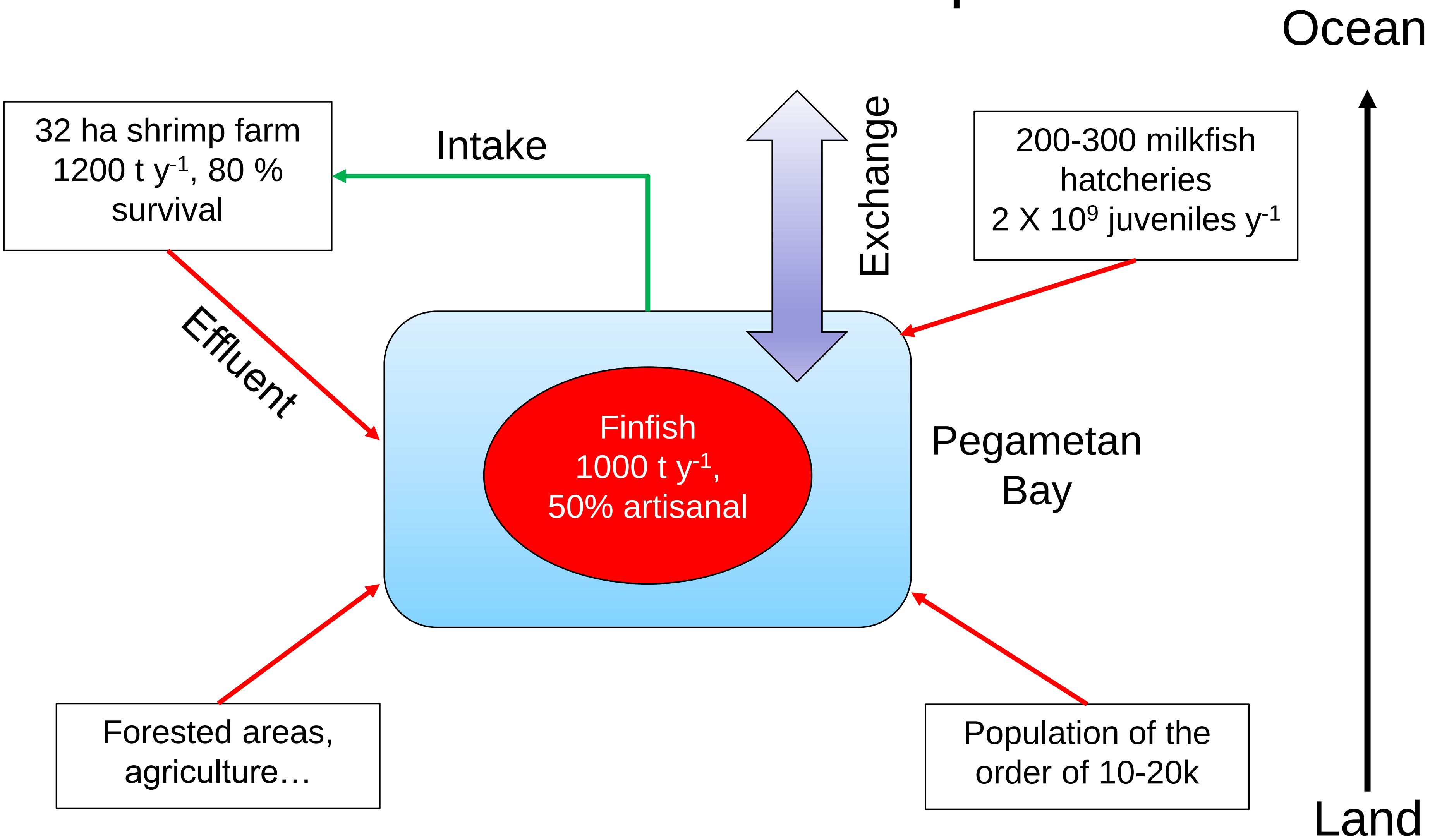
Bay: 10 km^2, (broader domain ~35 km^2); Max. depth: 20m

Pegametan Bay: one of two EcoShrimp project sites where system-scale carrying capacity is being modelled.

Shrimp culture – general farm layout

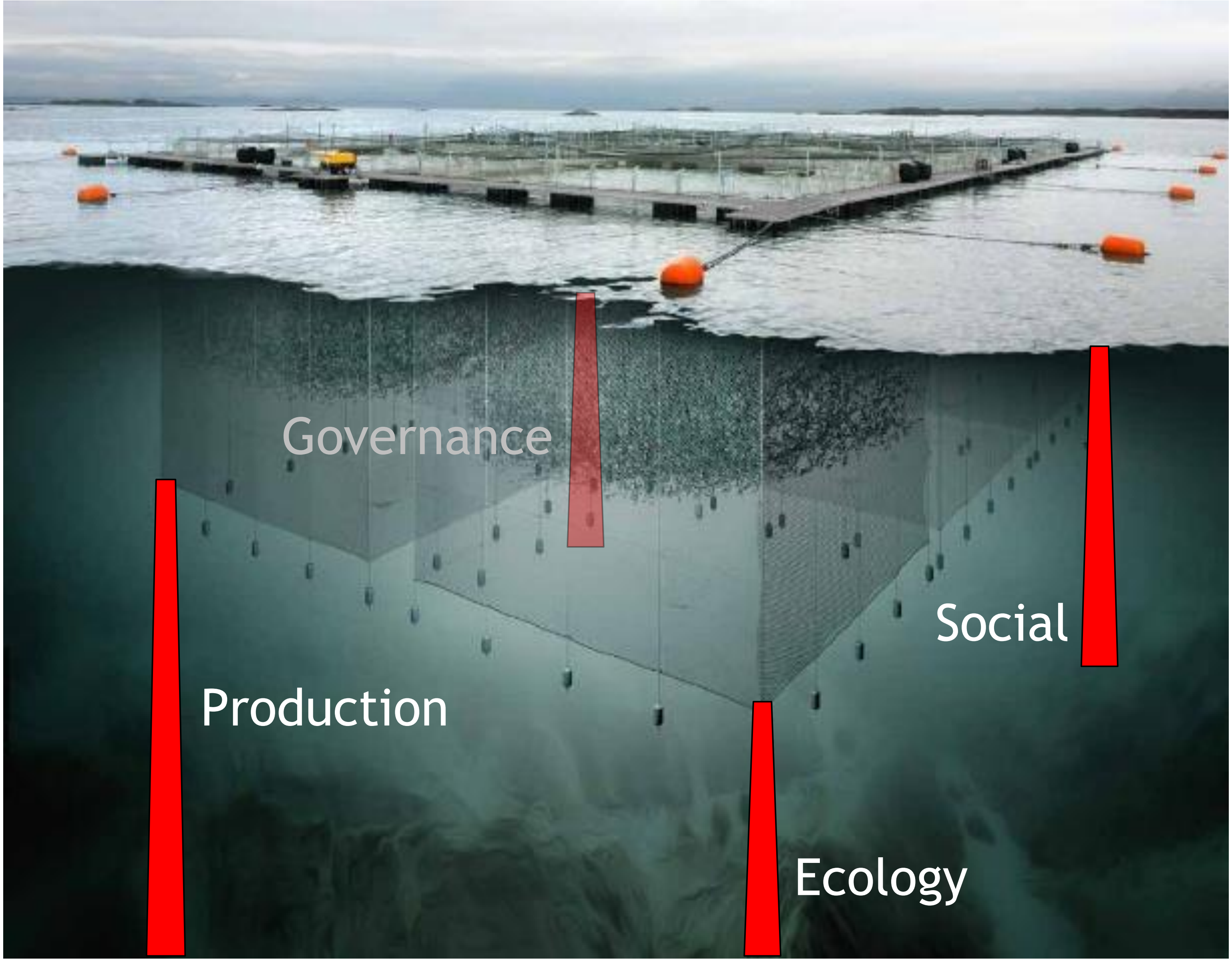


The back of the envelope...



