Environmental indicators and modeling studies for assessing sustainability of marine aquaculture

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Outline

1. Law to ensure sustainable aquaculture production

2. Environmental indices for marine finfish culture

   (1) Benthos community

   (2) Topography

   (3) Aquaculture waste

3. Modeling to assess aquaculture environments

1. Law to ensure sustainable aquaculture production

In 1999, the "Law to Ensure Sustainable Aquaculture Production" was established to promote the improvement in the environmental quality.

The Law stipulates that aquaculture farmers should enact the "Aquaculture Ground Improvement Program".

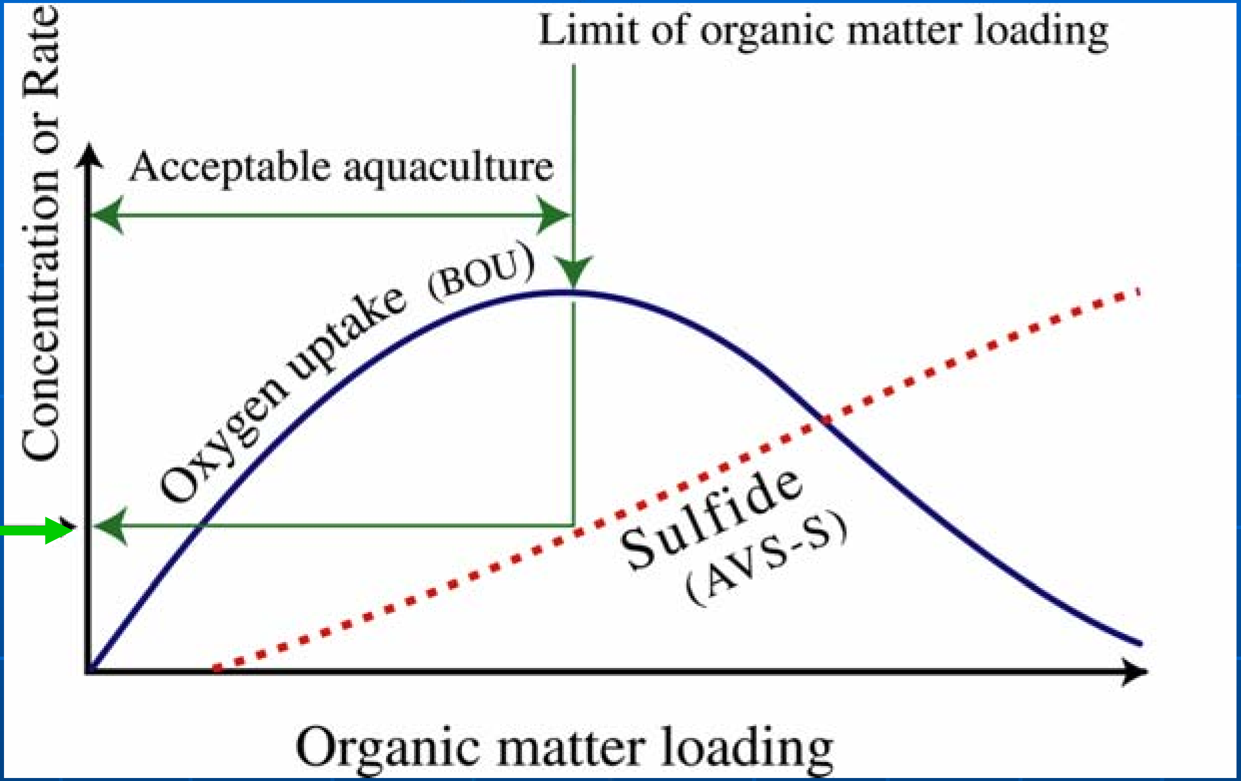
When a farm is in extreme deterioration, the local governor recommends the farmers to improve the farm environments.

If the farmers do not follow the recommendation, the governor can make the environmental status public.

Environmental criteria used in the Basic Guidelines for the Law

Item	Indicator	Criterion for identifying healthy farms	Criterion for identifying critical farms
Water in cages	Dissolved oxygen	>4.0 ml/l	<2.5 ml/l
Bottom environment	Sulfide (AVS-S)	Less than the value at the point where the benthic oxygen uptake rate is maximum	>2.5 mg/g dry sediment
	Benthos	Occurrence of animals throughout the year	Azoic conditions during >6 months

Standard value of Sulfide



Concept of environmental criterion (indicator: AVS-S)

2. Environmental indicators for marine finfish culture

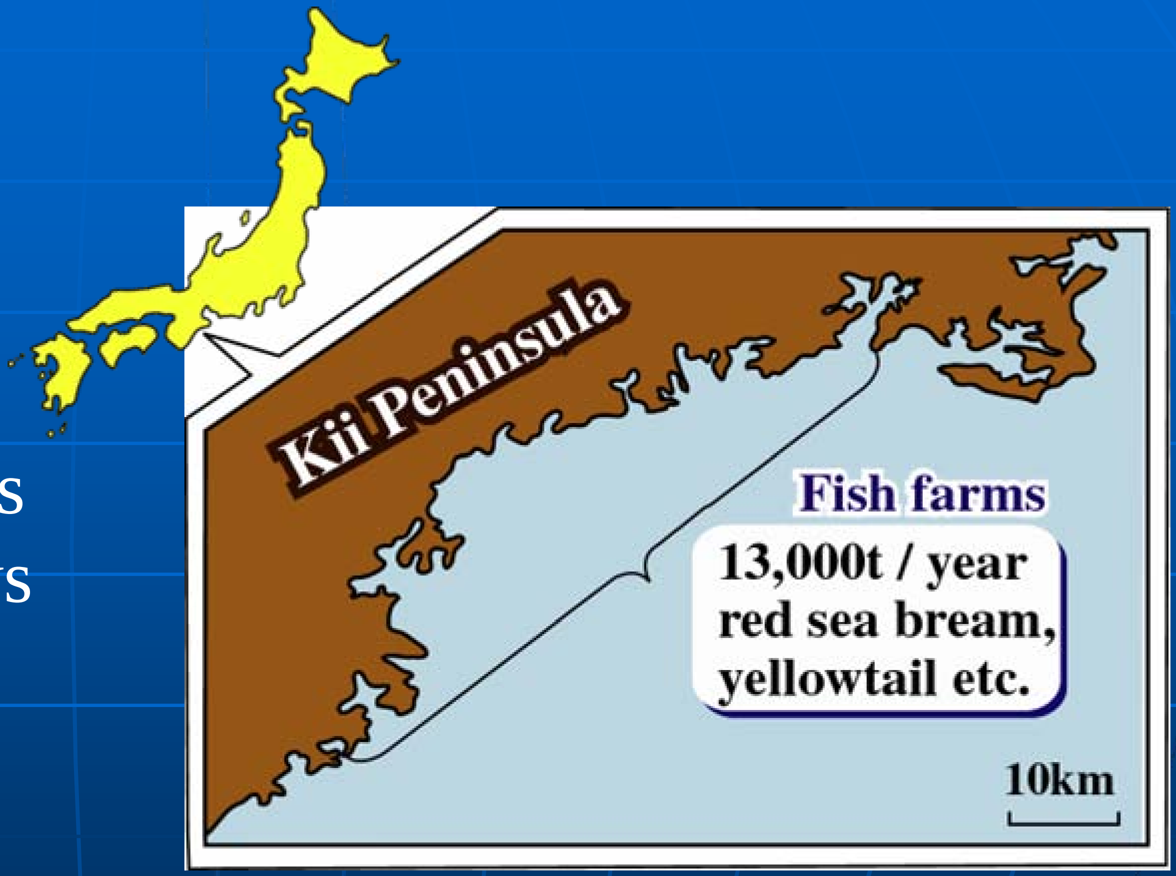
(1) Benthos community

(2) Topography

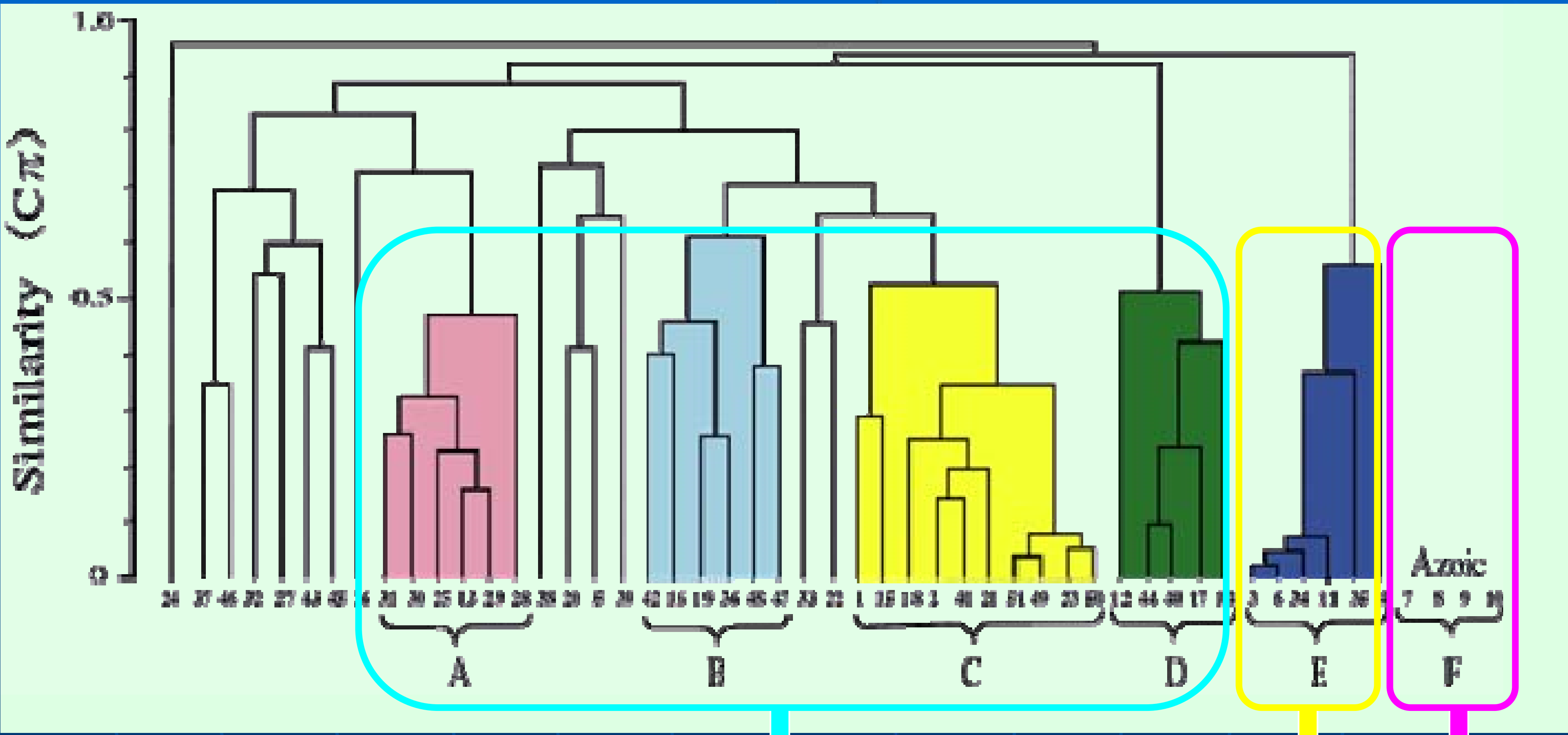
(3) Waste feed

(1) Benthic community

Macrofaunal samples were collected from 51 stations at 22 fish farms located in 10 small bays



