Global Review of
Nutrients, Pelagic Ecosystems, and Carrying Capacities for Farmed Salmon

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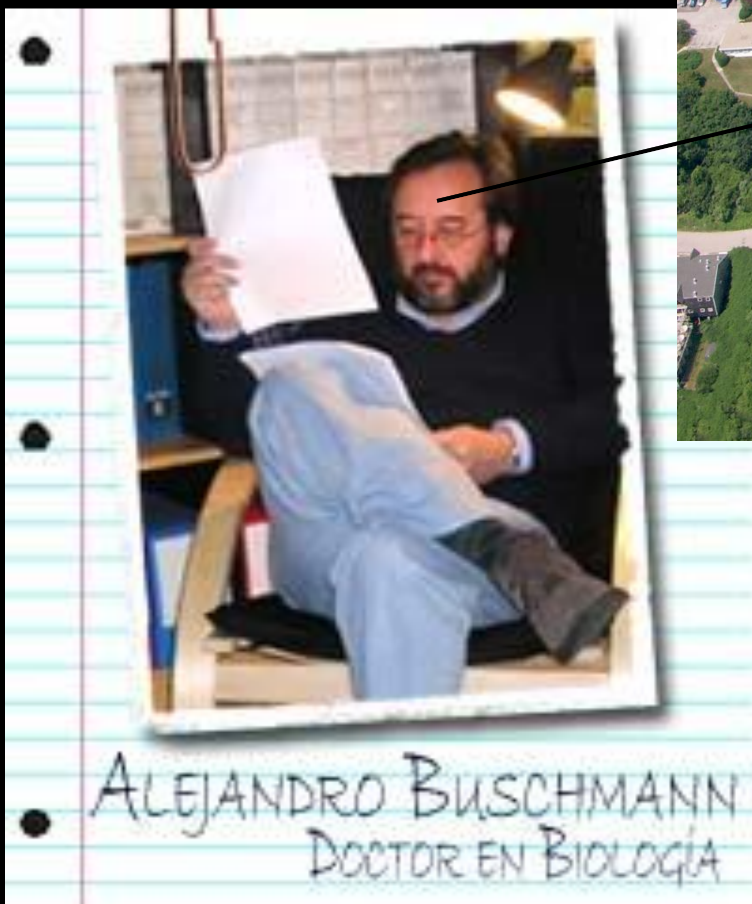
UNIVERSITY OF
Rhode Island

Whispering Pines
Conference Center

Gregor with Camera


EXIT
FIRE


ALEJANDRO BUSCHMANN
DOCTOR EN BIOLOGÍA

BCP Making his San Antonio Presentation

Photographed by Gregor Reid

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Objectives and background of the study:

(1) Review status of current research and understanding of issues

(2) Identify existing research efforts and key research groups

(3) Identify significant gaps and/or areas of disagreement

(4) Recommend scope, time frame, and costs for addressing gaps.

Environmental Loadings and Impacts are related to:

*Standing stock: seasons, densities, sizes of fish

*Production: seasons, densities of fish

*Conversions: Physiology, feeds

*Quality/Quantities of feed: seasons, densities

*Temperature/3 D Hydrodynamics

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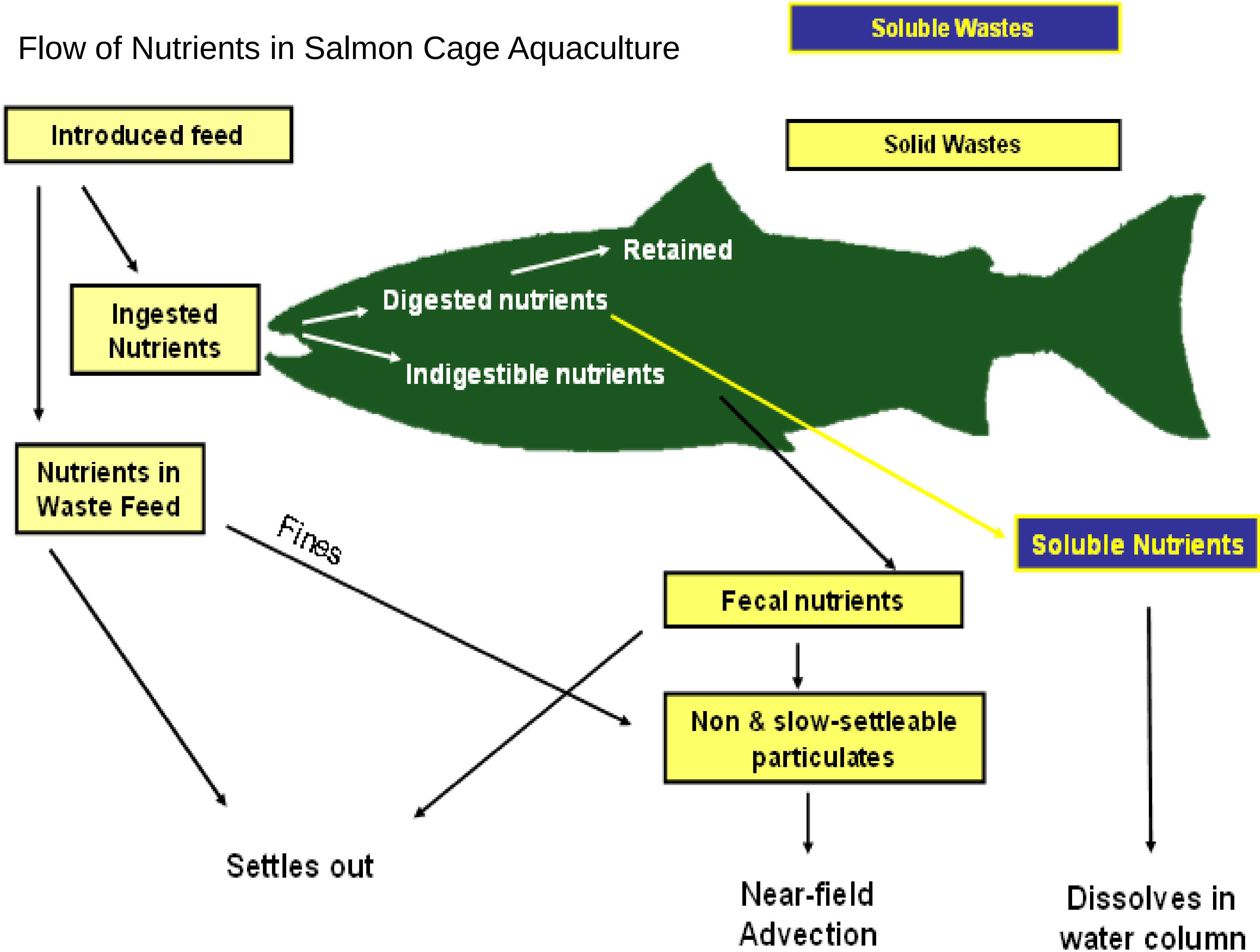
Chapter 1: Nutrient releases from salmon aquaculture