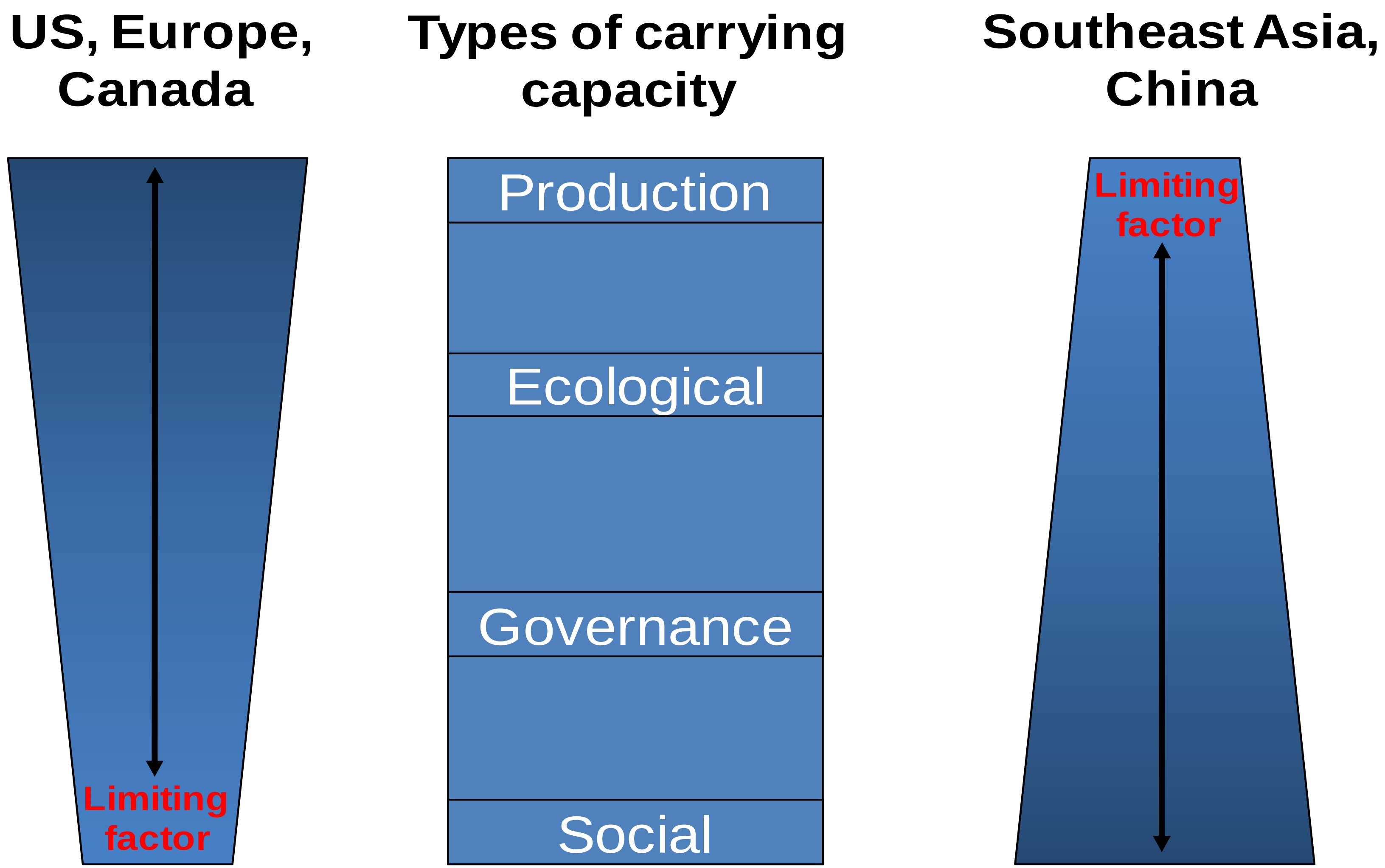
Pegametan Bay (north Bali) has a range of uses, is fringed by a coral reef, and requires an integrated management approach.

Carrying Capacity – a Multidimensional Problem



Four pillars for sustainable aquaculture. In the West, the social pillar is limiting.

Different types of carrying capacity for aquaculture



Different parts of the world see carrying capacity in very different ways.

Ecosystem Approach to Aquaculture (FAO)

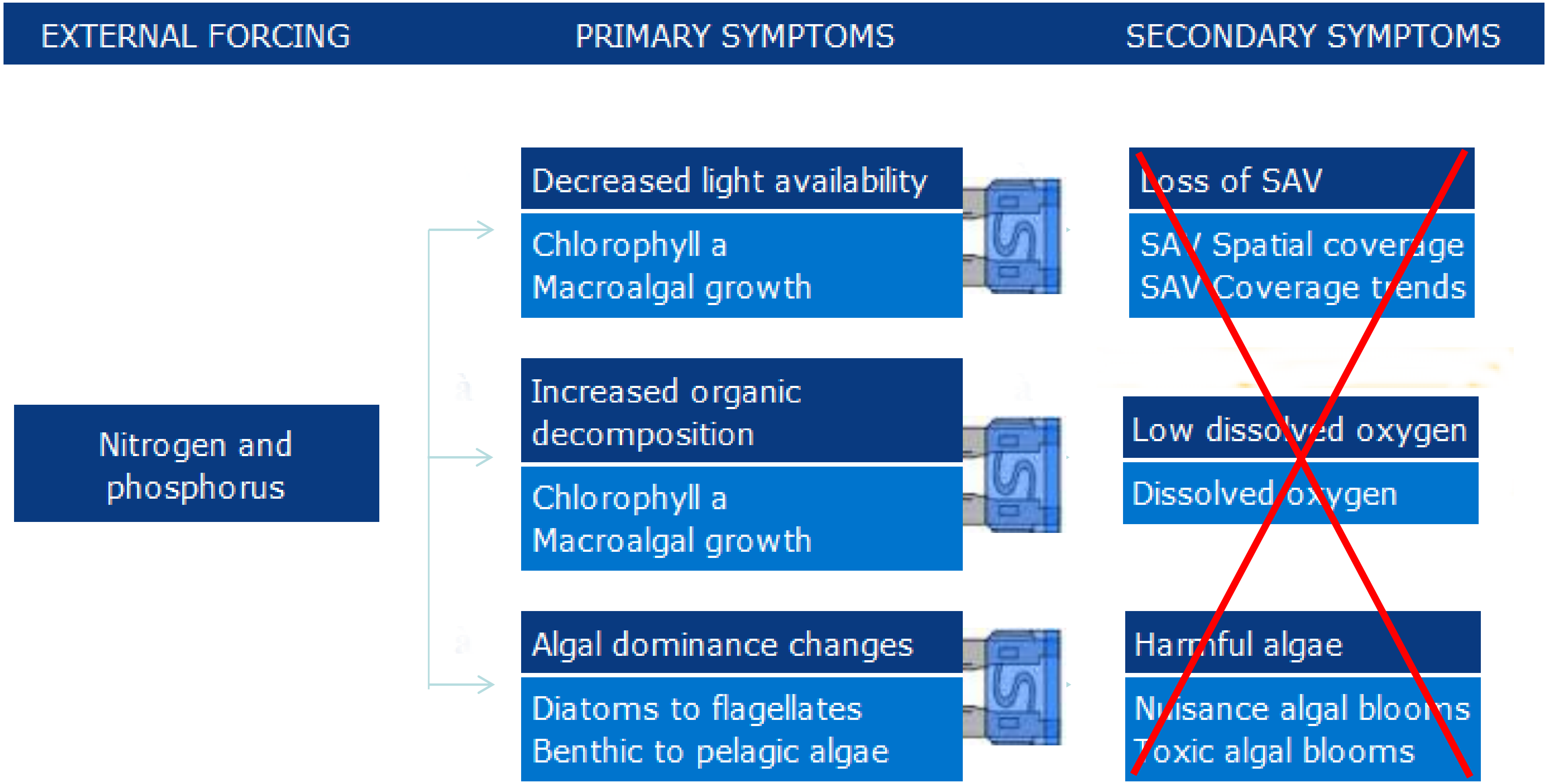
Three principles

- Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience;
- Aquaculture should improve human-well being and equity for all relevant stakeholders;
- Aquaculture should be developed in the context of other sectors, policies and goals.

Soto, 2010

EAA: ecosystem balance, social equity, multiple uses.

Conceptual model of eutrophication



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

Nitrogen loading and offsets for major areas of the world

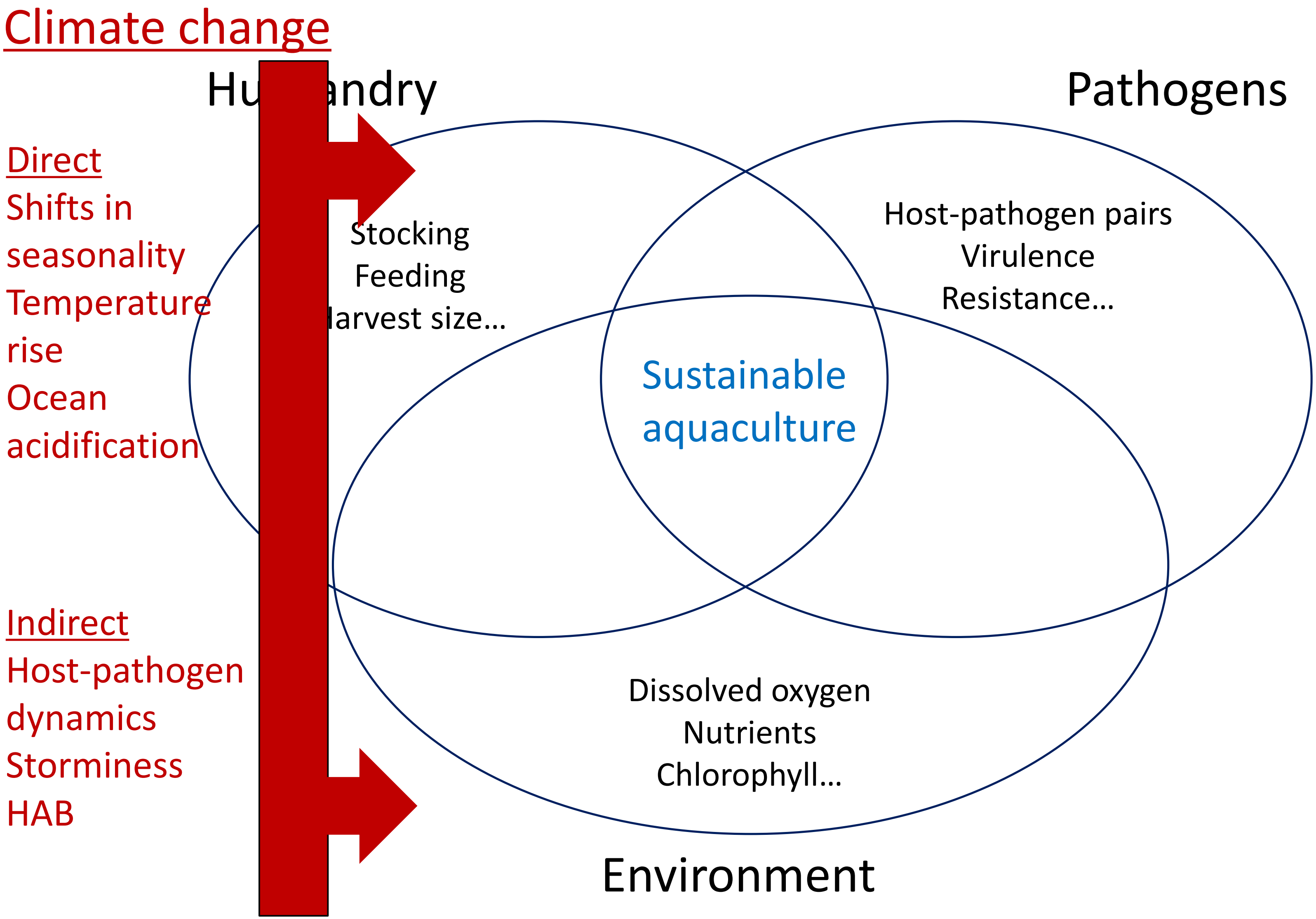
	Europe	USA	Canada	China	Total
Total N load (10^3 t N y^{-1})	4142.6	3514.0	733.3	2706.0	11095.9
Fed aquaculture N load (10^3 t N y^{-1})	68.8	0.9[*a]	3.3	32.8[*b]	105.8
Organic extractive N removal (10^3 t N y^{-1})	37.2	7.6	3.0	586.7	634.5
Proportion of total N load due to fed aquaculture (%)	1.7	0.02	0.5	1.2	
Proportion of fed aquaculture N load offset by bivalves (%)	54.1	870.2	89.6	1790.8	
Proportion of total N load offset by bivalves (%)	0.9	0.2	0.4	21.7	