Cluster analysis of the macrofauna



Healthy zone

Cautionary zone

Critical zone

Values of benthic components for identifying cautionary and critical conditions of fish-farm environments (after Yokoyama et al. 2004)

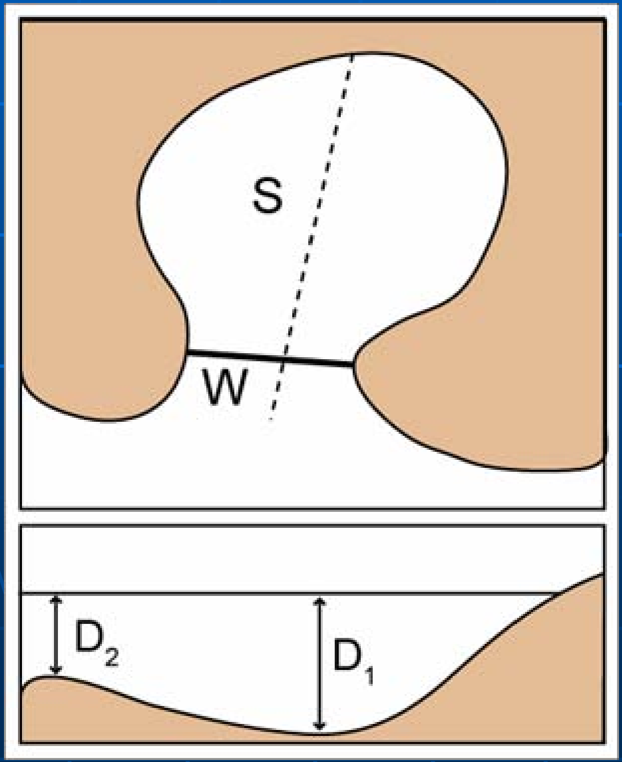
Benthic components	Cautionary condition	Critical condition
Sediment		
Total organic carbon (mg/g dry)	> 20	> 30
Total nitrogen (mg/g dry)	> 2.5	> 4
Total phosphorus (mg/g dry)	> 4	> 6
Chemical oxygen demand (mg/g dry)	> 30	> 75
Acid-volatile sulfide (mg/g dry)	> 0.5	> 1.5
Macrobenthos		
Biomass* (g/m^2)	< 10	0
Density ($individuals/m^2$)	< 1500	0
Number of species ($/0.04\ m^2$)	< 20	0

* Wet weight of animals, excluding the shells of molluscs

(2) Topography

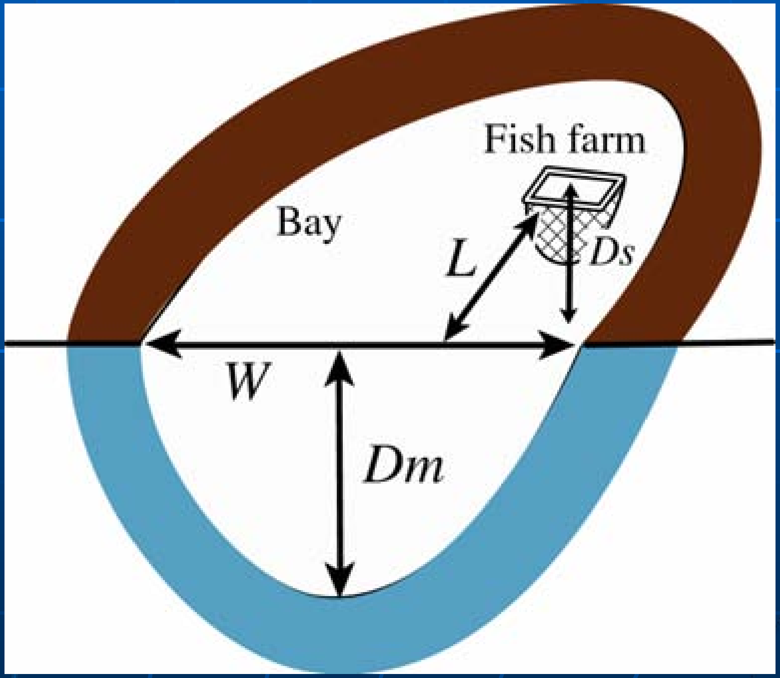
Enclosed index

$$EI = \frac{\sqrt{S} \times D_1}{W \times D_2}$$



Embayment degree

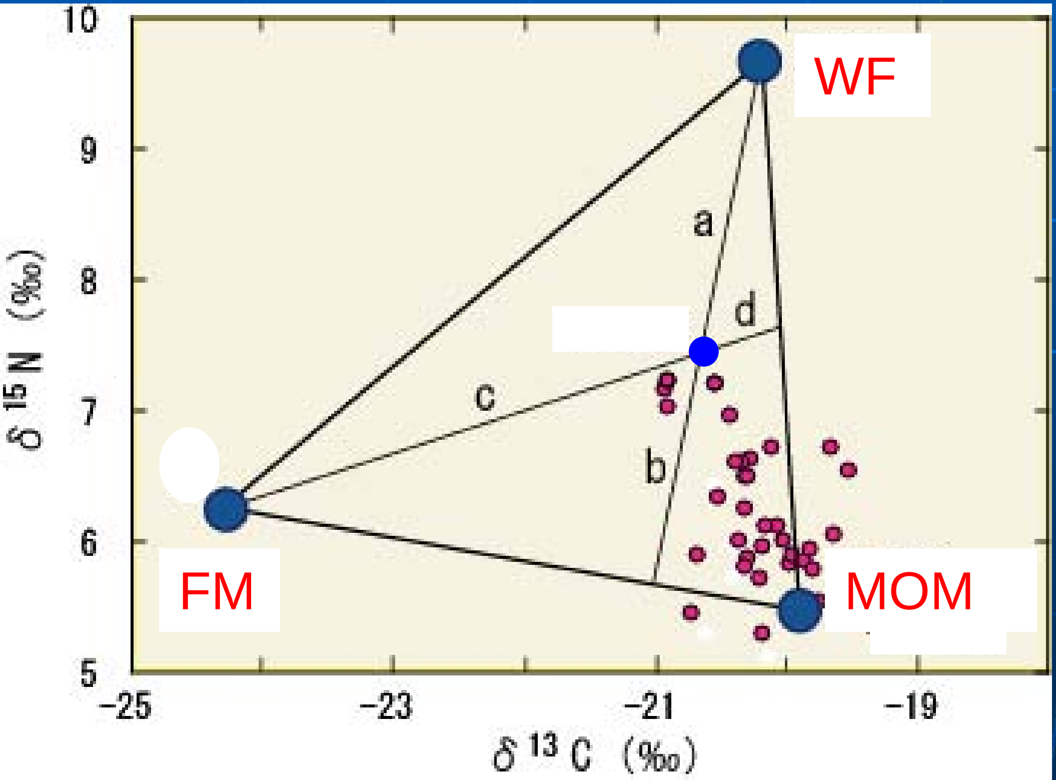
$$ED = \frac{L}{W} \times \frac{45}{Dm} \times \frac{20}{Ds}$$



(3) Aquaculture waste (waste feed, fecal matter)

Stable Isotope Analysis (3 source method)

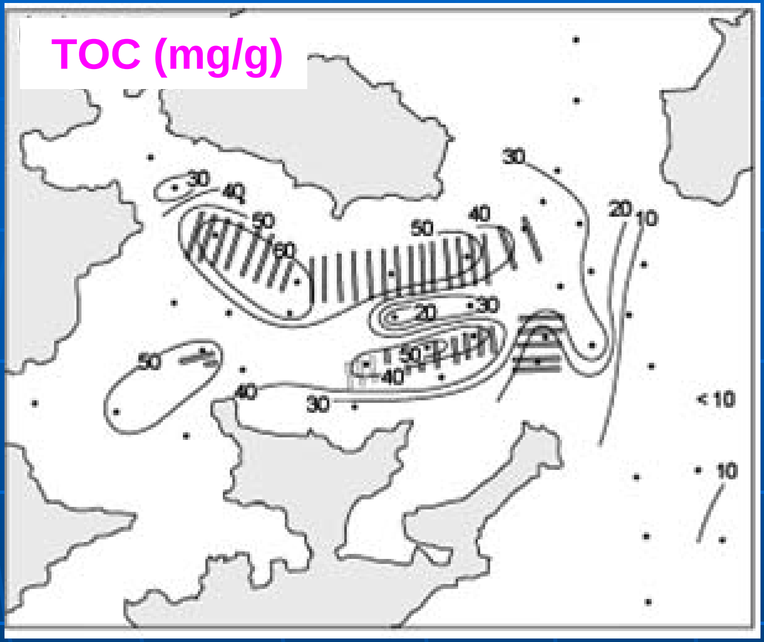
Sedimentary organic matter includes three main organic matter sources; waste feed (WF), fecal matter of cultured fish (FM), and natural marine organic matter (MOM).