Dr. Gregor K. Reid, University of New Brunswick, Canada

Flow of Nutrients in Salmon Cage Aquaculture



Feed quality and quantity issues

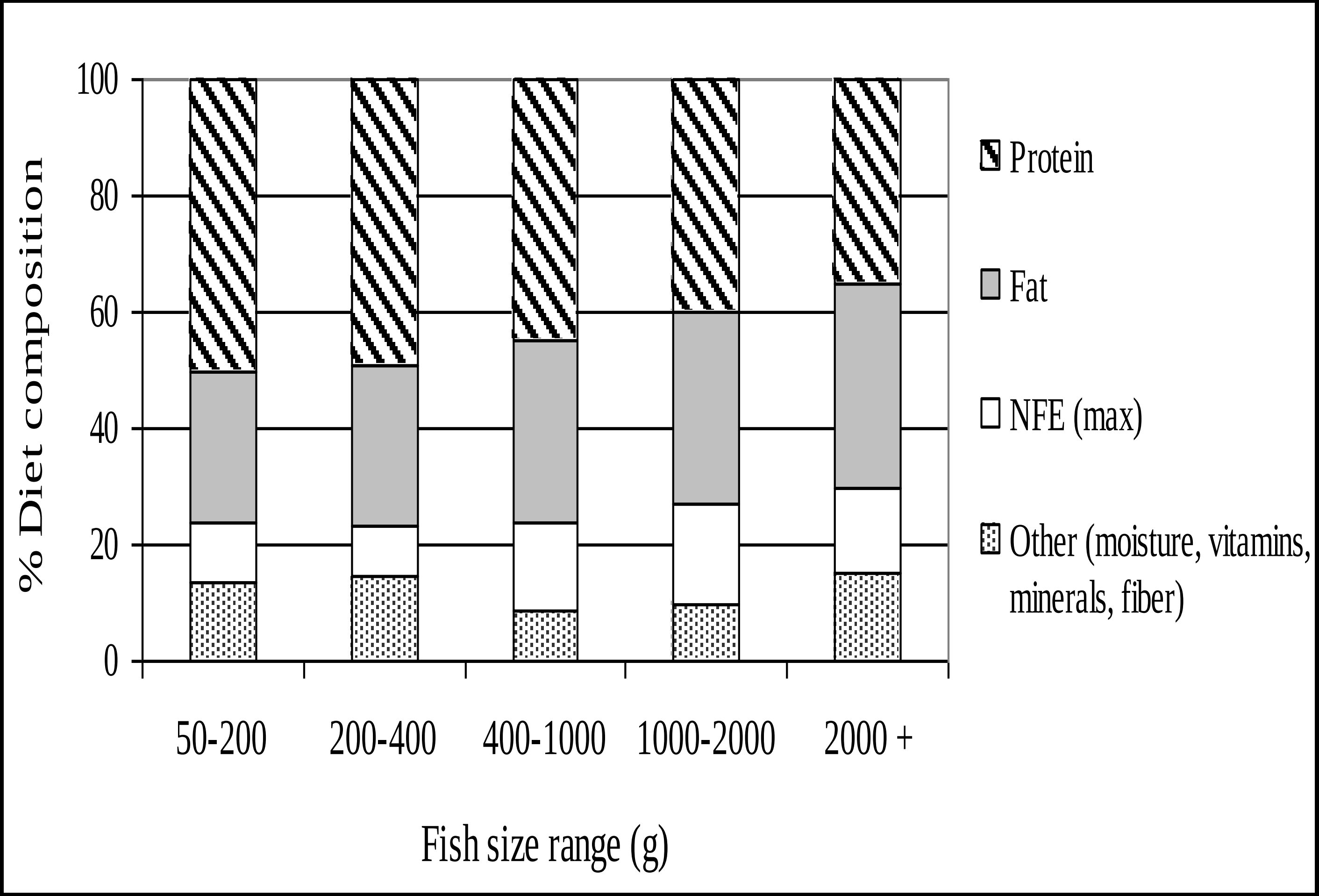
Feed use increases with fish size; feed composition changes

Protein levels exceeded minimal amino acid requirements (Lovell, 2002)

Protein levels reduced “protein sparing” with lipids (Wilson, 2002)

Today = Proteins 35-50%, Lipids 25-40%

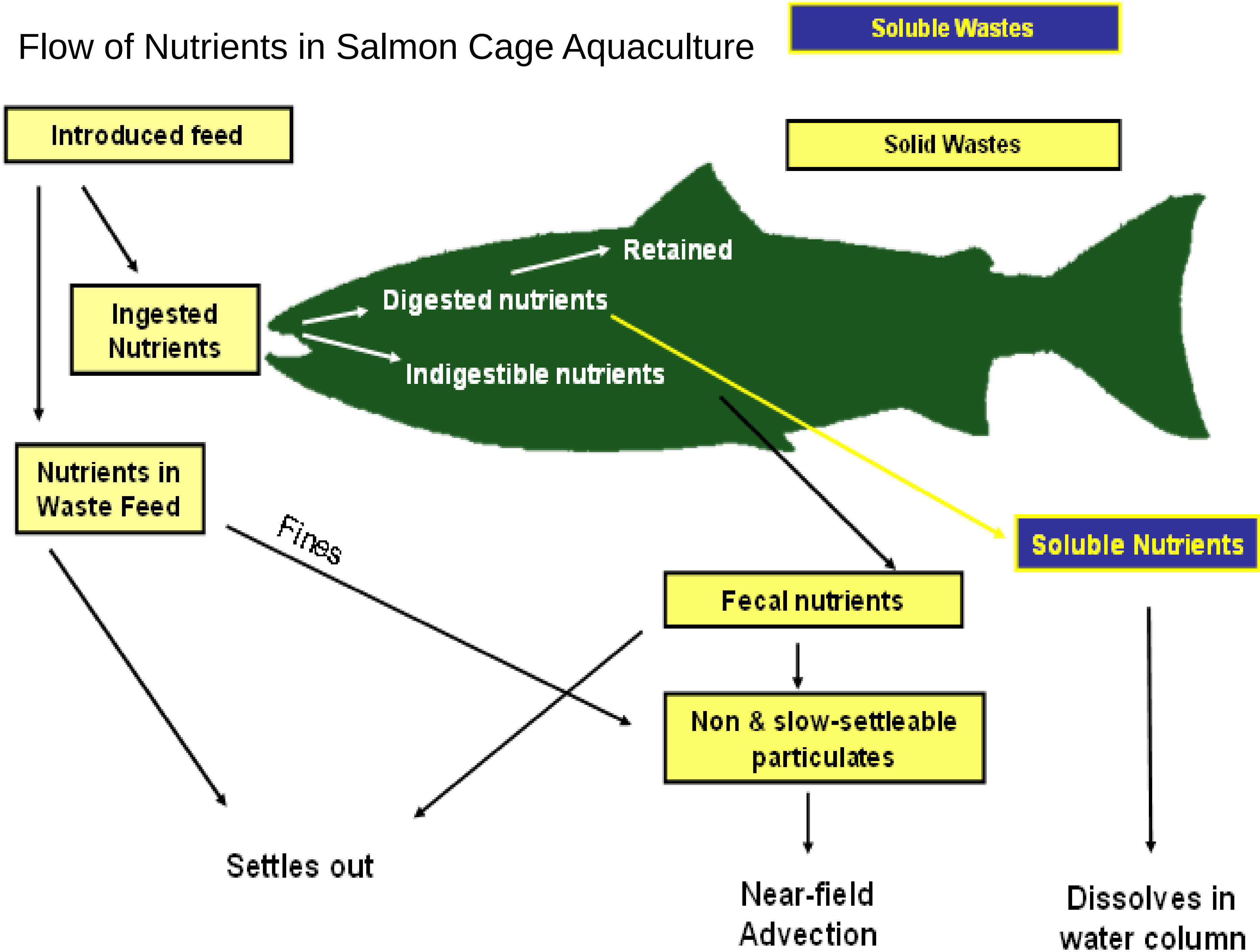
Mean dietary composition vs. fish size from feed composition data



Typical Atlantic salmon feed for grow out sized (>2000g) fish

	Proximate composition (%)
Protein min)	39
Fat (min)	33
Carbohydrates (max)	10
Fibre (max)	1.5
Phosphorus (approx.)	1.2
Minerals (max)	6.8
Moisture (max)	8.5

Flow of Nutrients in Salmon Cage Aquaculture



Intake and Solid Nutrient Waste
[Feed loss; fines; fecal materials]