[*a] – Only marine aquaculture, mainly salmonids; excludes 229 x 10^3 t live weight y^{-1} freshwater production, of which 67% are channel catfish.

[*b] – Only marine aquaculture; excludes 27,150 x 10^3 t live weight y^{-1} freshwater production, of which 49% are grass carp, silver carp, and bighead carp

EU shellfish culture offsets half of Norwegian finfish aquaculture;
US and China shellfish offsets greatly exceed finfish loads, but in both cases (on very different scales) there is a freshwater finfish input;
Chinese coastal shellfish culture offsets over 20% of the *total* N load.

Key factors for sustainable aquaculture



Multi-stressor analysis requires integrated models. ABC (Aquaculture, Biosecurity, and Carrying Capacity) was developed to address these issues.

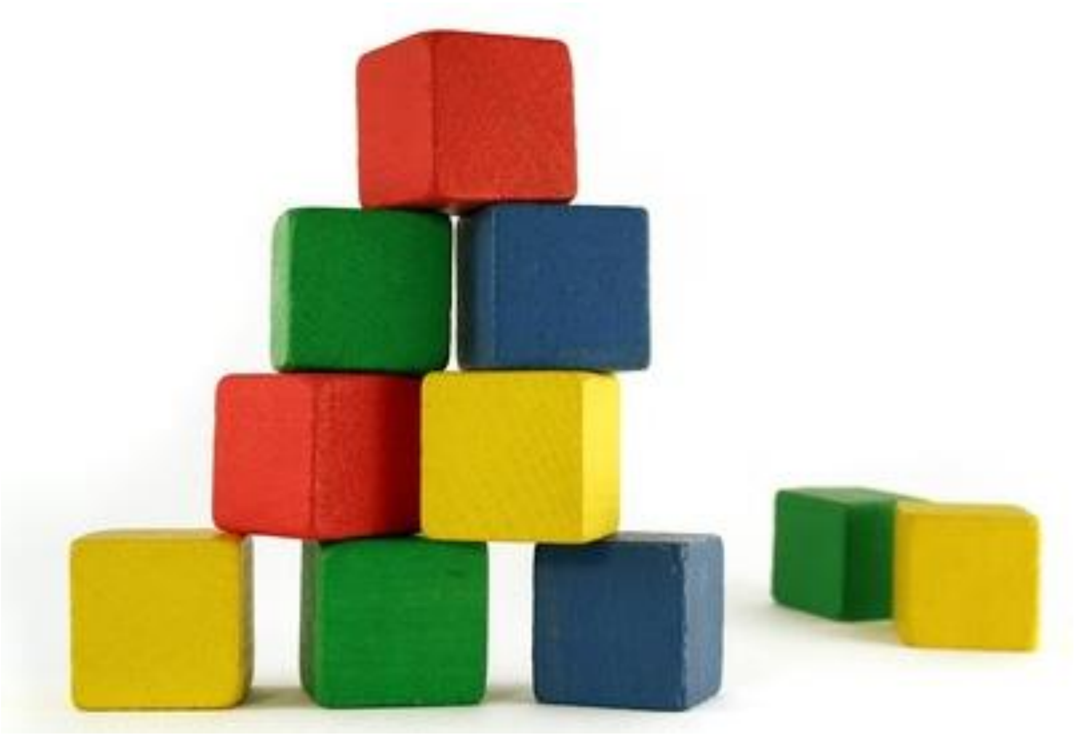
Summary

- Food from the sea will increasingly rely on cultivation;
- Tools for site selection and carrying capacity, risk analysis, and economic performance can help;
- The East grows all the fish, the West has all the tools…
- For sustainable world growth of aquaculture, it is important to foster better environmental practices in developing countries, and to promote information democracy.

All slides
http://ecowin.org/sima/

Individual models

The building blocks for simulating growth



Reproduce individual growth based on physiology, account for environmental externalities. Adapt to respond to climate change drivers.

Why individual models are important

Production – what does growth depend on?

- Food supply, question depends on type of organism
- Environmental conditions for optimal use of food (growth) Shellfish food depletion, finfish current speed examples

Environmental effects – consequences of activity

- Dissolved materials from metabolism
- Particulate matter from food waste (both in feeding and ingestion)

Types of cultivated organisms

Widely varying diets and potential trophic interactions

Type	Food source	Examples
Inorganic extractor	Dissolved nutrients	Kelp, Nori
Organic extractor	Particulate organic matter - phytoplankton and detritus	Mussels, oysters
Organic extractor	Particulate organic matter - Benthic detritus	Sea cucumber, sea urchin
Fed aquaculture	Pelleted feed, ‘trash’ fish	Gilthead bream
Mixed sources (often depends on whether culture is intensive or extensive)	Pelleted feed, organic waste (chicken manure etc), benthic macrofauna, phytoplankton	Shrimp, tilapia (e.g. *Oreochromis nilocticus*)

The combination of different types is an optimization approach called Integrated Multi-Trophic Aquaculture (IMTA).

Two main types of approach – Approach I

Generic growth models

- Uses growth equations such as Michaelis-Menten, or a growth constant
- Environmental effects are calculated indirectly (e.g. nitrogen removed as a proportion of shellfish biomass

Very simple oyster growth model

http://insightmaker.com/insight/7053

Two main types of approach – Approach II

Detailed process models

- Use equations that represent physiological processes
- Environmental effects are calculated as the outcome of those equations
- Such models deal with mass expressed in different units (phytoplankton chlorophyll, POM dry weight, tissue wet weight) by using an energy-based approach
- The two most common approaches use net energy balance (NEB) and dynamic energy budget (DEB)

More complex carp growth model

http://insightmaker.com/insight/6799

Further reading: Yang Yi, 1998. Aquacultural Engineering 18, 157-173

Typical functions in a NEB model

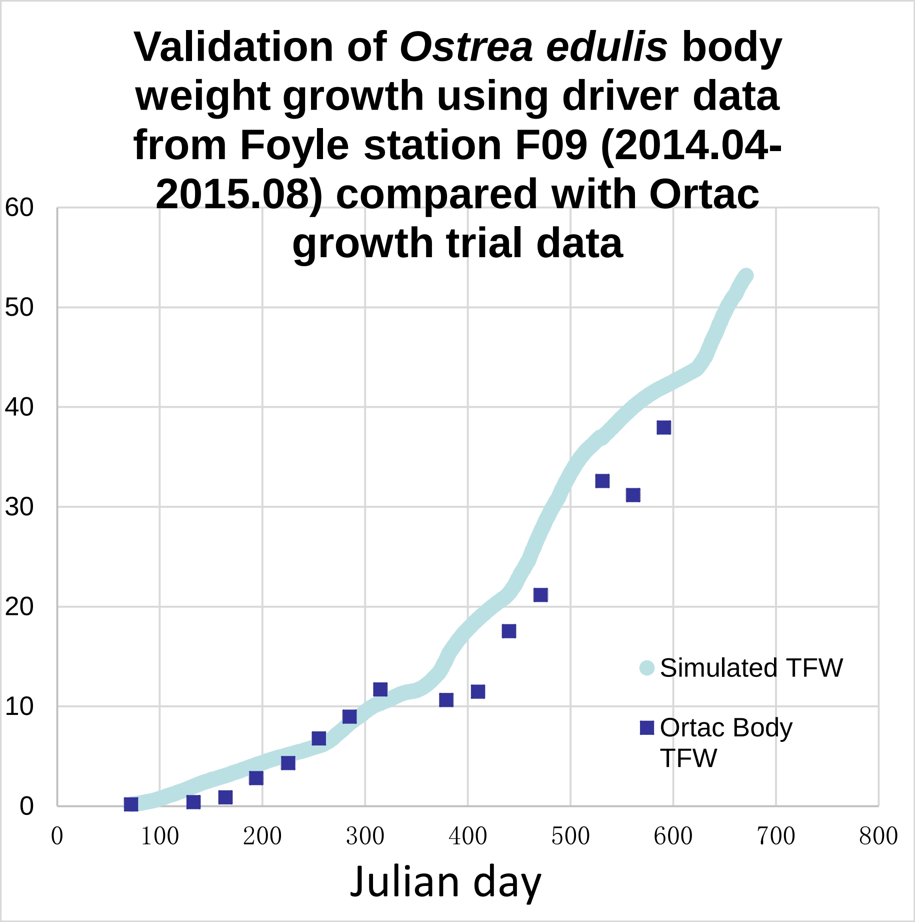
Application to filter-feeding shellfish such as oysters