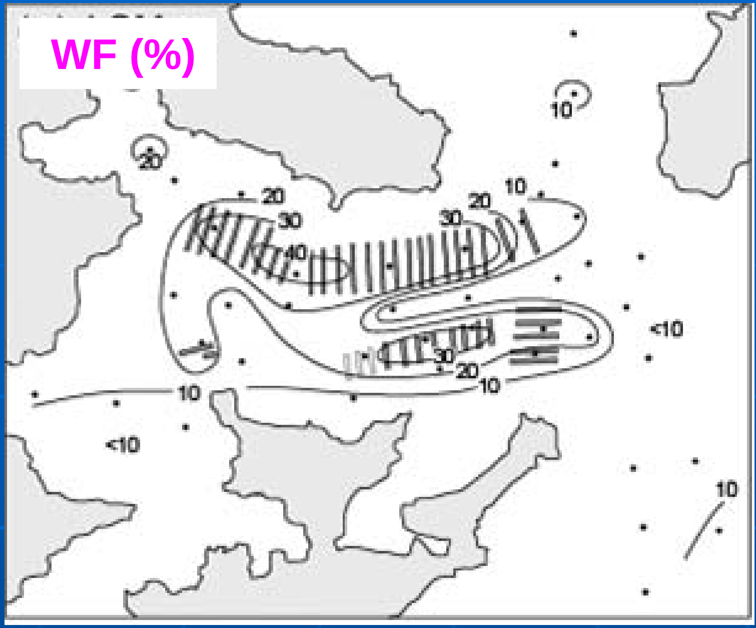


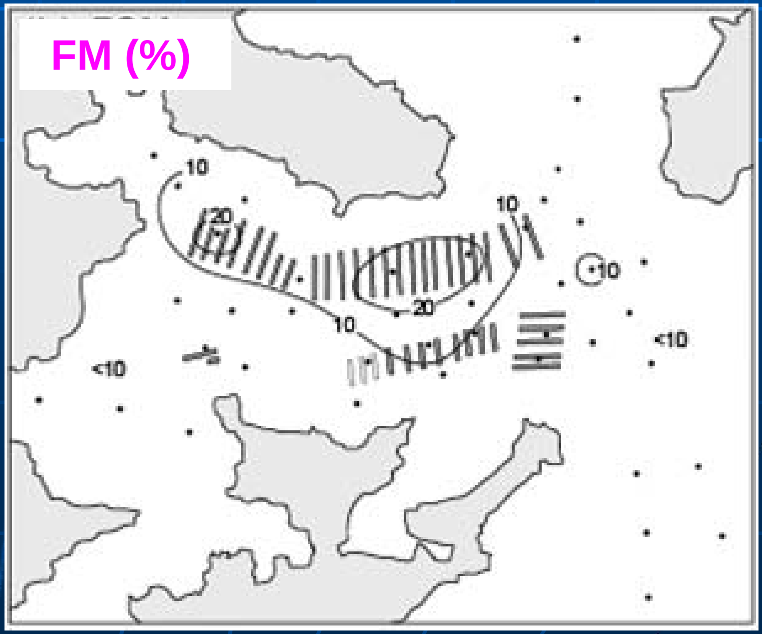
MOM: Natural Marine Organic Matter
WF: Waste feed (uneaten feed)
FM: Fecal Matter