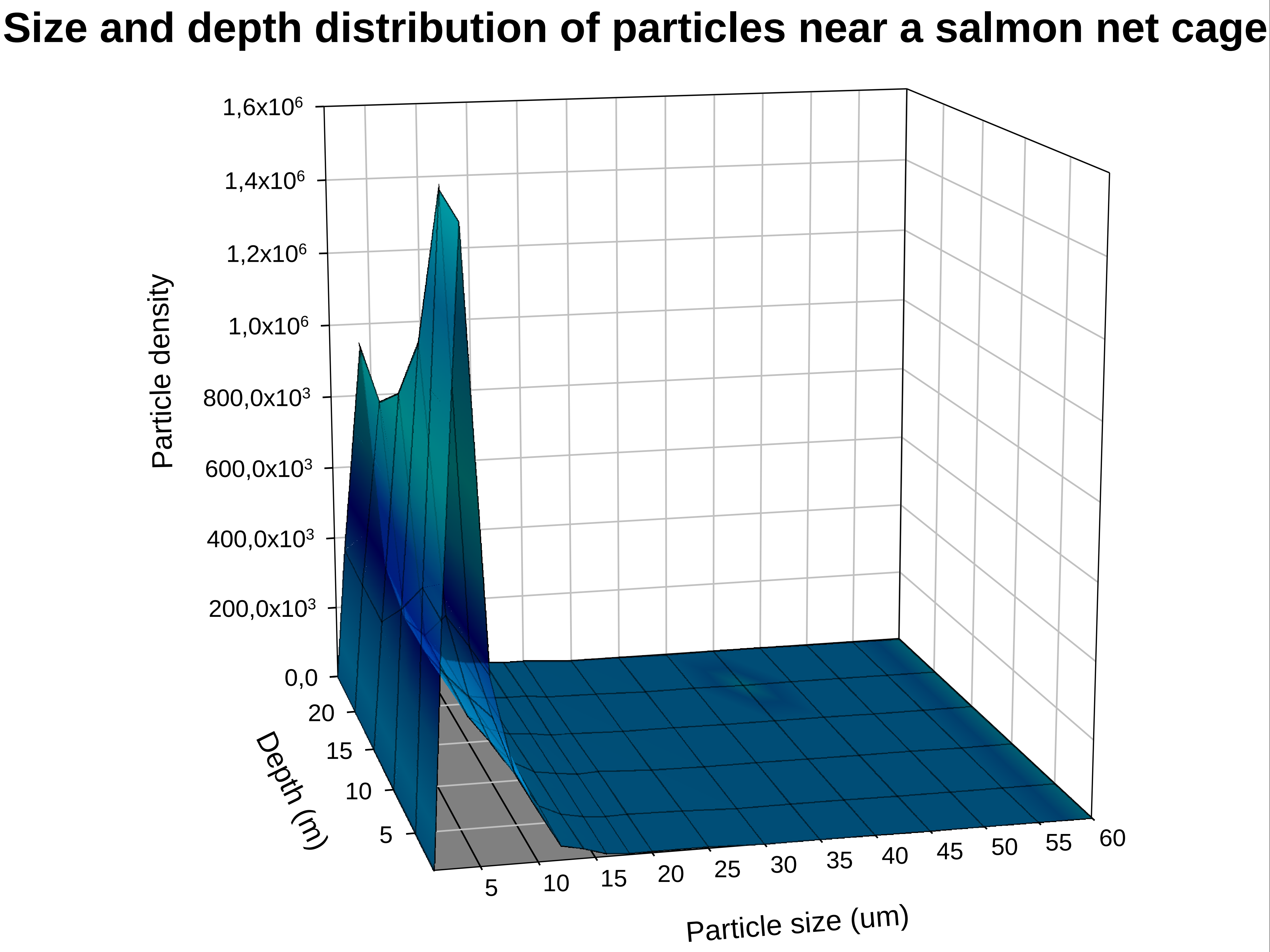
Feed loss

*20% (Beveridge, 1987) -- now between 3% (Cromey et al., 2002) and 5% (Bureau et al., 2003) Therefore, intake is ~95-97% of feed introduced

Fines (too small to be eaten; all is essentially waste to the environment)

*extrusion reduced amount; today due to amount of handling

*heterotrophic food web?



Size and depth distribution of particles near a salmon net cage
Particle density
1,6x10⁶
1,4x10⁶
1,2x10⁶
1,0x10⁶
800,0x10³
600,0x10³
400,0x10³
200,0x10³
0,0
Depth (m)
20
15
10
5
Particle size (um)
5
10
15
20
25
30
35
40
45
50
55
60

Nutritional mass balance approach to estimate fecal mass and composition (using a typical Atlantic salmon feed for grow out sized (>2000g) fish)

	Proximate compos. (%)	Digest (%)	Amount Digested (%)	Amount in feces (%)
Protein min)	39	90	35.1	3.9
Fat (min)	33	95	31.7	1.7
Carbohydrates (max)	10	60	6.0	4.0
Fibre (max)	1.5	10	0.15	1.3
Phosphorus (approx.)	1.2	50	0.60	0.6
Minerals (max)	6.8	50	3.5	3.4
Moisture (max)	8.5			
			Total dry fecal ~	15%

G. Reid

~95% of feed is consumed

~5% lost to the environment

Consumed feed produces ~15% feces

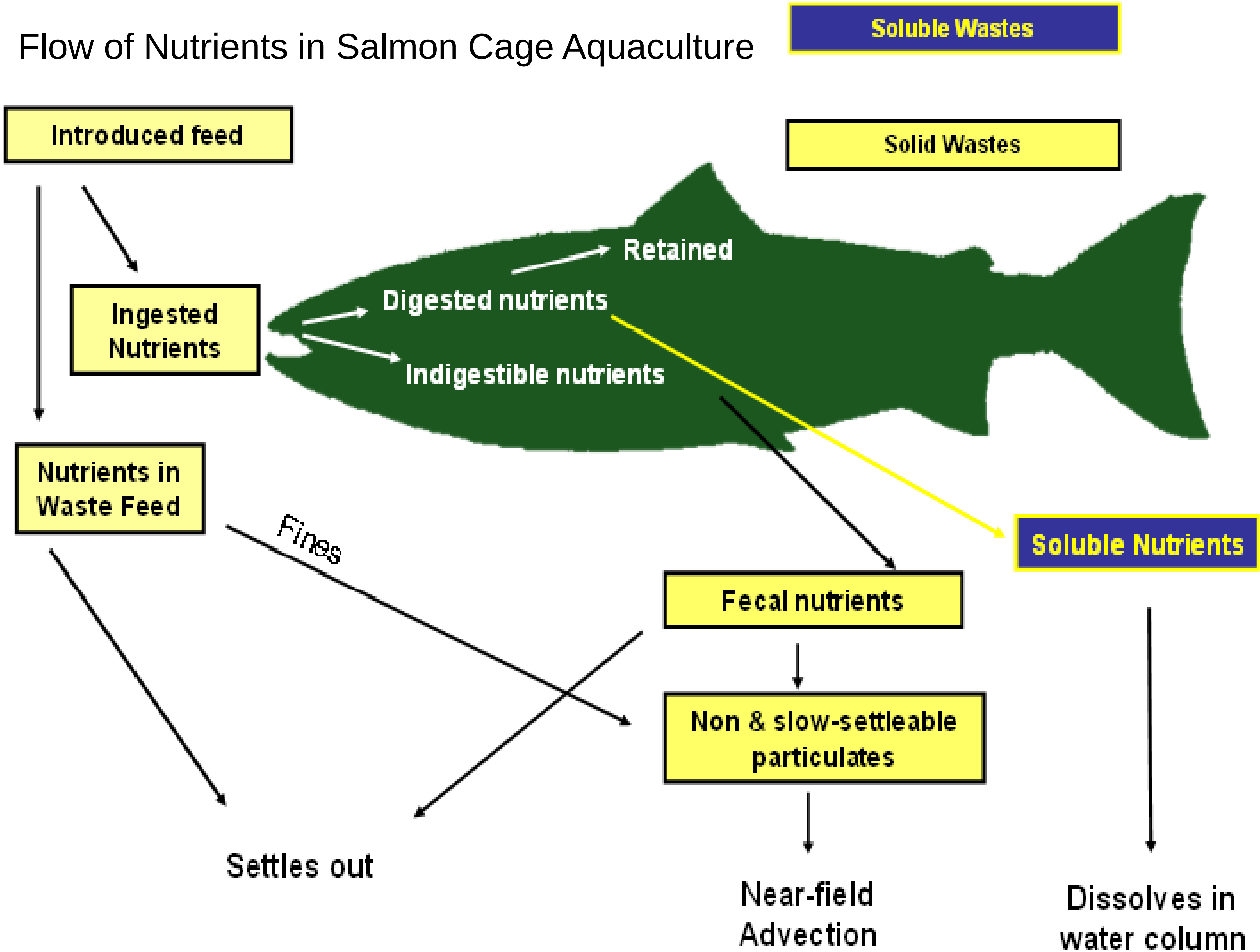
~85% soluble waste

Physical Properties of Solid Wastes

Settling velocities

Pellets – high and not widely variable
Fecal matter – low and highly variable (3.2-6.4 cm/sec.)

Flow of Nutrients in Salmon Cage Aquaculture



Soluble Nutrient Wastes

Nutrients digested (absorbed through the intestinal wall) are excreted because they are catabolized (converted) or, the amount digested exceeds metabolic requirements

Soluble nutrients dissolve in water; their initial dilution and transport are a function of hydrodynamics; persistence is determined by uptake by the marine planktonic ecosystem