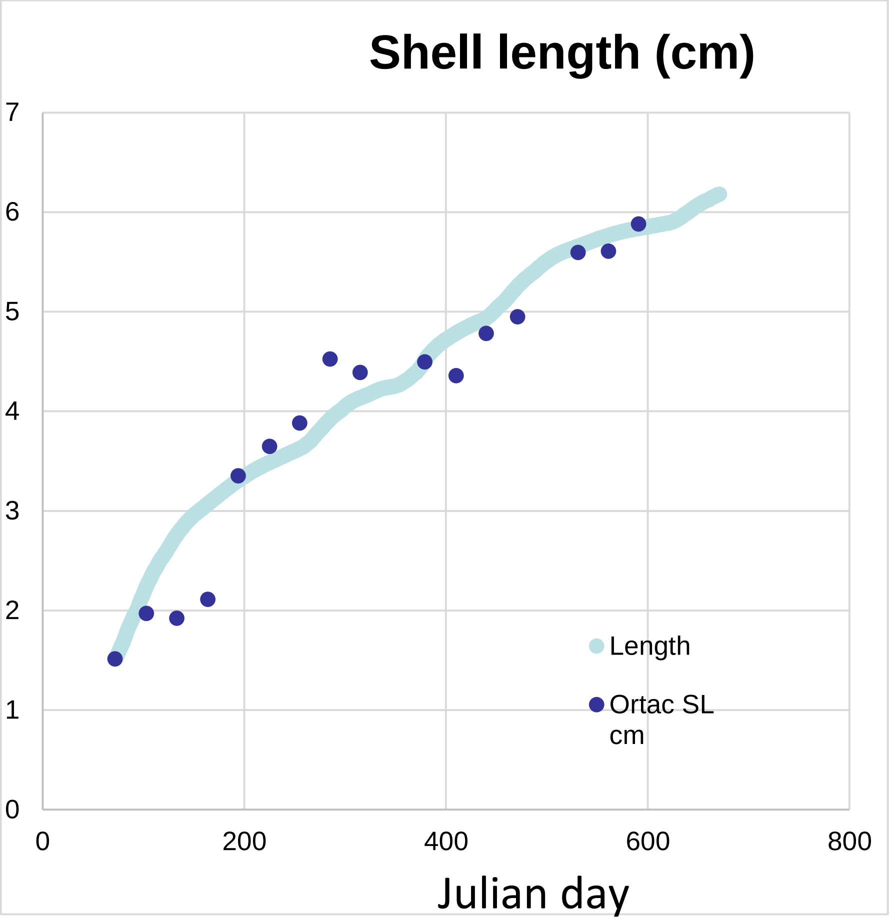
Process	Description	Dependencies
Clearance	Intake and outflow of water	TPM, allometry, T, S
Filtration	Intake of organic matter	Clearance, particle concentration
Pre-ingestive selection	Release of uningested matter as pseudofaeces	Particle composition and concentration
Assimilation	Assimilation of digested matter	Food composition, food mass
Elimination	Release of undigested matter	As above
Excretion	Waste products of metabolism	Allometry, T, S
Growth	Partition of growth into somatic tissue, gonad, and shell	Mass balance resulting from the proportion of energy for each component

http://insightmaker.com/insight/15724

Net energy balance models can provide an appropriate description of growth, food removal, and environmental components.

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

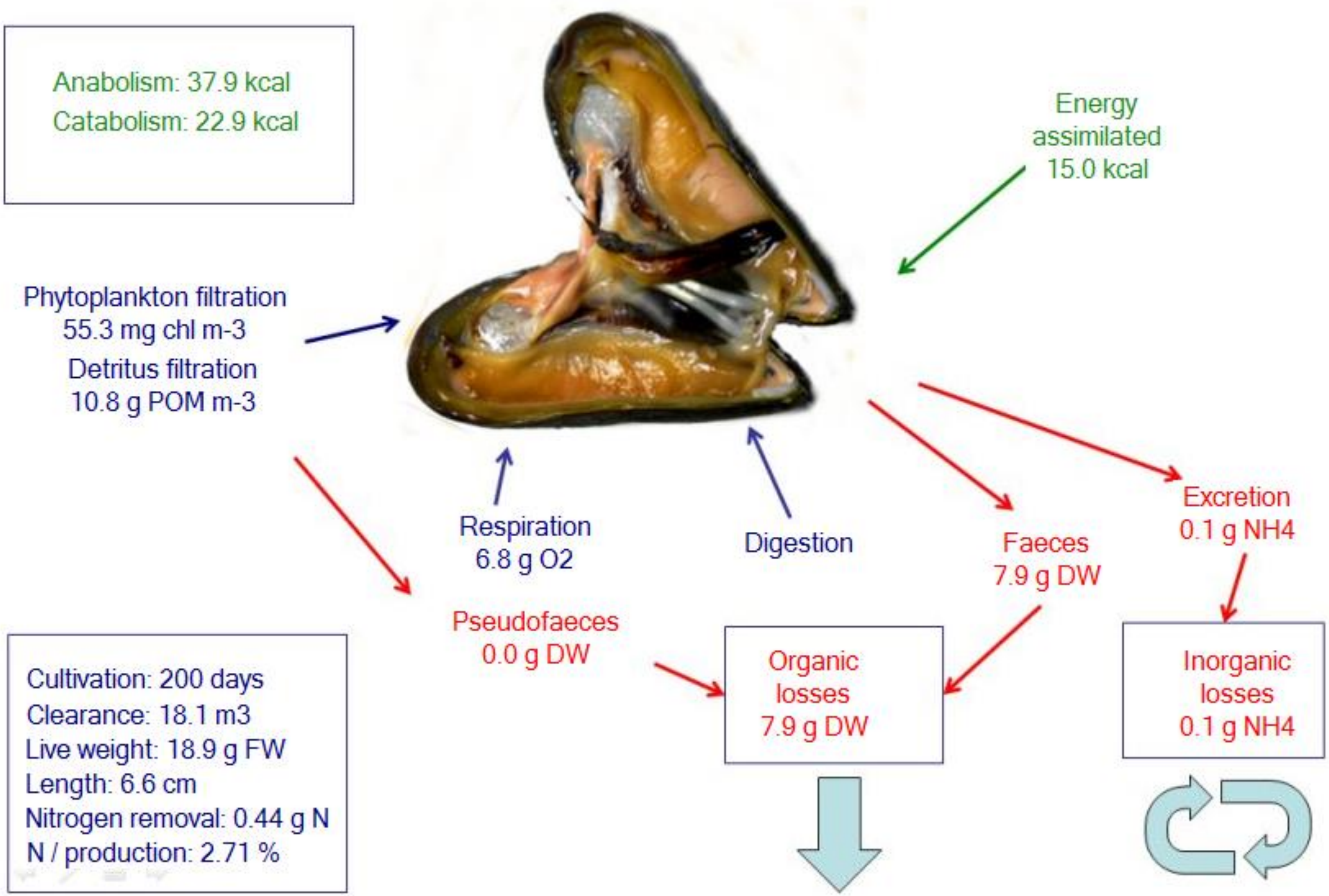




Model performance is an excellent match to Ortac growth data.

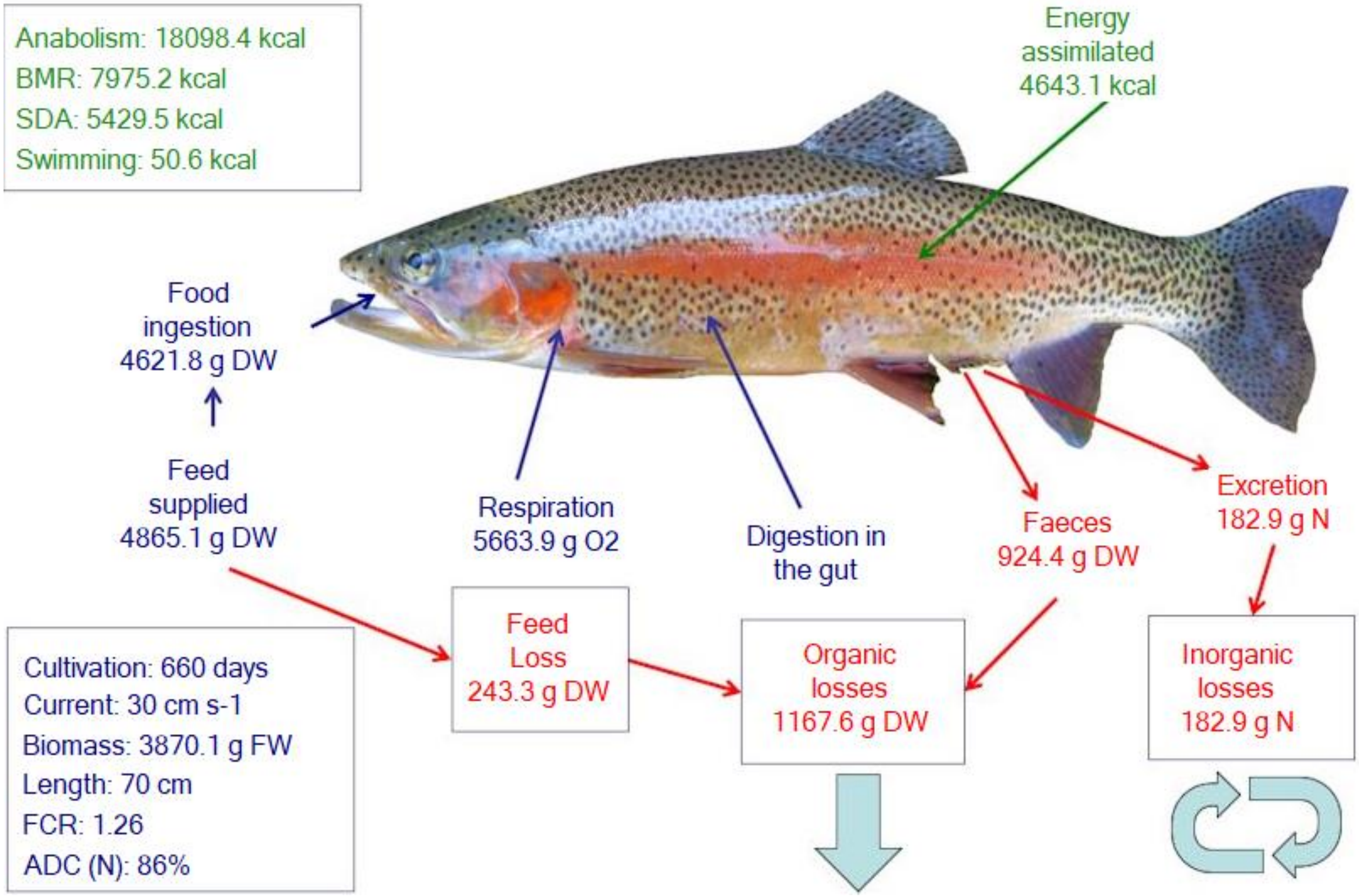
Mediterranean mussel growth model (AquaShell)