3 Source	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
MOM	-19.9	5.5
WF	-20.2	9.7
FM	-24.3	6.3

Field Observation of Sediments in the Fish Farm Area

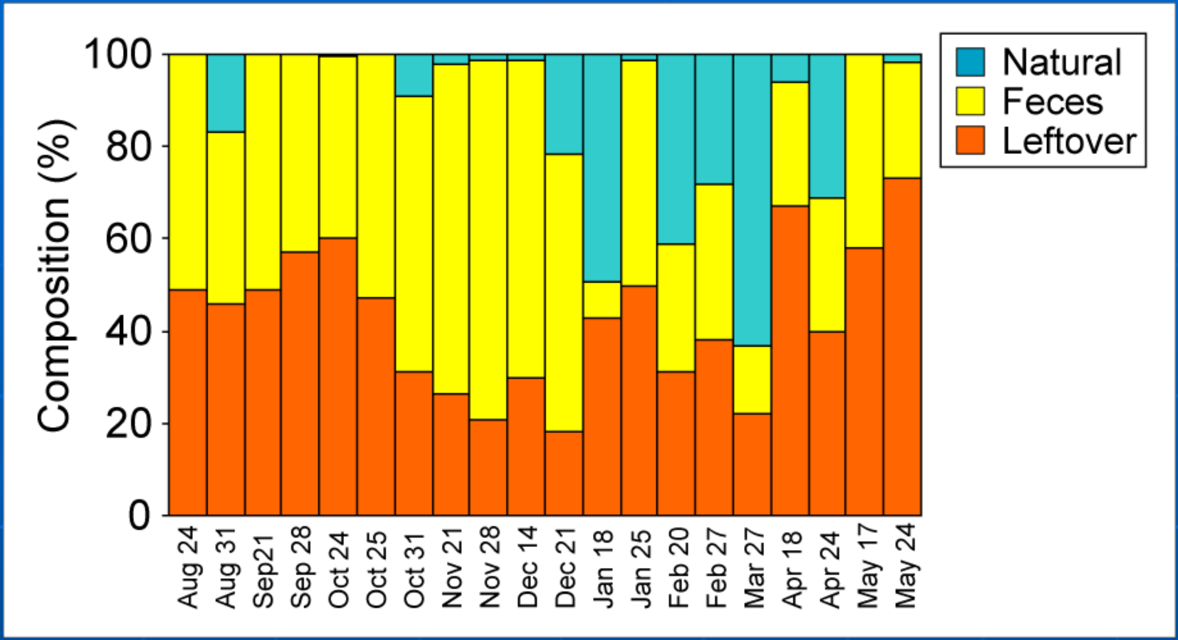


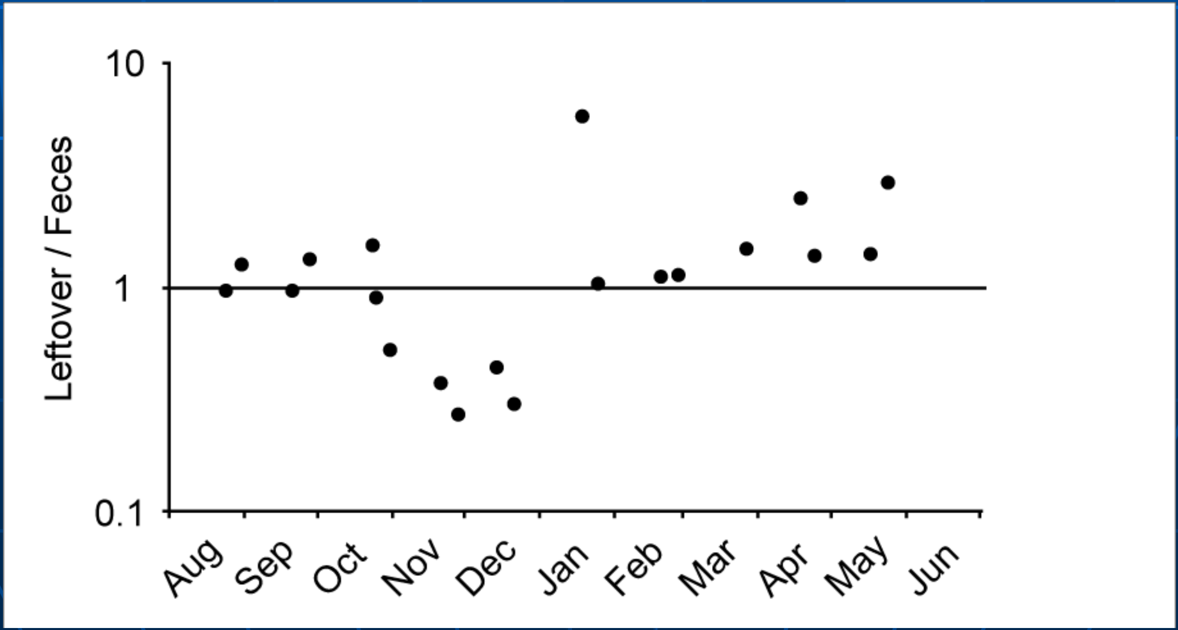




WF: Waste feed (uneaten feed)
FM: Fecal Matter

Composition of aquaculture derived organic matter in sediment



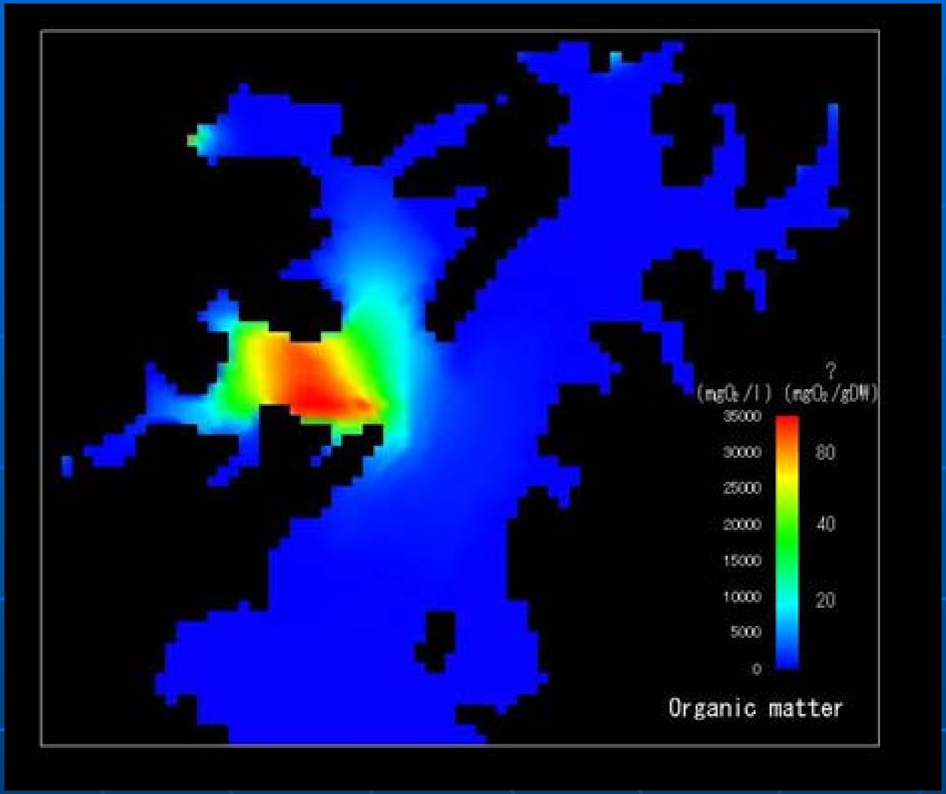


3. Modeling

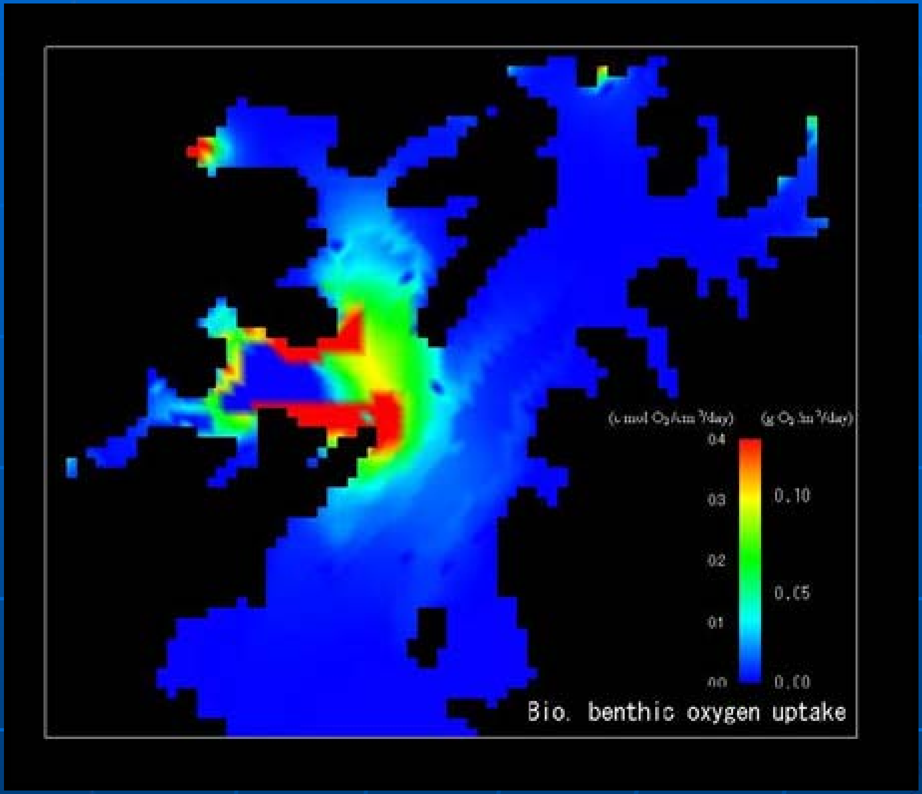
1) Benthic Oxygen Uptake Rate

2) Early diagenesis model

Result of the numerical simulation

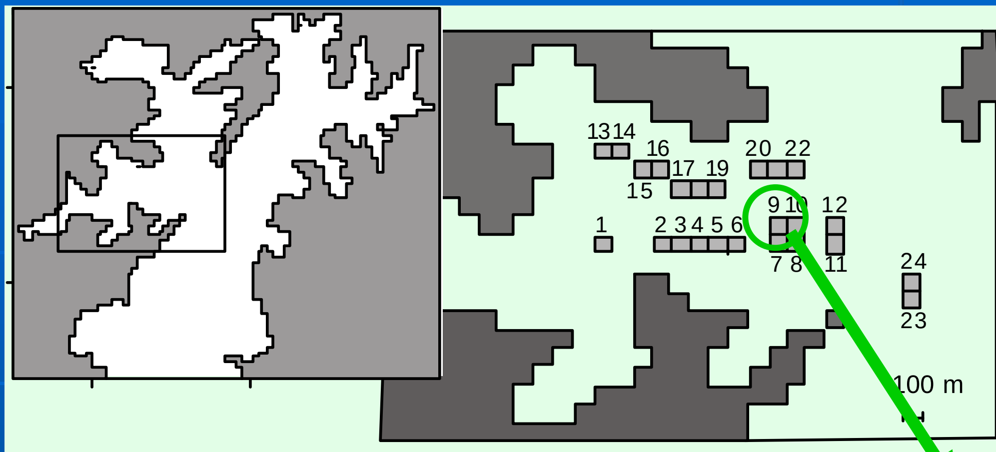


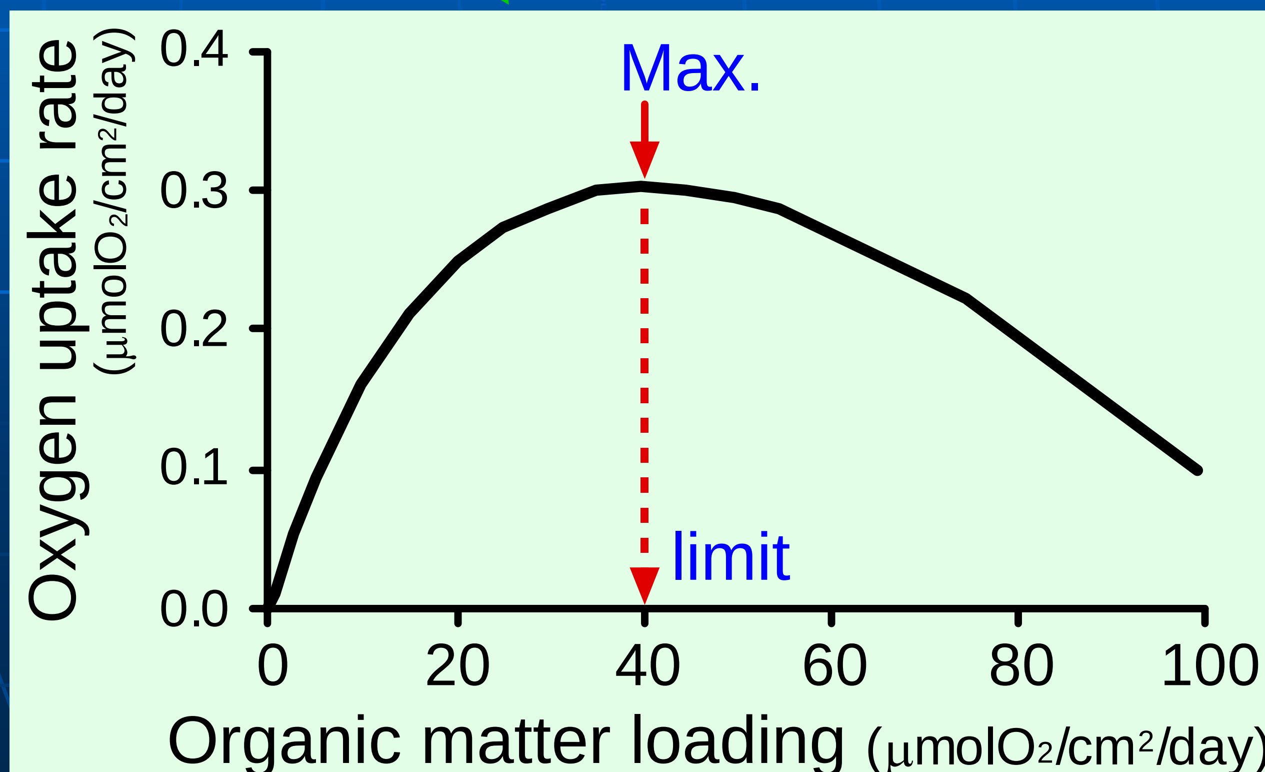
Organic matter content of the sediment

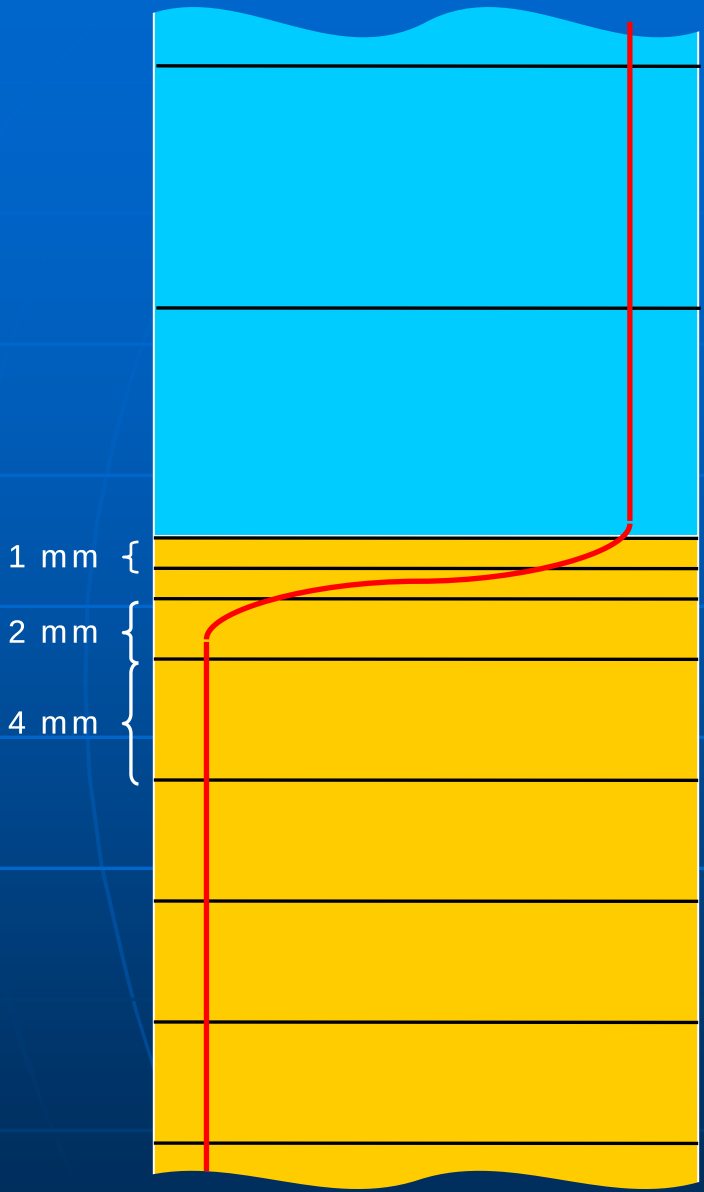


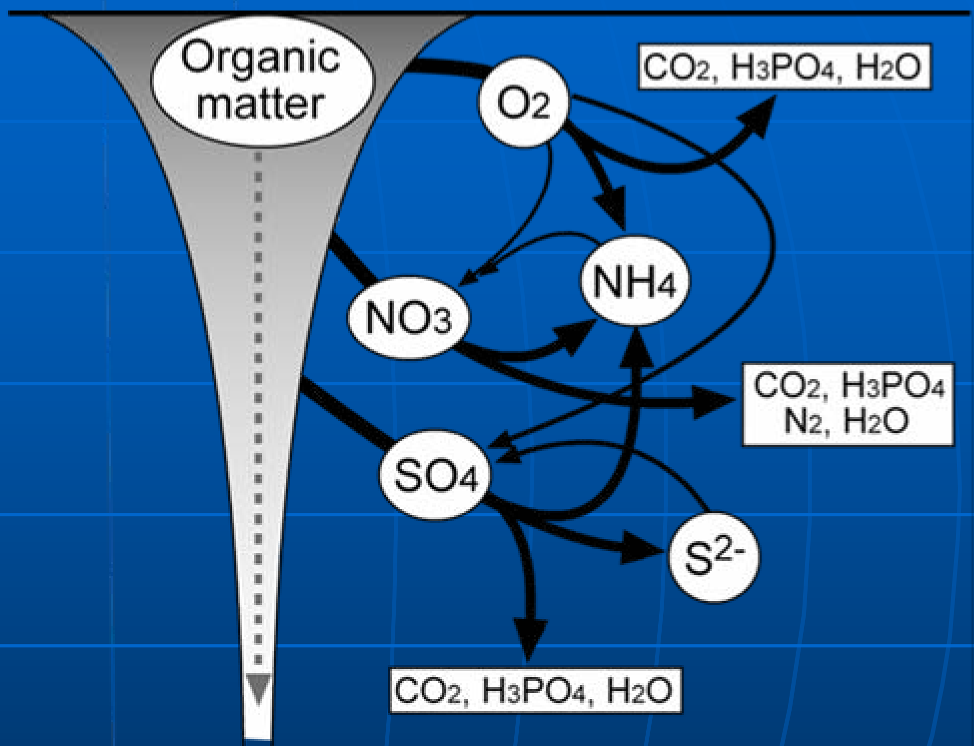
Benthic oxygen uptake rate

Estimation of the Maximum and the Limit Value

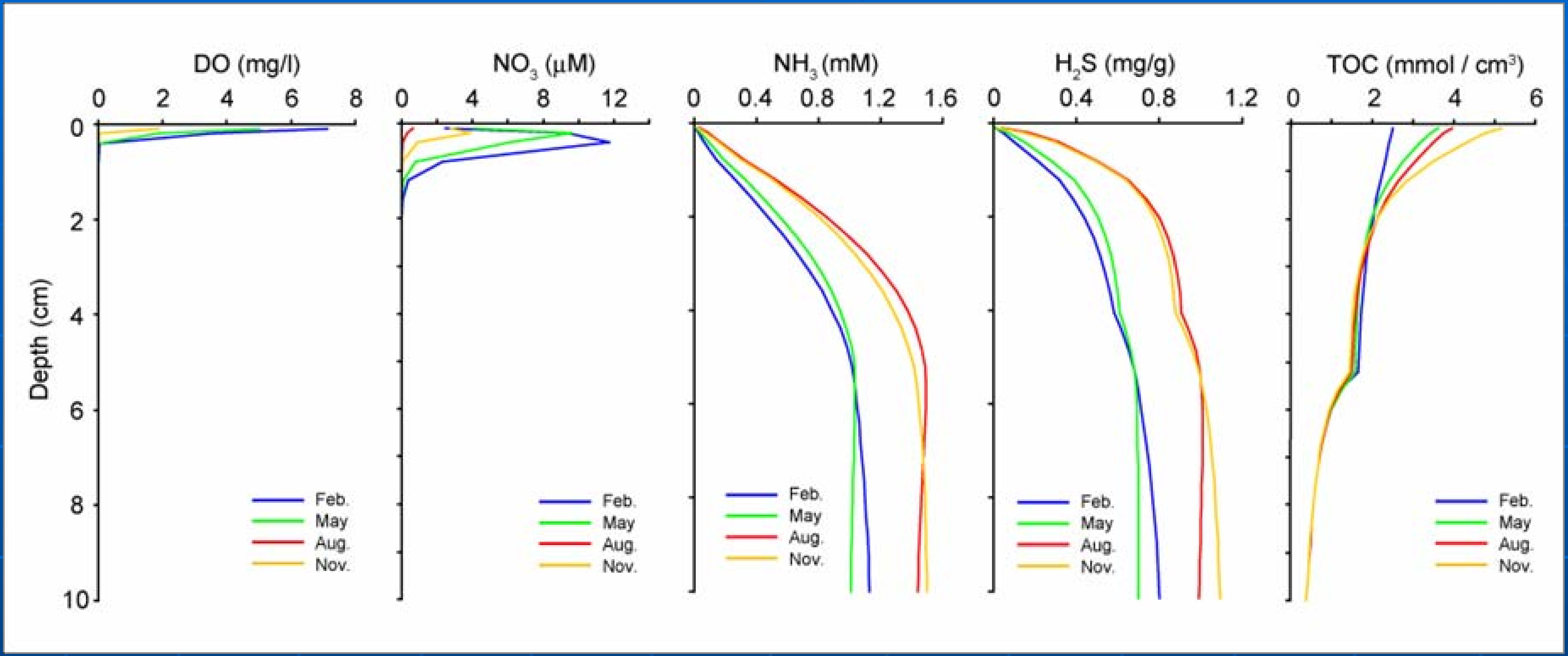




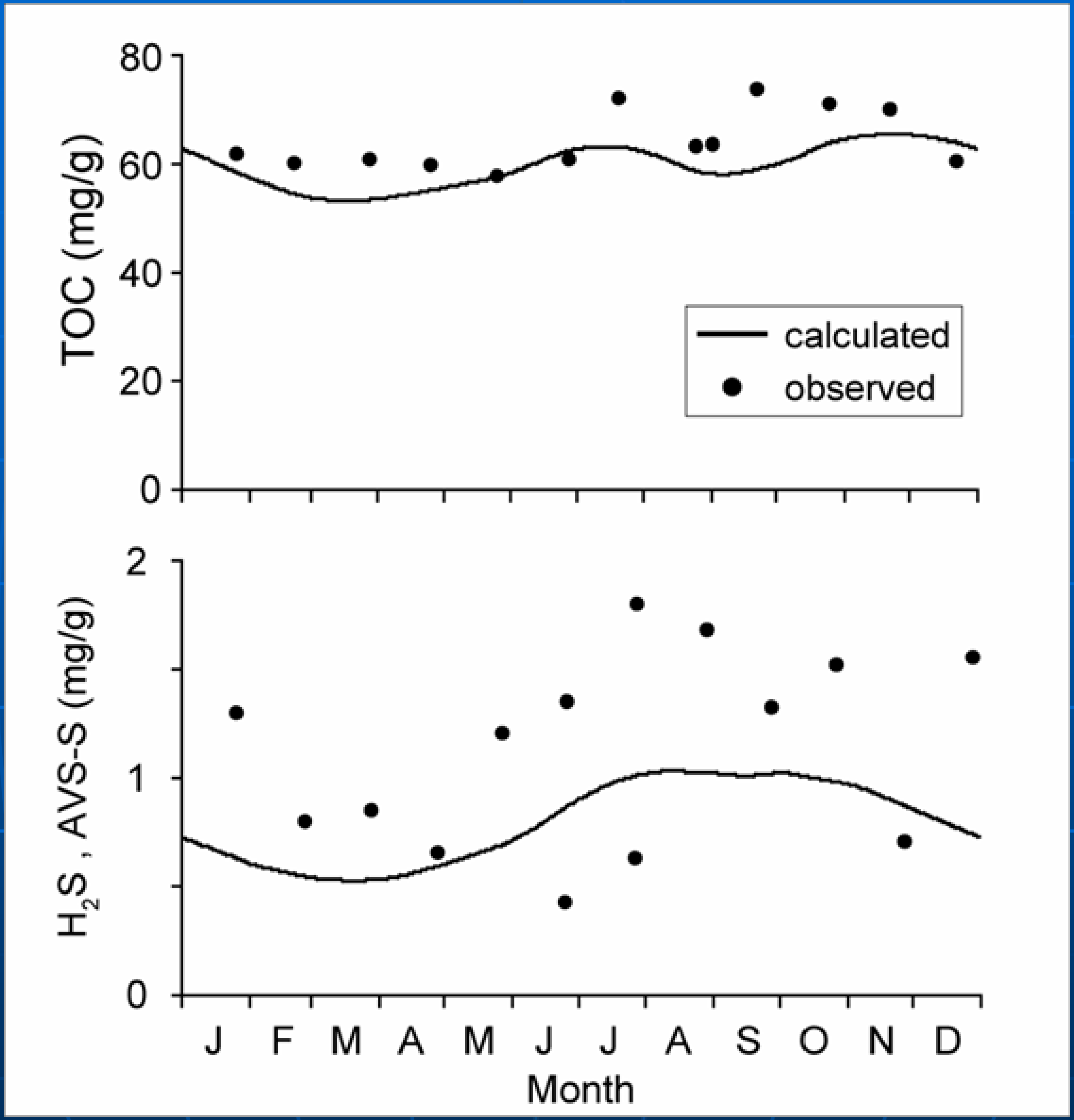




Schematic views of Early Diagenesis Model



Result of calculation (vertical profiles)



Seasonal fluctuations of TOC and sulfide content in the sediment

Models are used in variety of aquaculture sites.

- enclosed area, open ocean
- cage culture, longline culture
- finfish, shellfish, sea weed, etc.

New WG on Environmental Interactions of Marine Aquaculture

Terms of Reference

1. Evaluate current approaches of PICES countries to assess and model interactions of aquaculture activity with the surrounding environments.
2. Standardize methodology to assess interactions.
3. Assess methods to evaluate disease events and interactions between farmed and wild animals.
4. Technology transfer

E N D

Environmental indices for sustainability of aquaculture

“Sustainability indicators are different from impact indicators”

However, understanding impact of aquaculture activity is essential to assess the sustainability.

To assess the sustainability, it is necessary to estimate the impact and to predict the change of environment.

Three zones of the fish farms in Kumano-nada based on the macrofauna and chemical factors (adapted from Yokoyama et al. 2002b, 2004)

Zone	Macrofauna	Chemical factors