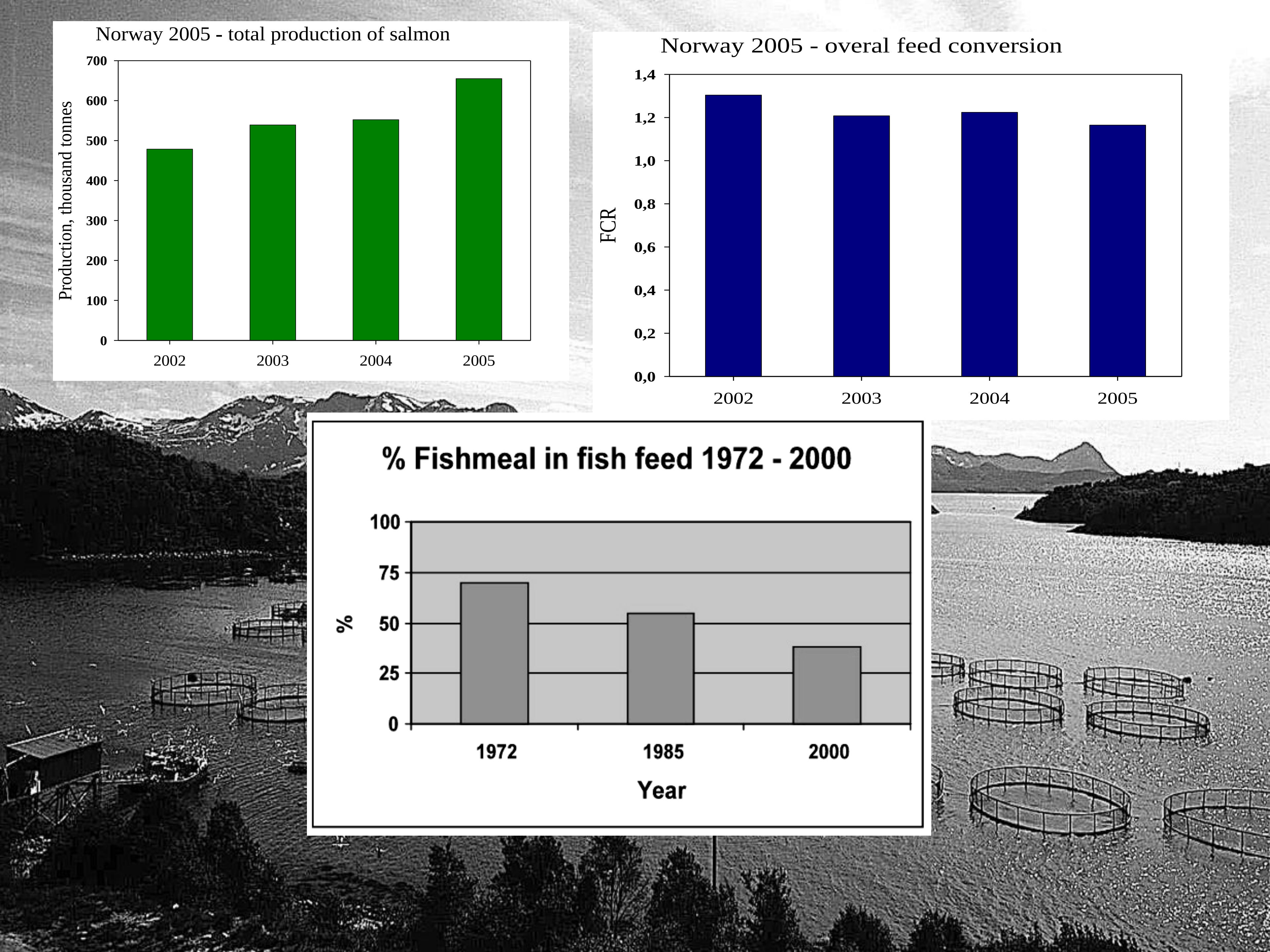
Protein is metabolized and discharged as ammonium NH_4^+ through the gills and to a lesser extent as urea in urine.

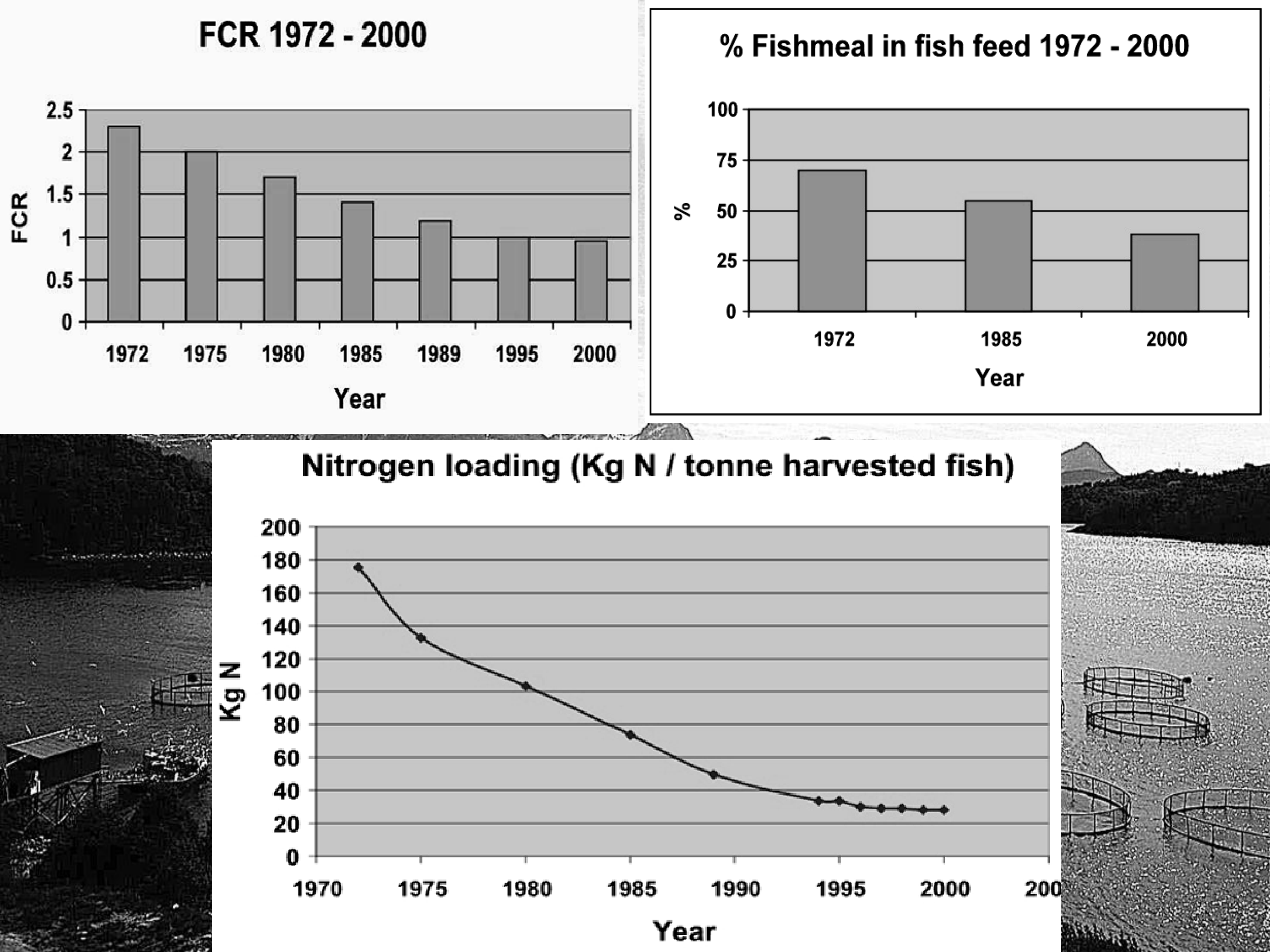
Phosphorus is discharged at PO_4^+

Lipids are metabolized to carbon dioxide and water

	Protein Feed Composition (%)	Digestibility (%)	Amt Digested (%)	Carcass Composition (%)	Retained in Growth (1.1 FCR)	Soluble Nitrogen Loading (%)
	39	90	35	18.5	16.8	2.9

Improvement in world FCR from 1.7 to 1.3 from 1993 to 2003


Norway 2005 - total production of salmon
Production, thousand tonnes
0
100
200
300
400
500
600
700
2002
2003
2004
2005
Norway 2005 - overal feed conversion
FCR
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
2002
2003
2004
2005
% Fishmeal in fish feed 1972 - 2000
%
0
25
50
75
100
1972
1985
2000
Year


FCR 1972 - 2000
FCR
2.5
2
1.5
1
0.5
0
1972
1975
1980
1985
1989
1995
2000
Year
% Fishmeal in fish feed 1972 - 2000
%
100
75
50
25
0
1972
1985
2000
Year
Nitrogen loading (Kg N / tonne harvested fish)
Kg N
200
180
160
140
120
100
80
60
40
20
0
1970
1975
1980
1985
1990
1995
2000
200
Year

Comparisons of salmon wastes with municipal wastes

QUALITY: Salmonids do not produce fecal coliform bacteria

Municipal wastes have severe pathogenic and chemical concerns (coliforms and ~200 identified contaminants)