Mass balance



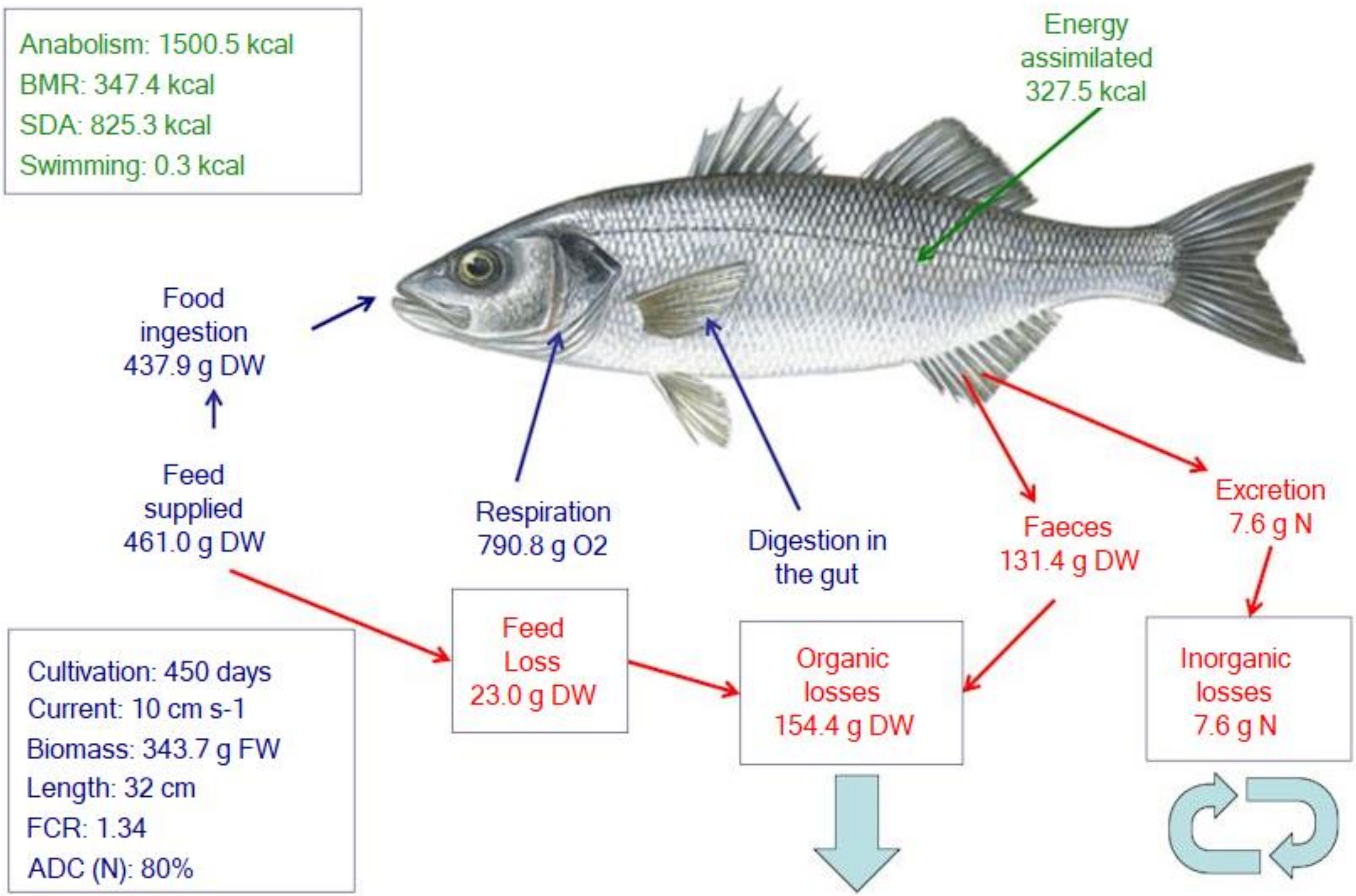
Simulation of Mediterranean mussel growth using environmental drivers provides outputs on production and environmental effects.

AquaFish individual growth model
Mass balance for rainbow trout



Model developed using feed tables courtesy of J. Johansen. Growth includes both pre- and post-smolt.

AquaFish individual growth model
Mass balance for European seabass



Model developed using feed tables courtesy of Culmarex. Growth is similar to the seabream model.

Synthesis

- Cultivated species have widely differing feeding habits
- Individual growth models help identify what variables need to measured in the environment
- Individual models are the building blocks for population modelling
- More detailed models of growth provide a better representation of environmental effects
- These models are useful to analyse species interactions, and in particular IMTA
- Although common processes may be formulated, there is almost always a need for local calibration
- There is always a need for local validation

All slides

http://ecowin.org/sima

Workshop on ecological modelling

Your mission

Grow an oyster

Use supplied data, conceptualise and implement the model

- Use Excel for a first mass balance approach
- Use Insight Maker to develop a dynamic model
- Experiment with different growth scenarios

Grow your own oyster

Parameterization of individual growth model

Variable or parameter	Value	Notes
Chlorophyll ($\mu g\ L^{-1}$)	4	Feed the oyster on algae
Clearance rate ($L\ h^{-1}$)	2.5	Intake food from the environment
Assimilation efficiency	0.8	Absorb food from the gut
Metabolism	0.9	Lose absorbed energy to metabolism
Carbon (POC) : chl ratio	50	Conversion of chl to carbon
POC to POM (DW) ratio	0.38	Conversion of carbon to dry weight
Dry tissue weight to live weight	1/30	An oyster has lots of shell
Culture period (days)	730	Good things come to those who wait

Will your oyster be big enough to eat?

Population models

- Review of different types of models
- Coupling of individual and population models
- Example applications

Population models

...come in all shapes and sizes

Lotka-Volterra

System of two coupled differential equations

$$\frac{dx}{dt} = x(\alpha - \beta y)$$

$$\frac{dy}{dt} = -y(\chi - \delta x)$$

Where:

x = prey

y = predator

α= prey growth rate

β = predation rate

χ = predator death rate

δ = predator growth rate

http://insightmaker.com/insight/467

βxy and δxy are a proxy for encounters of predator and prey, but the coefficients are different (the predator grows at a lower rate than prey is consumed. If either is zero, the equations take a first order form.

Population models

Use of weight classes

Partial differential equation

$$\frac{\partial n(s,t)}{dt} = -\frac{\partial\left[n(s,t)g(s,t)\right]}{ds} - \mu(s)n\left(s,t\right)$$

Where:

n = number of individuals s = weight class t = time

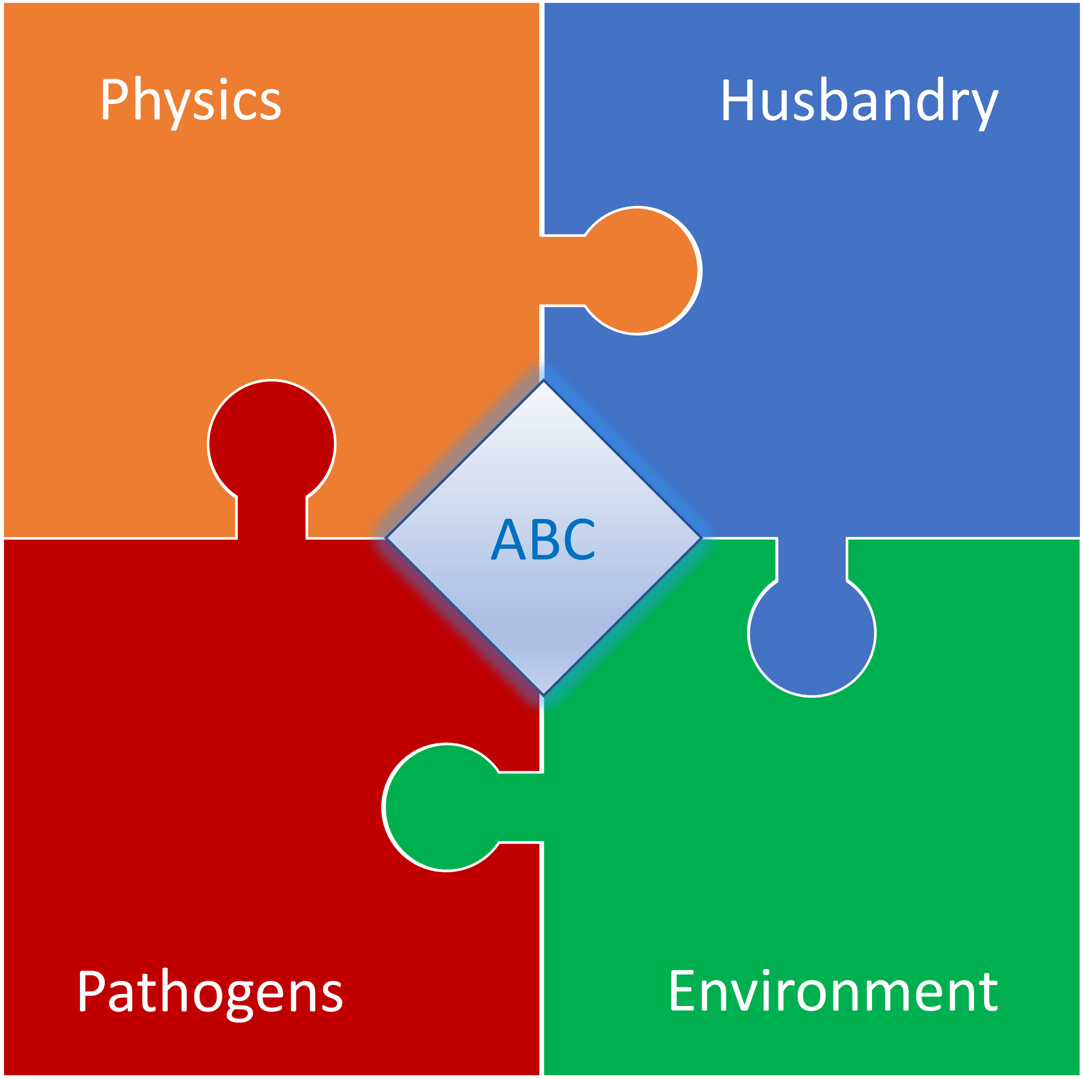
g = growth μ = mortality

http://insightmaker.com/insight/5760

http://insightmaker.com/insight/7013

This model moves individuals through a series of weight classes based on growth and mortality.

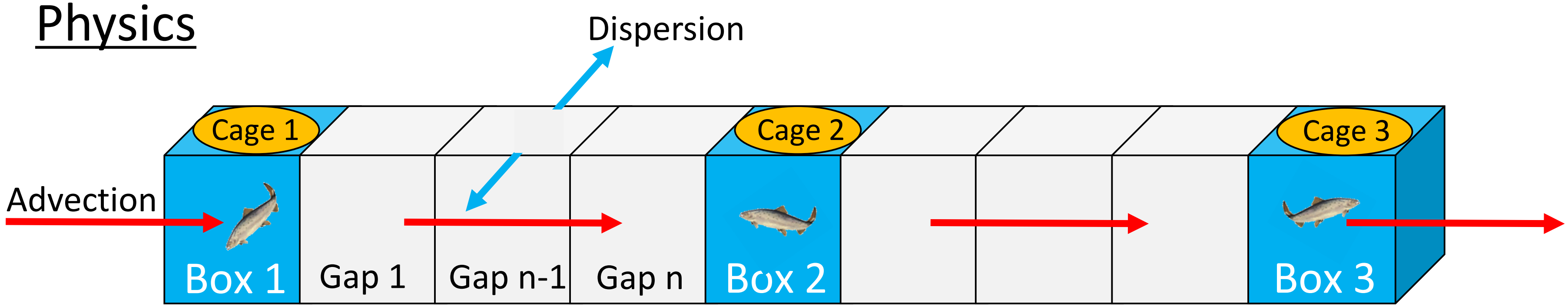
Integrated carrying capacity modelling



ABC integrates the four pillars of carrying capacity modelling for aquaculture.

ABC – General Approach

Physics



Husbandry

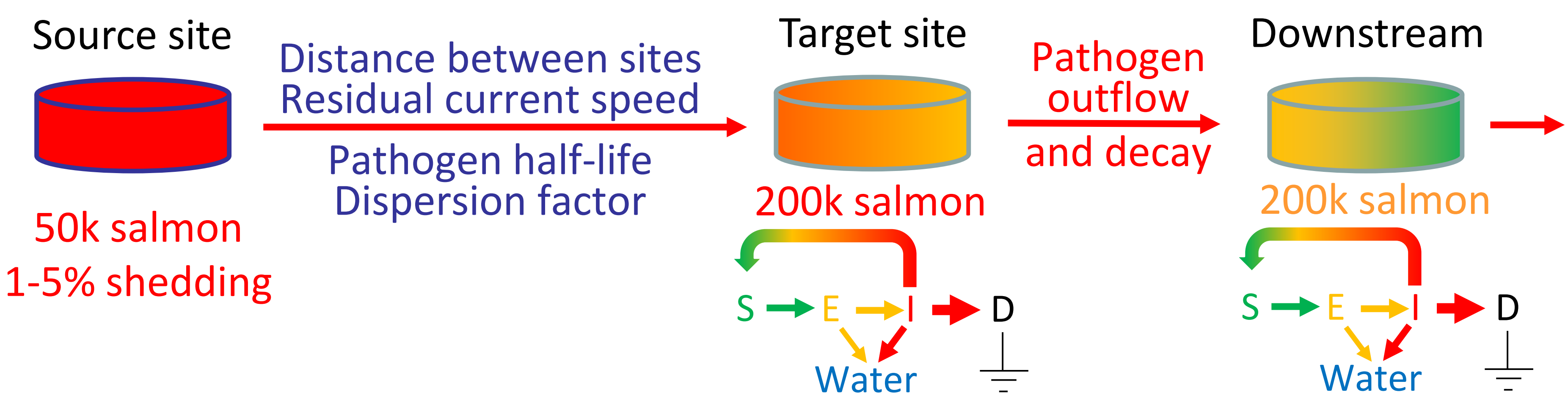
- IBM approach
- Feeding
- Growth
- Precision harvest
- Size-dependent mortality

Environment

- Environment on aquaculture
- Aquaculture on environment
- Key factors: dissolved oxygen, dissolved nutrients, organic waste, phytoplankton depletion

Pathogens

- Infection parameters
- Hill function for IHNv and OHv
- Physical and biological decay
- Response to climate change
- Waterborne or relay



ABC integrates physics, husbandry, environment, and pathogens.

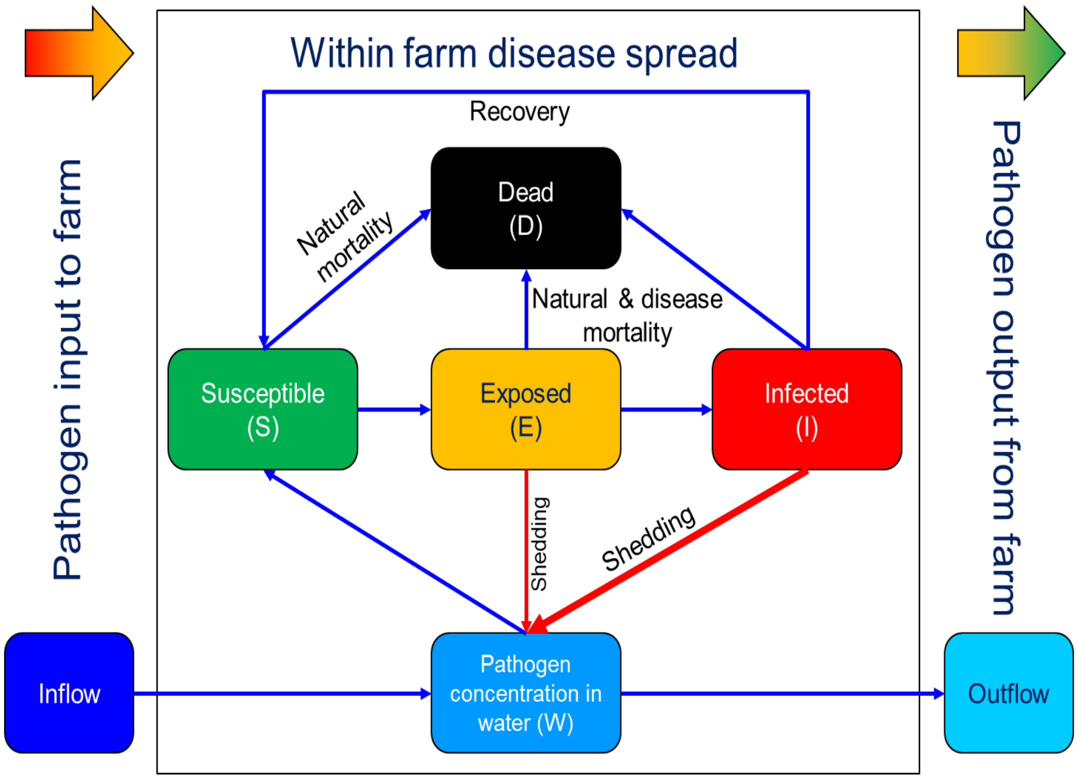
Flexible Disease Modelling Framework

<u>Hill function</u>

$$\beta_P = \frac{{P_s}^{\alpha}}{ID50^{\alpha} + {P_s}^{\alpha}}$$

- Sigmoidal dose-response curve
- β_p = probability of infection
- α is the Hill coefficient of sigmoidicity
- ID50 = pathogen concentration for 50% infection
- Parameterisation still not easy—but possible