Healthy zone	Undisturbed –type assemblages: High species diversity throughout the year; variable species composition	High levels of dissolved oxygen throughout the year; low levels of sediment enrichment; low values of sediment sulfide content
Cautionary zone	Disturbed-type assemblage: Predominance of Prionospio pulchra, an indicator of eutrophic and hypoxic conditions, in summer; low values of biomass, density, and species richness in summer; increased densities in winter, but not as high as in the critical zone	Hypoxic conditions of the bottom water in summer; high levels of sediment enrichment; high values of sediment sulfide content
Critical zone	Azoic in summer; in winter, extremely high density (mean = 24,400/m^2) with a high proportion (mean = 66% in number of indivuduals) of Capitella sp., a worldwide indicator of organic pollution	Anoxic conditions of the bottom water in summer; extremely high levels of sediment enrichment; extremely high values of sediment sulfide content

Values of benthic components for identifying cautionary and critical conditions of fish-farm environments (after Yokoyama et al. 2004)

Benthic components	Cautionary condition	Critical condition
Sediment		
Total organic carbon (mg/g dry)	> 20	> 30
Total nitrogen (mg/g dry)	> 2.5	> 4
Total phosphorus (mg/g dry)	> 4	> 6
Chemical oxygen demand (mg/g dry)	> 30	> 75
Acid-volatile sulfide (mg/g dry)	> 0.5	> 1.5
Macrobenthos		
Biomass* (g/m^2)	< 10	0
Density (individuals/m^2)	< 1500	0
Number of species (/0.04 m^2)	< 20	0

* Wet weight of animals, excluding the shells of molluscs

Environmental quality standards for coastal fisheries grounds (JFRCA 2000)

Indicator	Criteria
Dissolved oxygen in bottom water	
Healthy environments for aquatic animals	> 6 mg/L
Minimum limit for fisheries grounds	4.3 mg/L (3.0 mL/L)
Critical conditions for survival of benthic animals	< 2.9 mg/L (2.0 mL/L)
Chemical oxygen demand of sediment	
Slightly deteriorated environment	> 20 mg/g
Highly deteriorated environment	> 30 mg/g
Acid volatile sulfides of sediment	
Slightly deteriorated environment	> 0.2 mg S/g (dry sediment)
Highly deteriorated environment	> 1.0 mg S/g
Organic Pollution Index*	
Normal sediments	< 0
Polluted sediments	> 0