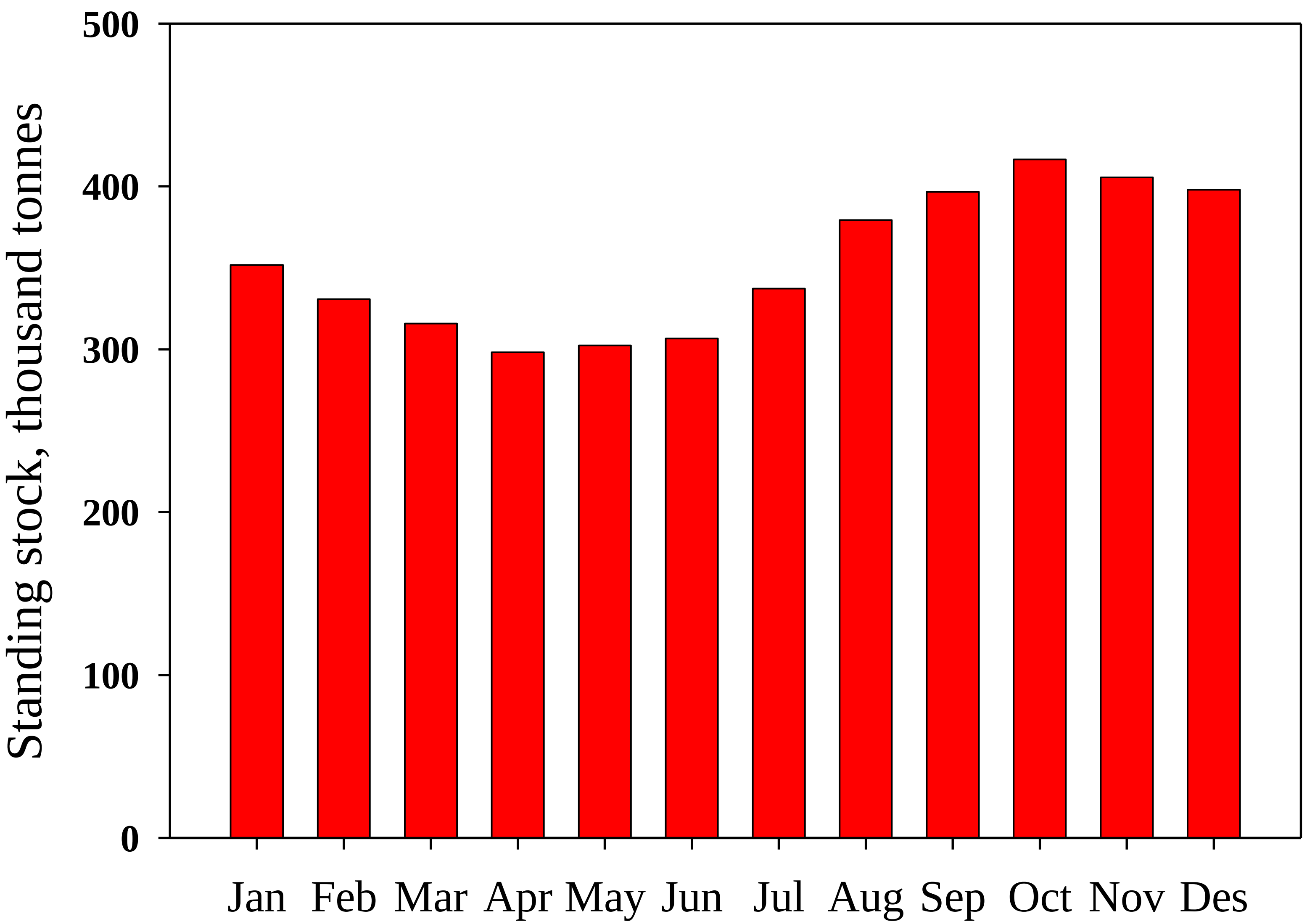
Salmonids have been known to produce contaminants, but quantities are very low; and salmonids can be grown without contaminants (IMTA)

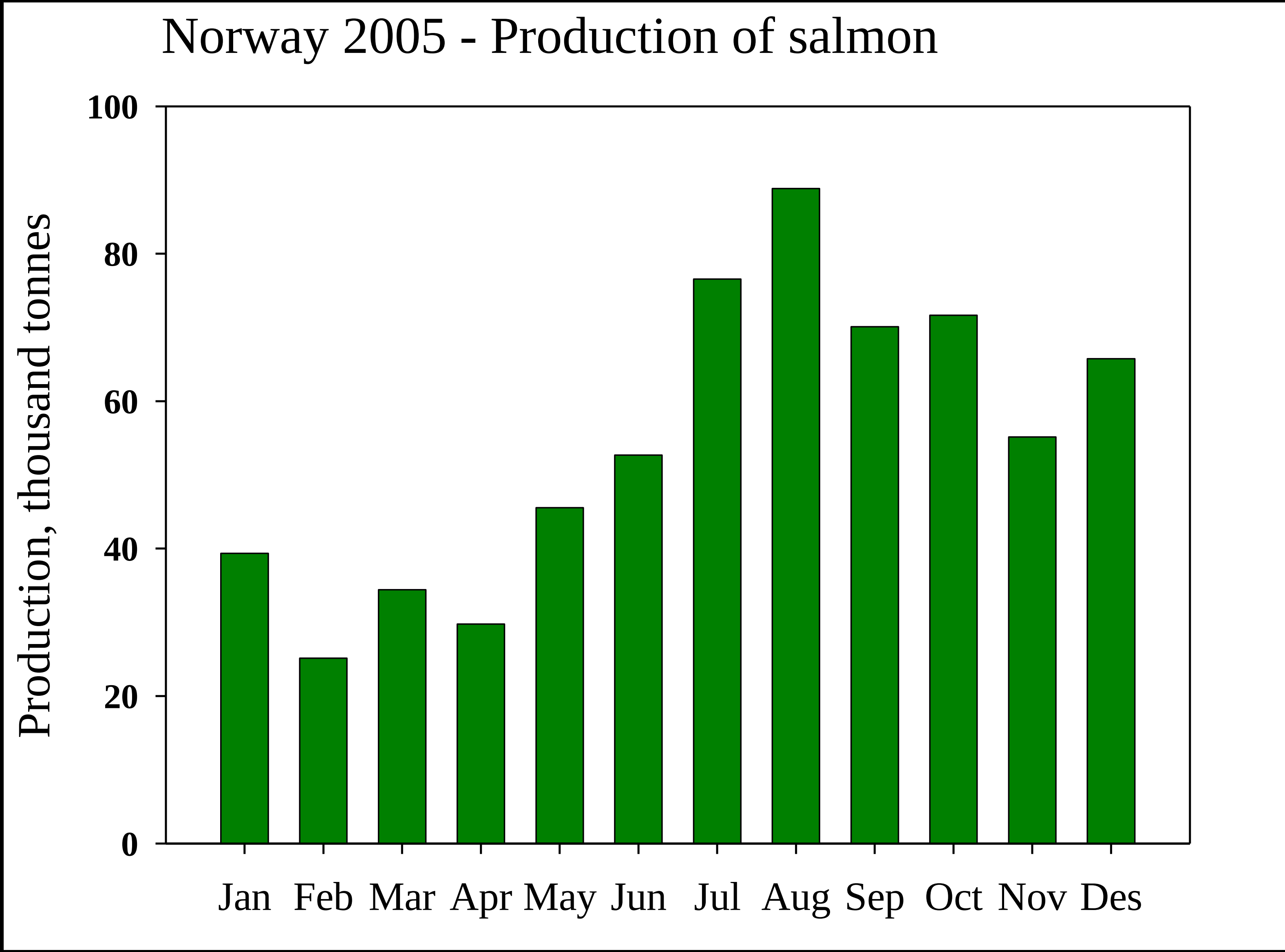
Compare loadings for individual contaminants and compounds

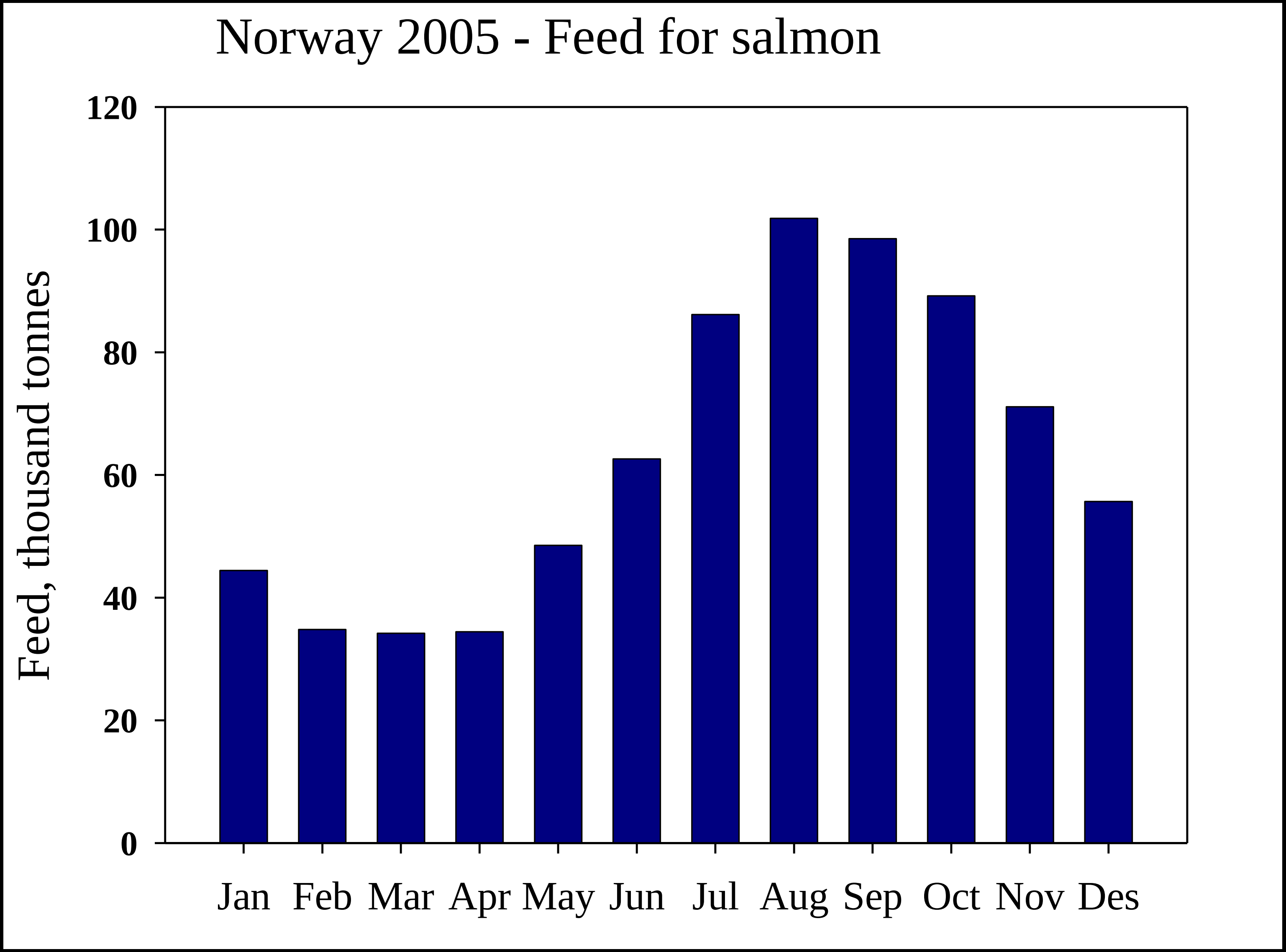
Chapter 2: Impacts on pelagic ecosystems