- Adaptable to different environmental conditions, pathogens (with direct life-cycle) and host species
- Applicable to finfish and shellfish
- Explicit physiological growth model
- Coupled to transport model to evaluate spread between sites
- Parameterised and validated for two key host-pathogen systems: Infectious Hematopoietic Necrosis virus (IHNv) in salmon & Oyster Herpes virus (OHv)

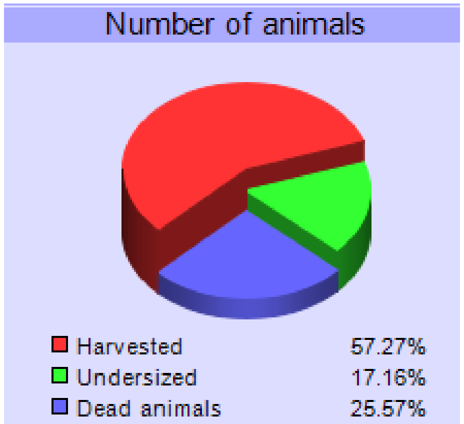


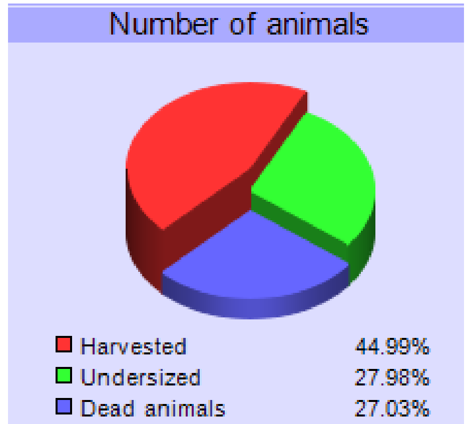
Stochastic pathogen models <u>coupled</u> with deterministic production models

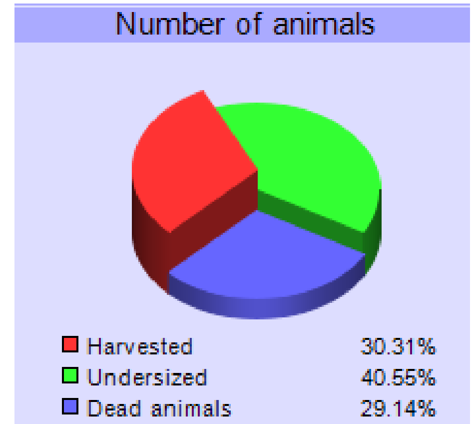
Husbandry – Food depletion for Pacific oysters

Three 1 ha culture areas with 100 m gap, 200 oysters per m^2

Area 1 → Area 2 → Area 3







Indicator	Area 1	Area 2	Area 3	Total
Seed (kg)	1300	1300	1300	3900
Harvest (Total Physical Product, kg)	*80,200*	62,998	42,400	185,598
Average Physical Product (APP)	61.7	48.5	32.7	-
Non-harvestable oysters (kg)	21,880	34,113	*47,894*	103,887
Clearance rate (m^3 X10^6 per cycle)	24.1	25.6	26.7	76.0
Net N removal as % of production	2.99	3.18	3.40	-
Net N removal as % of harvest	3.80	4.90	*7.26*	-

500 day growth cycle; weight at harvest: 70 g; precision aquaculture (HWR).
Mean clearance rate per oyster: 1.06-1.46 L h^{-1}

Salmon culture with IHNv pathogen

Infectious Hematopoietic Necrosis virus

- Five cages with 200,000 Atlantic salmon (*Salmo salar*) in each
- 300 m gap between cages
- Outbreak of IHNv at a cage 3000 m upstream
- Early stage (day 40) and late stage infection (day 405) of culture
- ABC simulates effects on growth, mortality, and environment

A	KBR	KBS	KBT	KBU	KBV	KBW	KBX
Julian day	Sam 7505 (20) (g TFW)	Sam 7506 (20) (g TFW)	Sam 7507 (20) (g TFW)	Sam 7508 (20) (g TFW)	Sam 7509 (20) (g TFW)	Sam 7510 (20) (g TFW)	Sam 7511 (20) (g TFW)
327	300.9514204	[illegible]	[illegible]	255.7639008	263.5577914	267.5236888	337.5279879
328	306.0430385	[illegible]	315.1314893	[illegible]	[illegible]	271.7020857	343.6507868
329	311.1694387	263.5149877	320.5071426	[illegible]	271.7257705	275.9052647	349.8204182
330	316.2800721	267.3845998	325.8673645	267.3845998	[illegible]	[illegible]	355.9759479
331	321.4735181	271.3121818	331.3155421	271.3121818	[illegible]	[illegible]	362.2360803
332	[illegible]	[illegible]	336.7992303	275.2598794	[illegible]	288.6166225	368.5405821
333	[illegible]	[illegible]	342.2643549	279.1888744	288.2542415	292.8717935	374.8272102
334	[illegible]	283.1749703	347.8163085	283.1749703	[illegible]	[illegible]	381.2171741
335	342.5166473	287.1797162	353.4015914	287.1797162	[illegible]	[illegible]	387.6489213
336	347.8150186	291.1637478	358.9651494	291.1637478	335	305.849239	394.0589785

Live weight (Box 3) / Live weight (Box 4) / Live weight (Box 5)

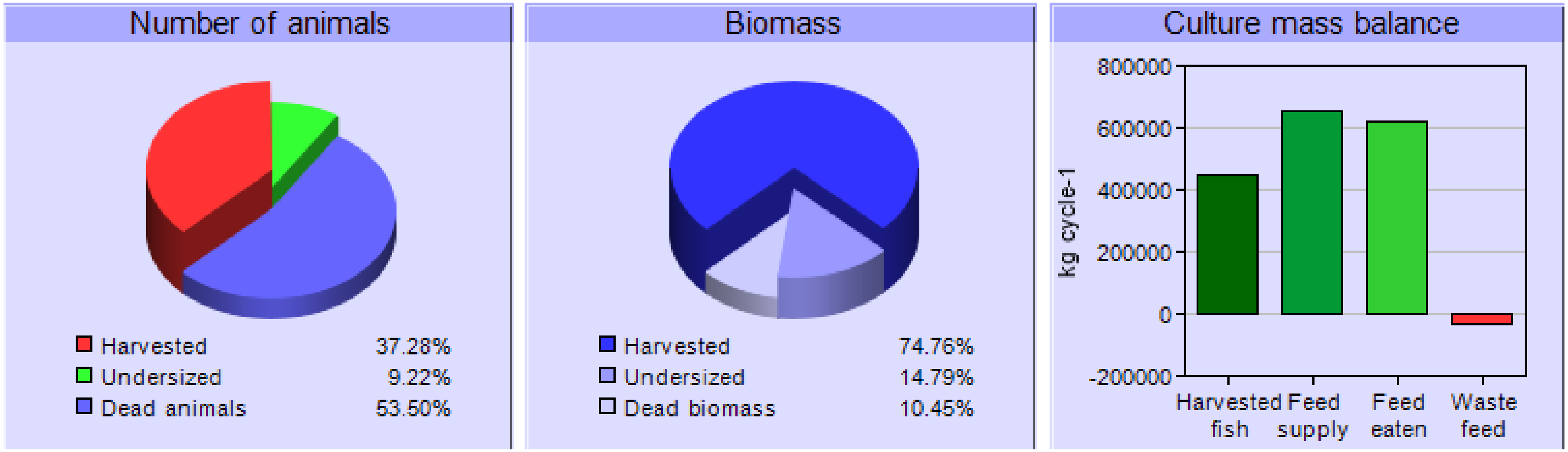
Susceptible
Exposed
Infected
Recovered
Removed

Fish transition from susceptible to exposed to infected. Some recover, some die.

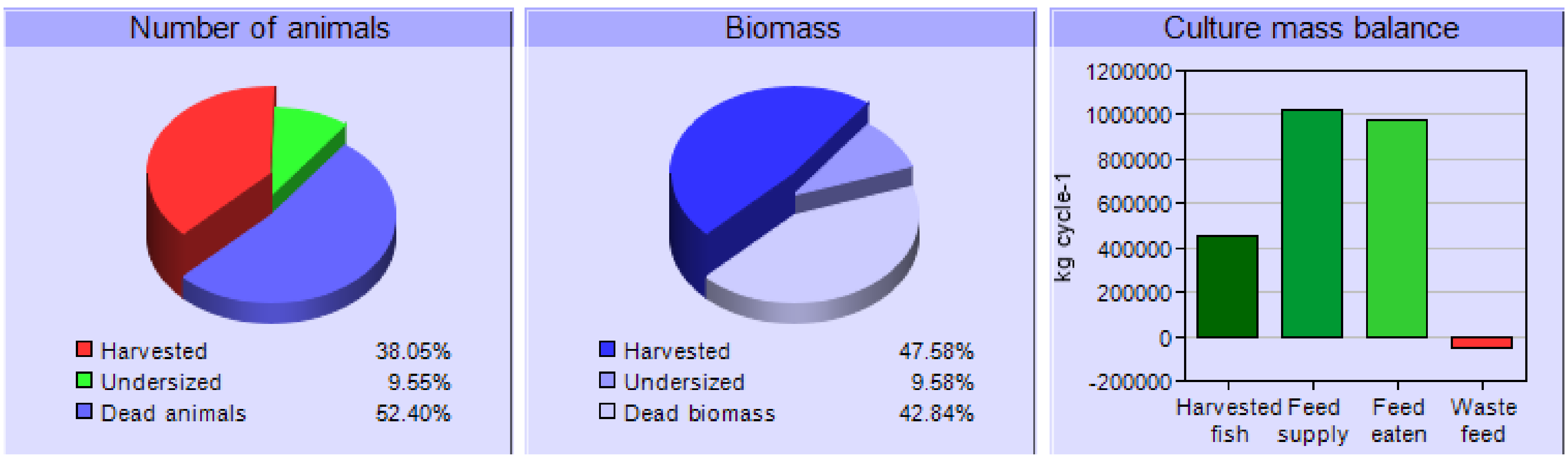
Effect of IHNv on salmon culture performance