* Complex combination of three or four environmental factors

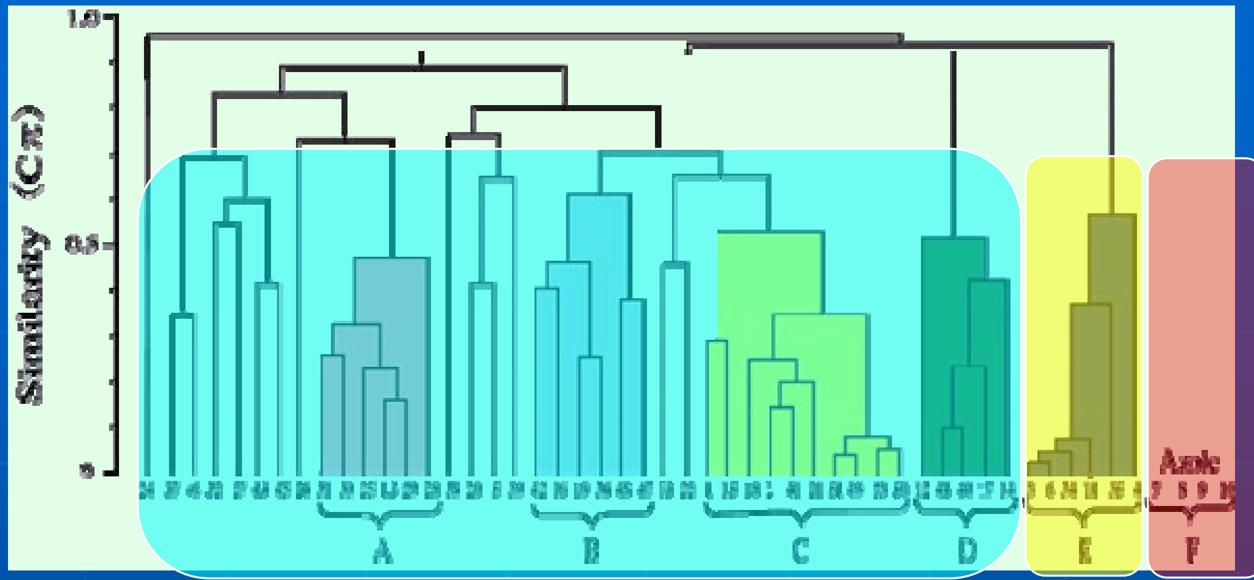
Marine aquaculture production in Japan (2006)

Species	Weight (MT x 1,000)	Value (billions of yen)	Major production region
Finfish	259	215	
Yellowtail (*Seriola quinqueradiata*)	154	117	Kagoshima, Ehime, Ooita
Red sea bream (*Pagrus major*)	72	58	Ehime, Mie, Kumamoto
Puffer (*Takifugu rubripes*)	4	9	Nagasaki, Kumamoto
Flounder (*Paralichthys olivaceus*)	5	7	Ooita, Ehime
Coho salmon (*Oncorhynchus kisutch*)	12	6	Miyagi
Shellfish (mollusks)[a]	422[b]	73	
Oyster (*Crassostrea gigas*)	208[b]	36	Hiroshima, Miyagi, Okayama
Scallop (*Patinopecten yessoensis*)	212[b]	35	Hokkaido, Aomori, Miyagi
Pearl oyster (*Pinctada fucata martensii*)	0.03[c]	16	Nagasaki, Ehime, Mie
Other animals	12	10	
Prawn (*Marsupenaeus japonicus*)	2	9	Okinawa, Kagoshima
Sea squirt (*Halocynthia roretzi*)	10	1	Miyagi
Seaweed	488	112	
Nori (laver, *Porphyra yezoensis*)	367	91	Hyogo, Saga, Kumamoto
Tangle (*Laminaria japonica*)	41	9	Hokkaido, Iwate
Wakame (*Undaria pinnatifida*)	58	8	Iwate, Miyagi, Tokushima
Total	1181	450	

(a: Excluding pearl oyster b: including shell weight c: weight of pearls)

Concepts widely used in aquaculture management (Fernandes *et al.*, 2001)

Term	Definition
Carrying capacity	of a defined area refers to the potential maximum production of a species or population that can be maintained within that area in relation to the available food and environmental resources.
Holding capacity	is the potential maximum production which is limited by a non-trophic resources
Assimilative capacity	is the ability of an area to maintain a 'healthy' environment and 'accommodate' wastes.
Production capacity	is the maximum tonnage level that can be attained without producing a negative impact on the environment and on the farmed stock.
Environmental capacity	refers to the ability of the environment to accommodate a particular activity or rate of activity without an unacceptable impact

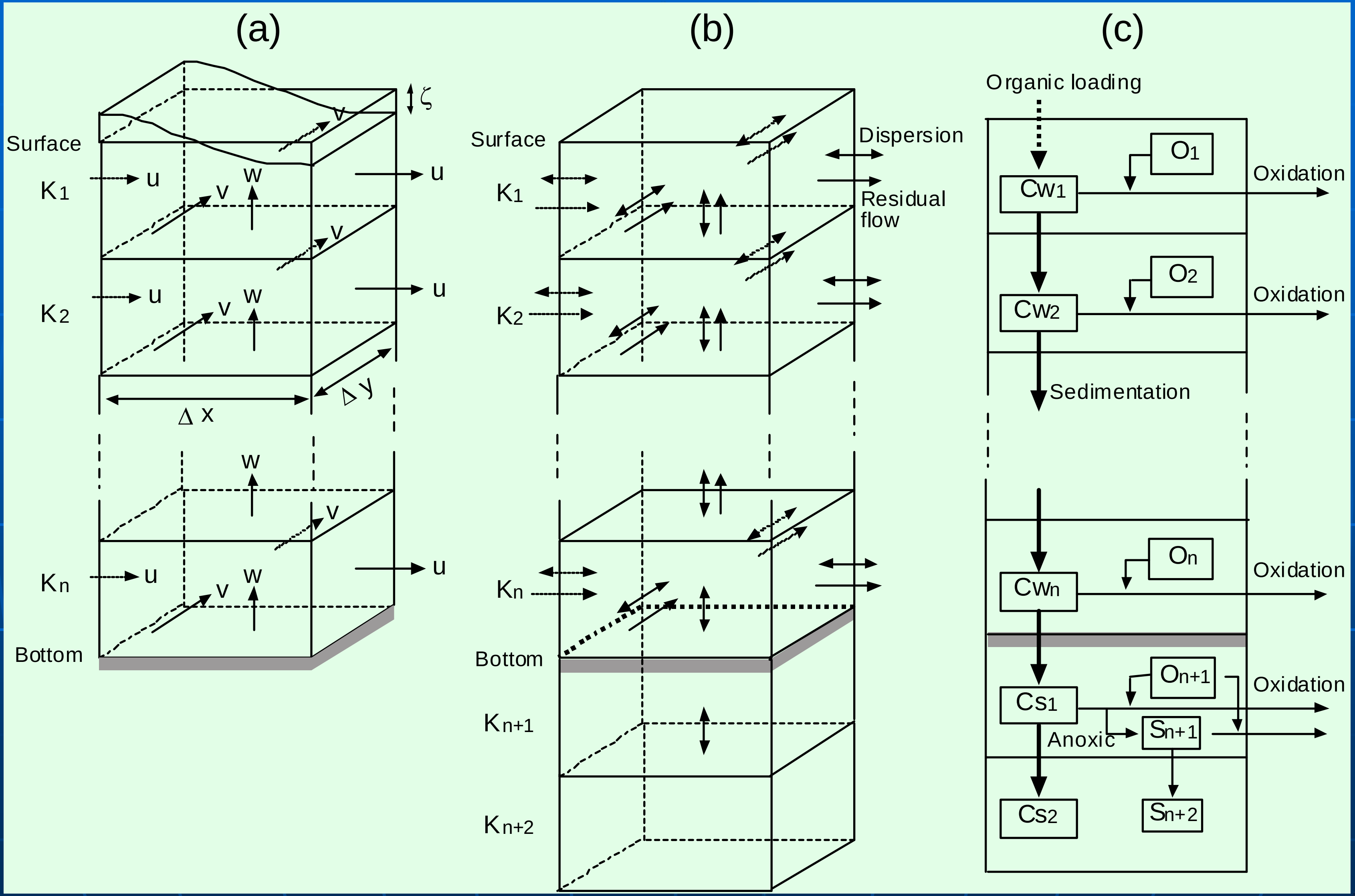


- A, B, C and D are characteristic of a healthy zone
  ・・・high diversity, saturated DO & unenriched sediments

- E is characteristic of a cautionary zone
  ・・・ pollution indicator species, small biomass, low density, hypoxia & enriched sediments

- F is characteristic of a critical zone
  ・・・ azoic conditions, anoxic & highly enriched sediments