Dr. Yngvar Olsen, University of Science and Technology, Norway

Norway 2005 - Standing biomass of salmon

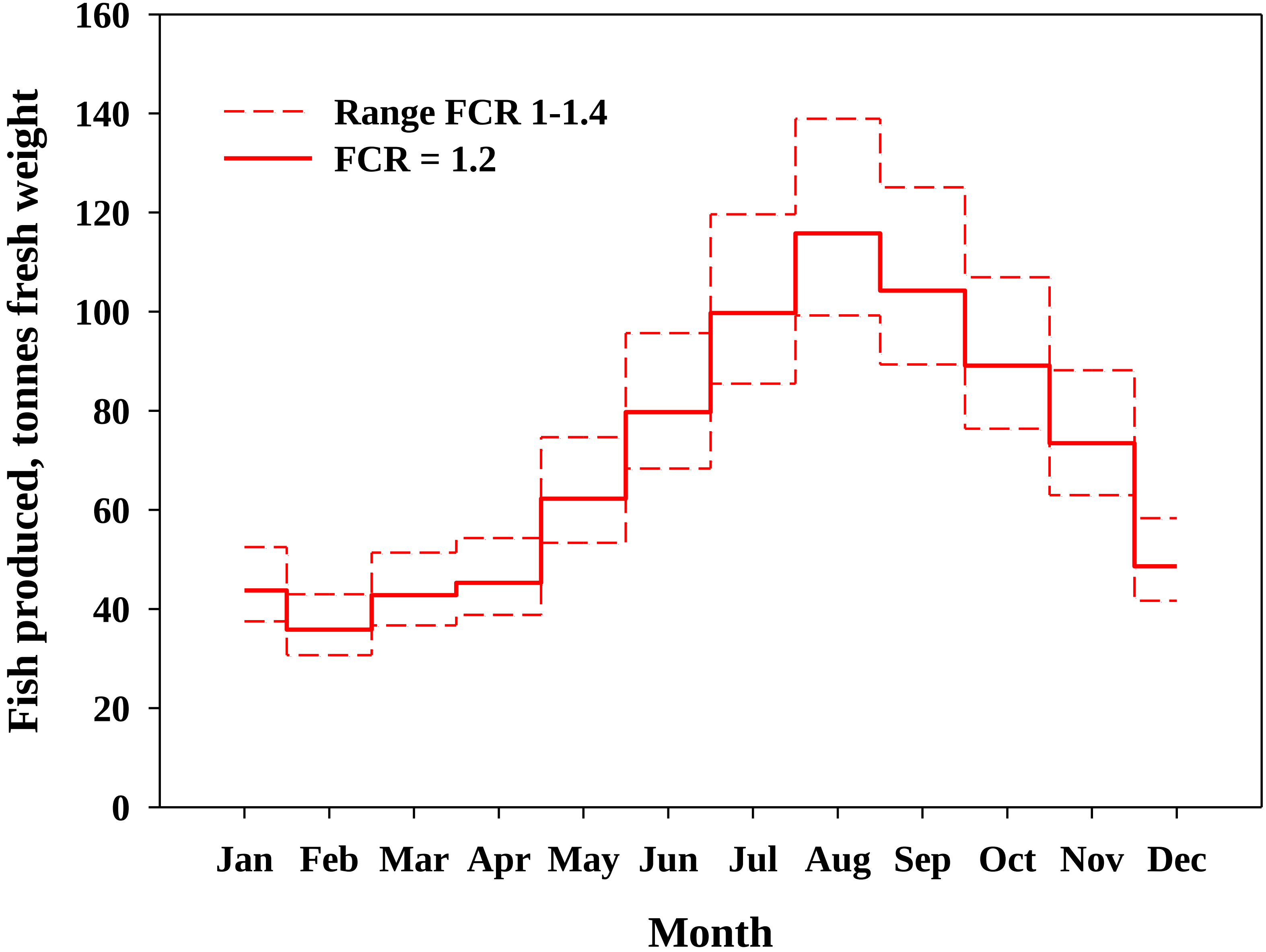


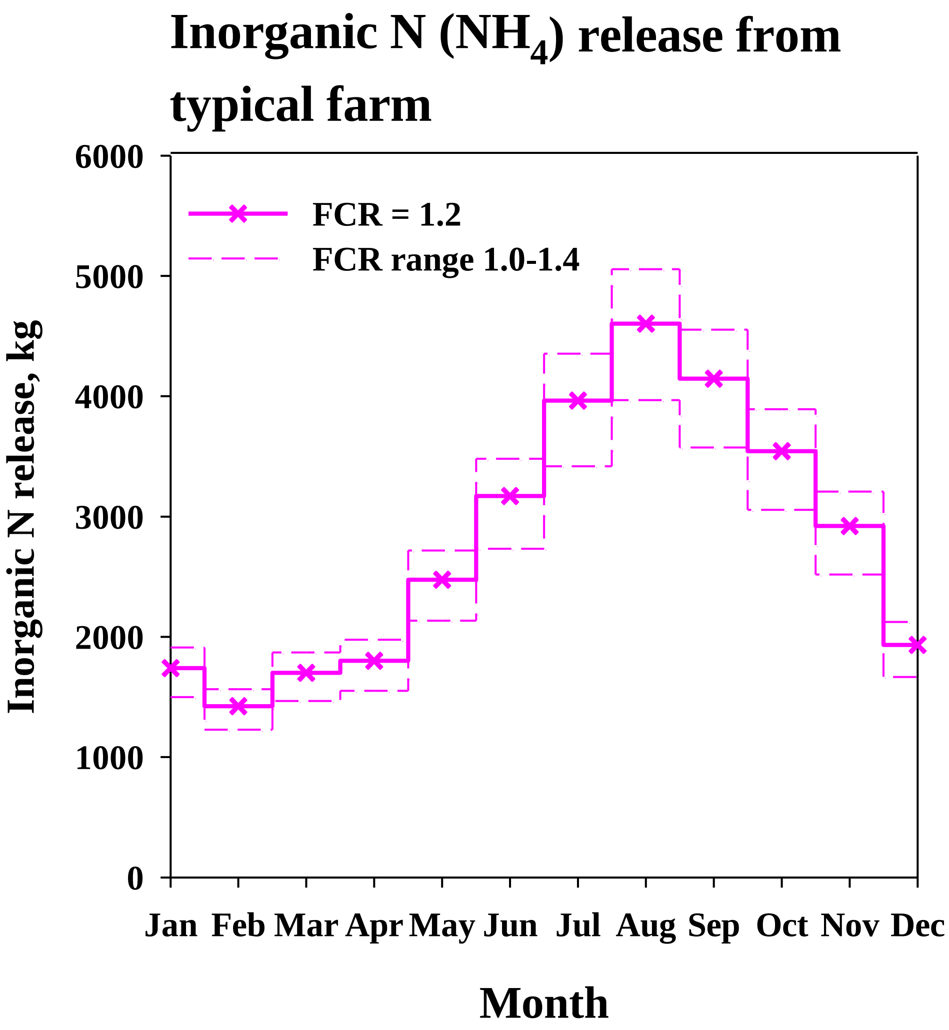

Norway 2005 - Production of salmon
Production, thousand tonnes
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Des