Climate change scenarios at early (day 40) and late stage (day 405)

Culture cycle early stage pathogen – *Biological* FCR for cage 1 = 1.78

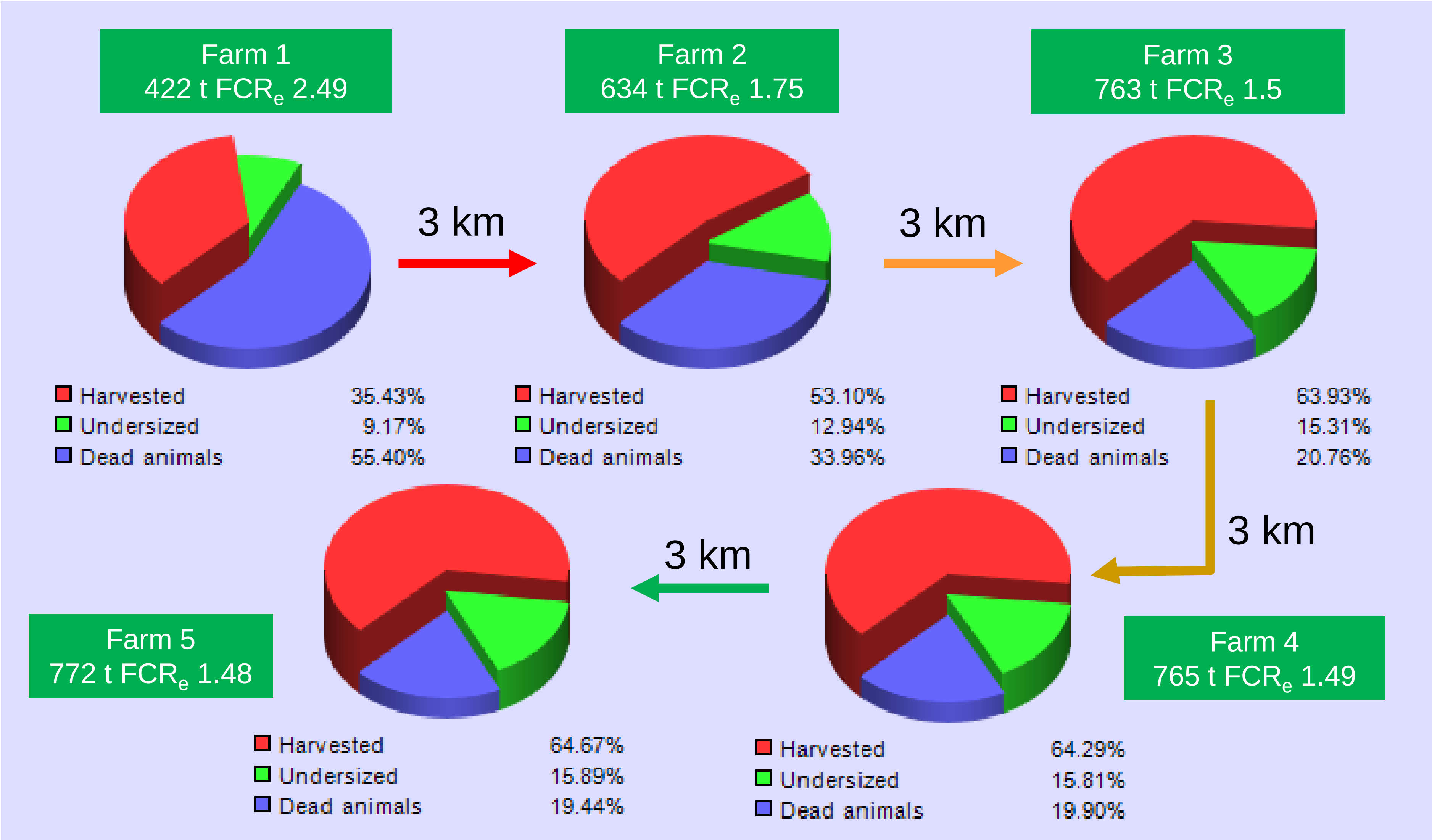


Culture cycle late stage pathogen – *Biological* FCR for cage 1 = *35.82*



Timing of pathogen release completely changes the ratio of dead biomass, the FCR, and has a massive impact on cost and profit.

Culture performance in 5 salmon farms spaced 3 km apart. Pathogen emission begins 405 days after culture start



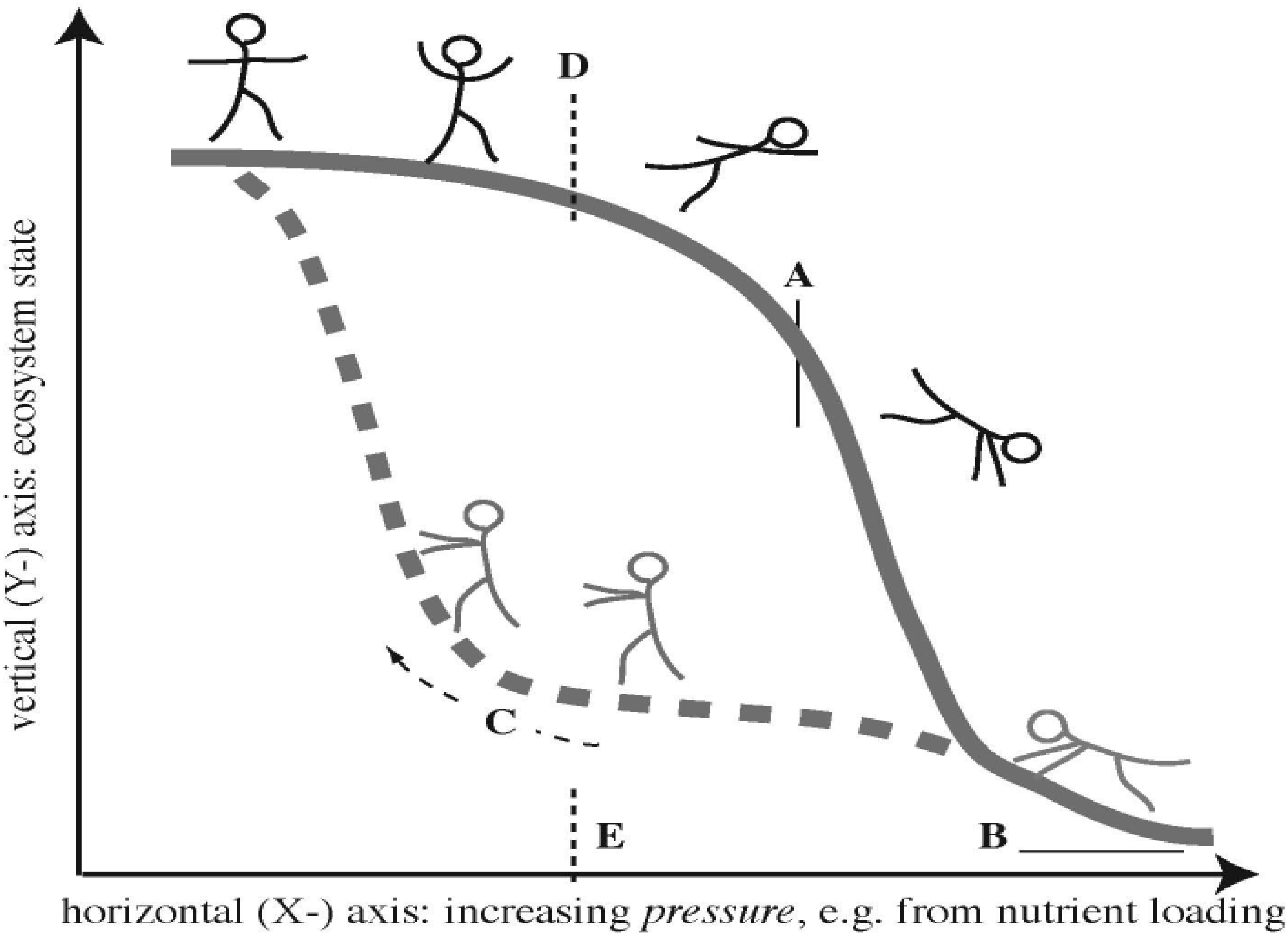
Yield in the last farm (15 km from pathogen source) is 83% higher than in the first farm. Farm 5 mortality is 35% of Farm 1, very similar to a background run.

Synthesis

- Aquaculture models must focus on the harvestable biomass and the overall environmental effects
- Individual models are the building blocks for population modelling, because they allow physiology and demography to be combined
- Population models can use an Individual-Based Model (IBM) approach with a quasi-deterministic structure
- An accurate definition of culture practice is critical for modelling success, since several aspects (e.g. stocking density, average mortality) are forcing functions
- Population models anchored in physiology, and coupled to physics and biogeochemistry, are an extremely valuable management tool

All slides
http://ecowin.org/sima

Resilience…


D
A
C
E
B
vertical (Y-) axis: ecosystem state
horizontal (X-) axis: increasing *pressure*, e.g. from nutrient loading