Schematic views of the numerical model

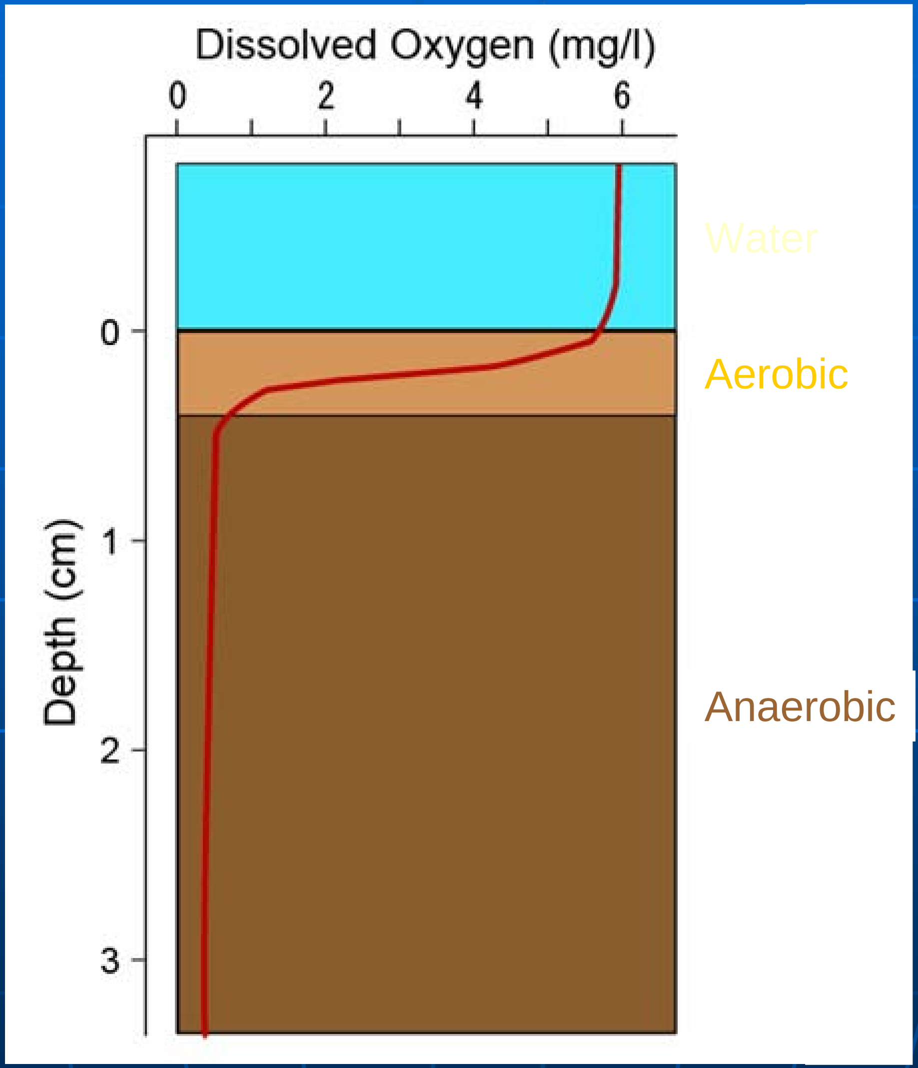


3D Flow Model

Advection and diffusion of organic matter & DO

Flow of organic matter

(2) Early diagenesis model



Vertical profile of oxygen

New WG on Environmental Interactions of Marine Aquaculture - EIMA

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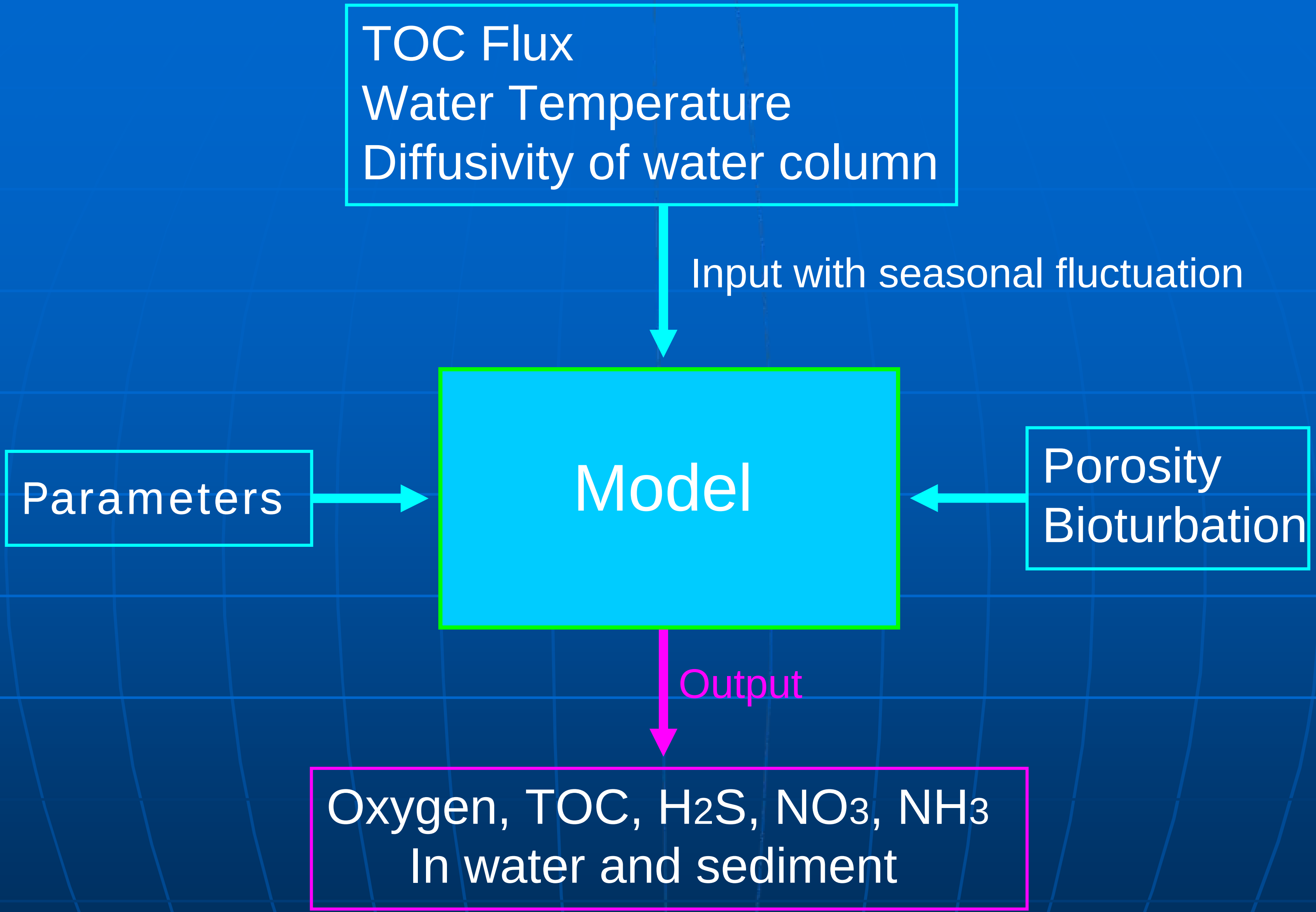
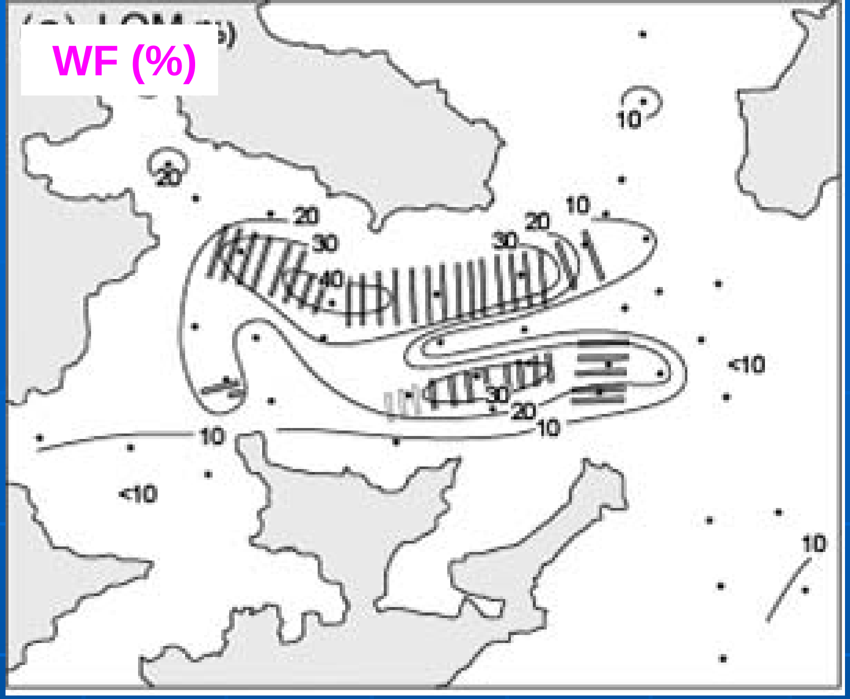
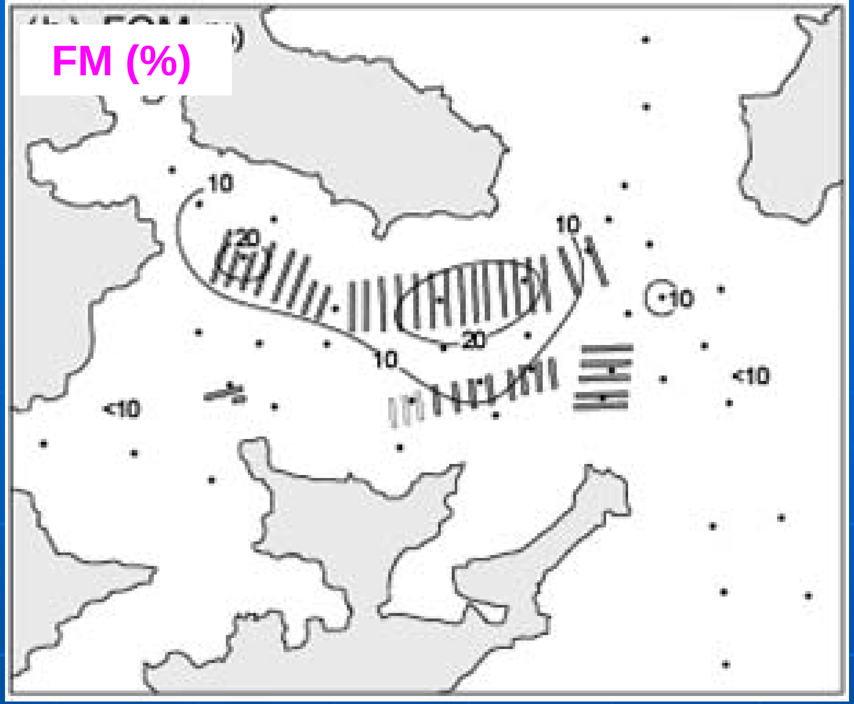


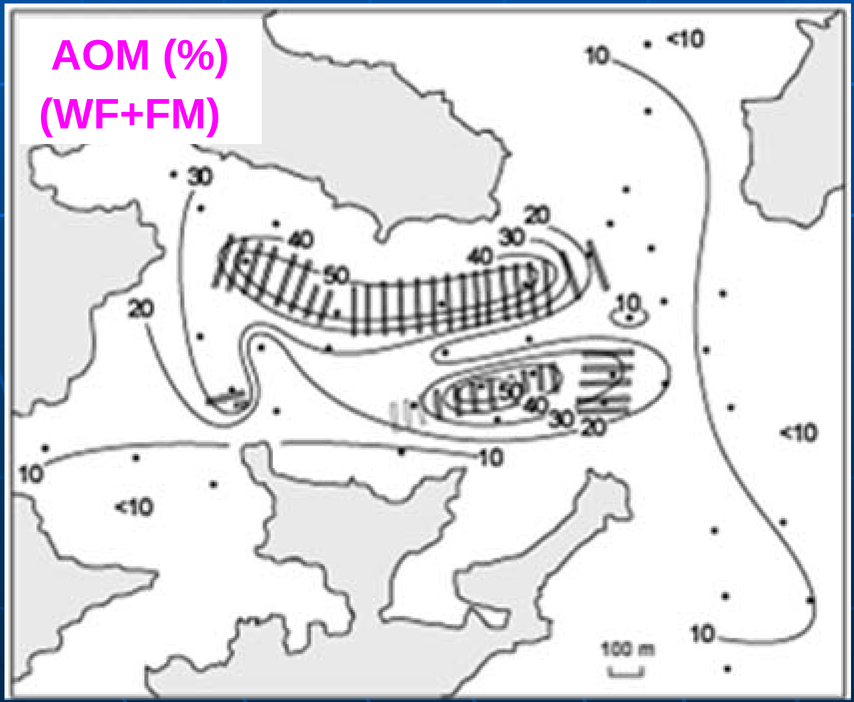
Flowchart of the model

★ threshold values of the environmental factors that classify environments into healthy, cautionary and critical conditions can be estimated.