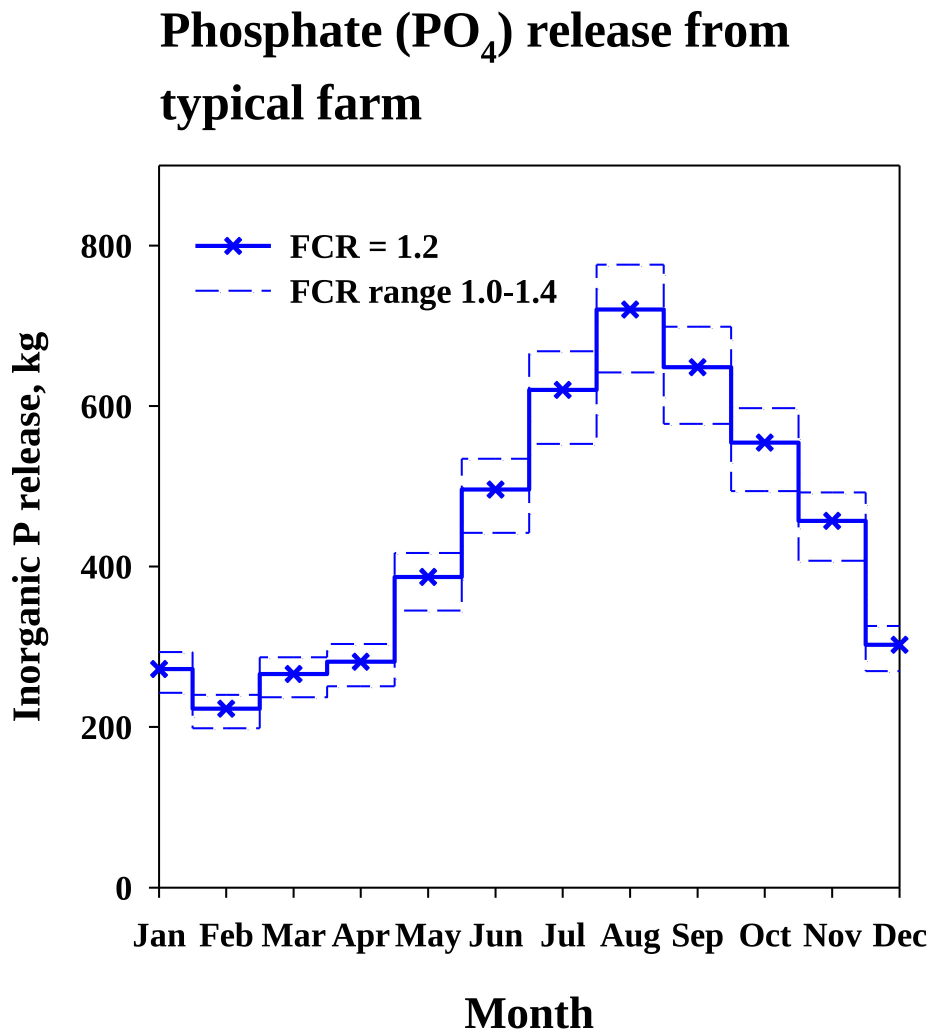


Norway 2005 - Feed for salmon
Feed, thousand tonnes
0
20
40
60
80
100
120
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Des

Production of typical Norwegian farm




Inorganic N (NH_4) release from typical farm
FCR = 1.2
FCR range 1.0-1.4
Inorganic N release, kg
6000
5000
4000
3000
2000
1000
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month


Phosphate (PO_4) release from typical farm
FCR = 1.2
FCR range 1.0-1.4
Inorganic P release, kg
800
600
400
200
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

Fate of the principal nutrient components released from salmon cages

Particulate N and P

- ✓ Large particles sink rapidly to the seafloor, consumed by fish or other benthic organisms
- ✓ Small particles of feed and faeces are immediately available for mussels and zooplankton
- ✓ Not available for phytoplankton and macroalgae

Dissolved inorganic N and P

- ✓ Immediately taken up by phytoplankton (food for mussels) and macroalgae. The growth response is delayed (some days).

Dissolved organic N and P

- ✓ Stable N and P components, available for phytoplankton on long time scale
- ✓ Consumed by bacteria

If eutrophication occurs = Magnitude of its concentration and if it's "limiting" in an environment

Leibig's Law of the Minimium

Marine = nitrogen
Freshwater = phosphorus

Light

Chain reaction, following nutrient input

Increased nutrient concentration (DIN, DIP)

Immediate reaction, hours

Nutrients taken up by algae (PON, POP)

Relatively slow, 2 – 5 days before response

Increased primary production

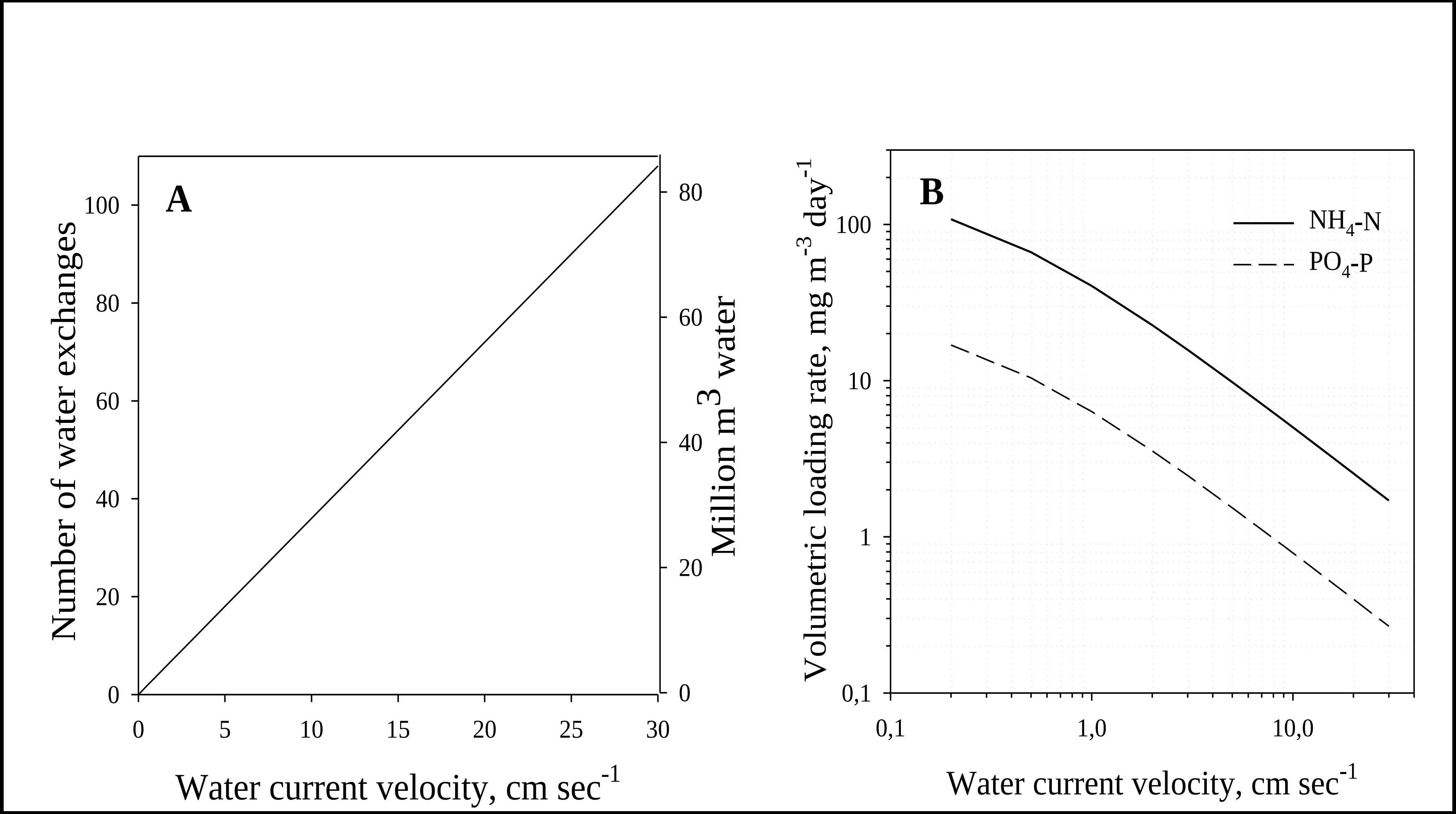
Accumulated production, 1 -2 days delay relative to production, accumulate "downstream"