Benthic components	Cautionary condition	Critical condition
Sediment		
TOC (mg/g)	> 20	> 30
TN (mg/g)	> 2.5	> 4
TP (mg/g)	> 4	> 6
COD (mg/g)	> 30	> 75
AVS (mg/g)	> 0.5	> 1.5
Macrobenthos		
Biomass (g/m^2)	< 10	0
Density ($/m^2$)	< 1500	0
No.of sp. ($/0.04\ m^2$)	< 20	0

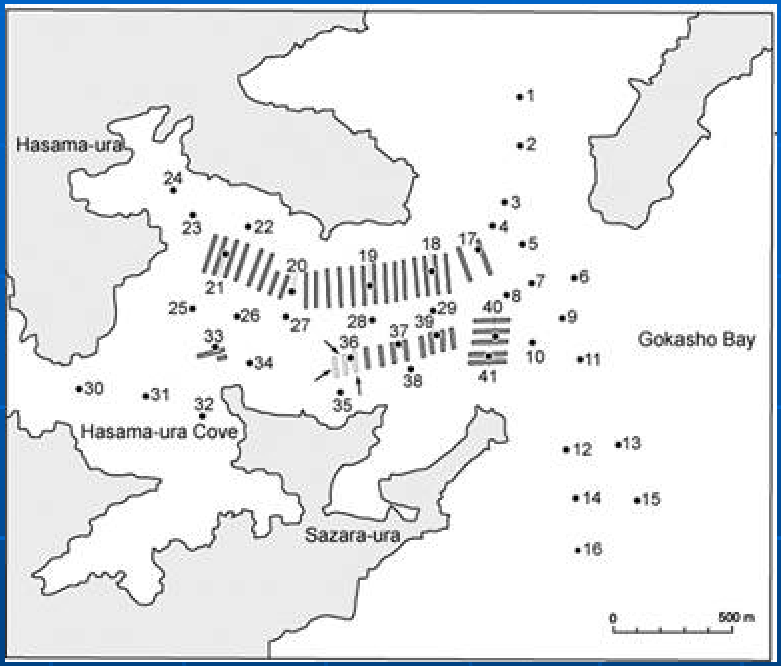




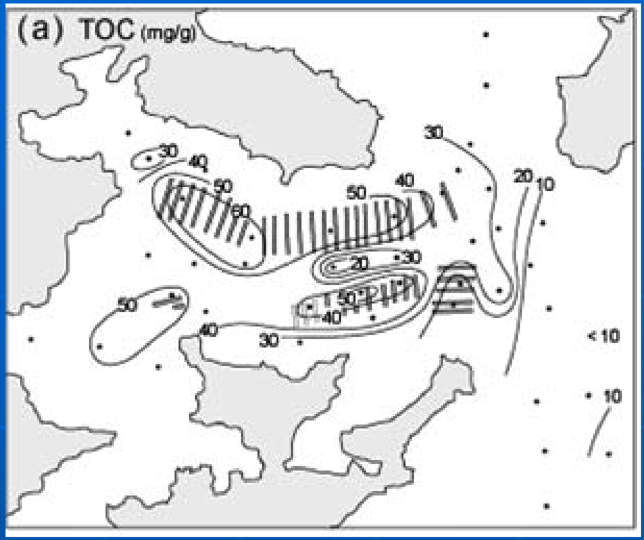


WF: Waste feed (uneaten feed)
FM: Fecal Matter
AOM: Aquaculture derived organic matter

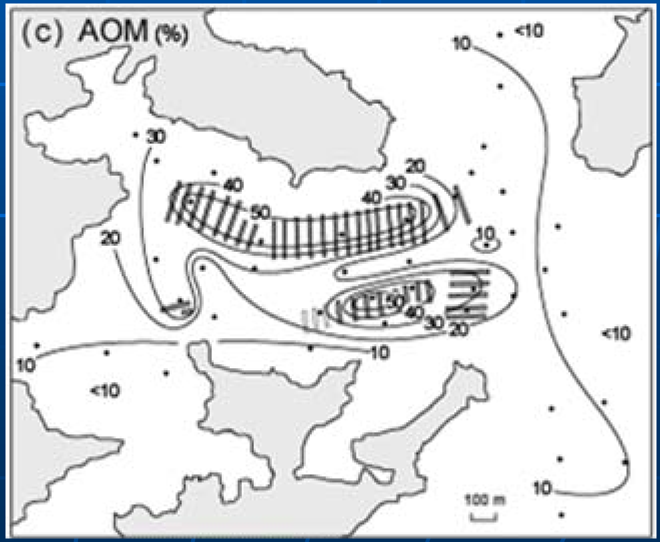
Field Observation of Sediments in the Fish Farm Area



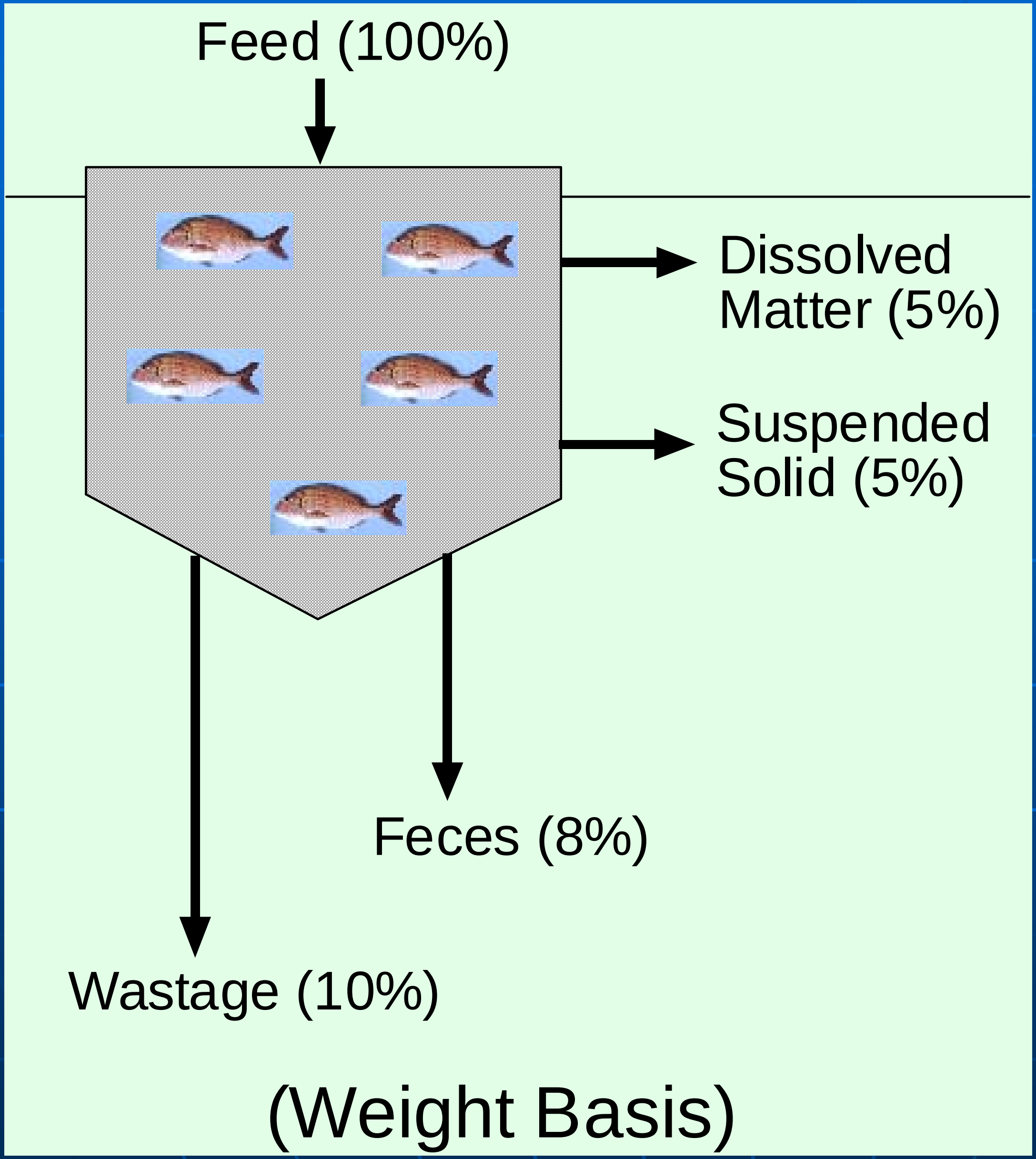
Sampling Stations



Total Organic Carbon in the Sediment (mg/g)

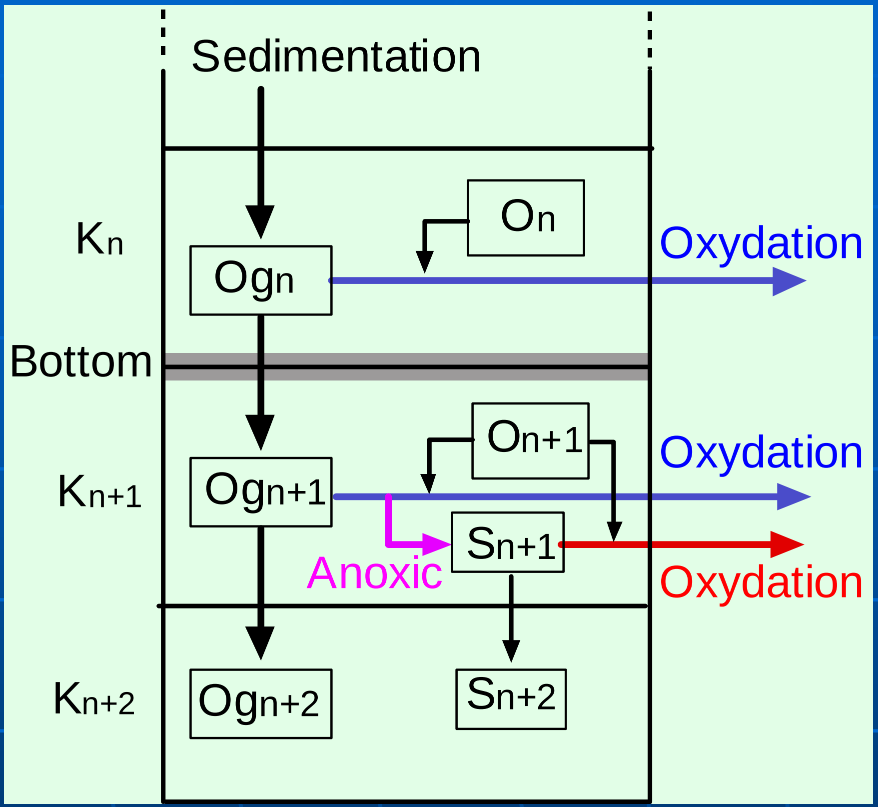


Aquaculture derived organic carbon (mg/g)



	COD (mg/wW)
Feed	155
Dissolved Matter	433
Suspended Solid	300
Feces	85

Flow of organic matter and the relational equations



- O_n: Dissolved oxygen
- Og_n: Organic matter
- S_n: Reduced substance

in the K_n layer.

Equations

Aerobic degradation rate

$$= a_1 \ (O_n - a_2) \ Og_n$$

Anaerobic degradation rate

$$= a_3 \, Og_n \ / \ (O_n - a_4)$$

Chemical oxygen uptake rate

$$= a_5 \, Og_n \, O_n$$

(Omori *et al.*, 1994)

Limit Values of Organic Matter Loading Rate (μ mol O_2/cm^2/day)