Increased biomass

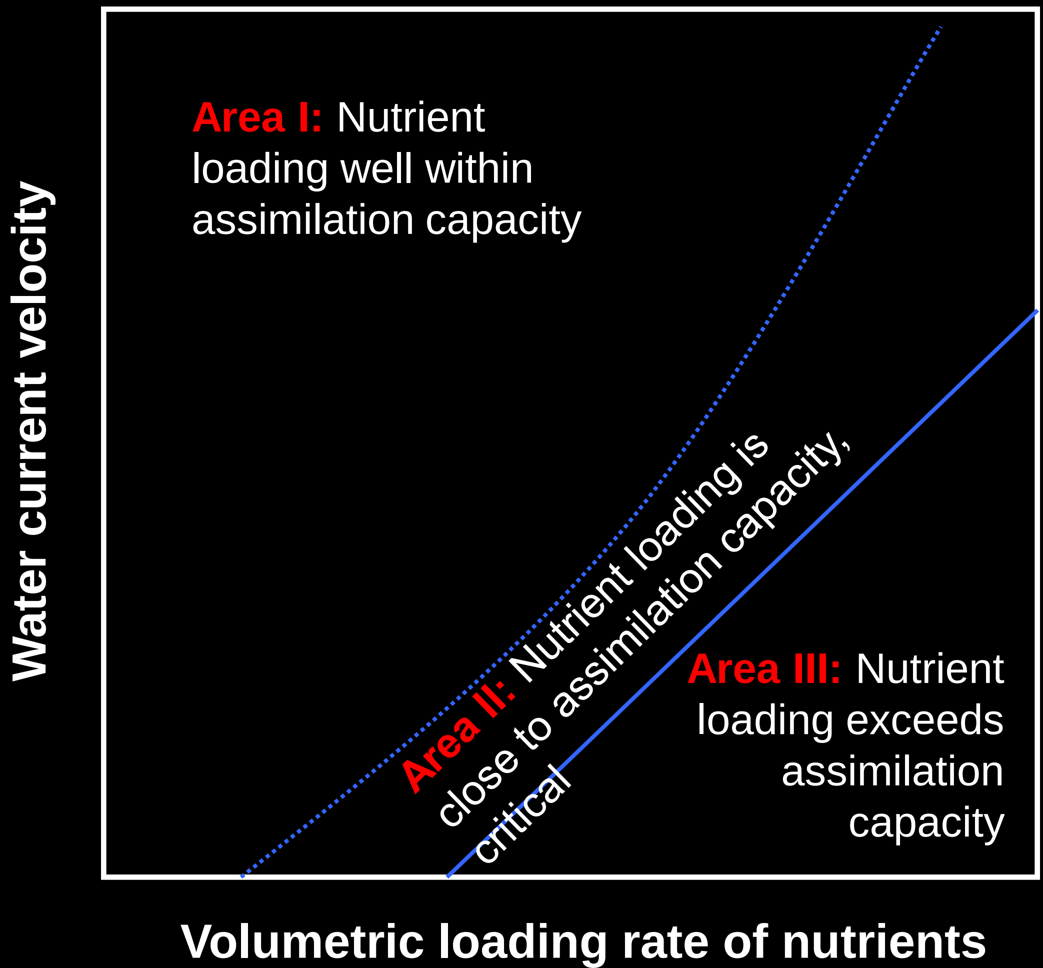
The phytoplankton biomass response following enhanced nutrient supply from a point source draining to dynamic waters has a delay of 3-7 days and will therefore be realised far downstream of the farm

Estimation of water exchange (A) and volumetric inorganic nutrient loading rate (B) as a function of water current velocity

Assumes: Production of 1000 MT salmon/year, plug flow pattern, no dilution of water downstream of the farm



Integrated scientific concept for assessing assimilation capacity of water column ecosystems



Area I: Water dynamics are strong enough to maintain nutrient loading within the limits of the assimilation capacity of the water column ecosystems

Area II: The critical zone where loading rate is coming close to the critical nutrient loading that exceeds assimilation capacity. Situations represents increased risks and calls for special attention

Area III: Nutrient loading exceeds the limits of the assimilation capacity, the water column ecosystem can loos its integrity, which may cause harmful coastal eutrophication

Chapter 3: Pelagic nutrient and ecosystems impacts of salmon aquaculture in Chile, with emphasis on dissolved nutrient loading and harmful algal blooms

Dr. Alejandro Buschmann, Universidad de los Lagos, Chile

Chapter 4: Salmon aquaculture and harmful algal blooms (HABs)

Dr. Stephen F. Cross, University of Victoria, British Columbia, Canada

Harmful Algal Blooms

- Scottish Executive Environmental Group (SEEG)

Reviewed 650 scientific papers and made regional comparisons

Many Harmful Algal Blooms (HABs) clearly attributed to regional processes that occur well outside of the direct influences of salmon farms

No indication that HABs were developed, sustained by nutrients from salmon farms

Inadequate waste composition; receiving water qualities; oceanographic conditions

Chile: hydrodynamics/tidal currents poorly understood, nutrient impacts downstream?

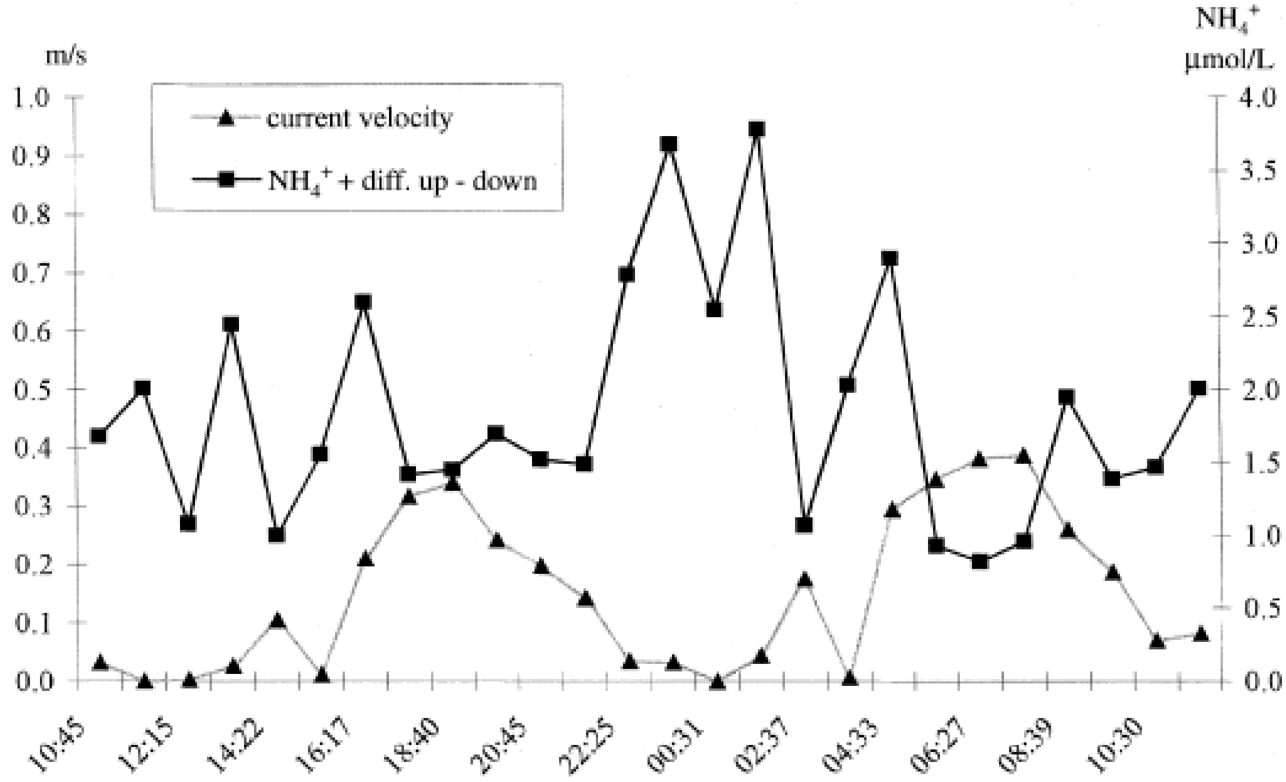
Seaweeds detect nutrient impacts better than instruments deployed infrequently

Induction of HABs? Some laboratory evidence in 1500 L tanks; Vergara (2001) limited field study

Effects of salmon culture in southern Chile

(Soto & Norambuena 2004)

Variables	Farm Mean	Farm Variance	Control Mean	Control Variance	P-value
Water column					
Transparency (m)	6.9	13.0	7.1	12.5	0.79
Chlorophyll *a* ($mg\ m^{-3}$)	5.0	35.2	3.3	17.5	0.21
NO_3 ($\mu mol\ L^{-1}$)	12.3	219.5	13.7	200.7	0.17
NH_4 ($\mu mol\ L^{-1}$)	1.5	19.3	0.9	7.4	0.07
DIP ($\mu mol\ L^{-1}$)	1.9	13.2	1.8	4.1	0.54
Probe measurements above sediments					
O_2 ($mg\ L^{-1}$)	7.5	0.75	8.12	0.75	0.06
pH	7.75	0.06	7.84	0.01	0.12
Redox (mV)	221.6	28197.2	279.4	3144.9	0.75
Delta Redox (mV)	−109.8	24094.2	2.6	64.3	< 0.0001
Sediment measurements					
Nitrogen ($mmol\ k^{-1}$)	124.1	206 189	31.9	14138.1	0.0001
Phosphorus ($mmol\ k^{-1}$)	114.8	393 529	20.7	1478	< 0.00001
Carbon ($mmol\ k^{-1}$)	412.6	557.9	192.2	201.5	0.0010
Particulate organic matter (%)	4.41	14.20	2.09	2.41	0.017
Species (taxa) richness in sediments (in 0.4 m^2)	3.5	3.2	7.8	24.6	0.0001
Species (taxa) evenness	0.44	0.11	0.61	0.12	0.05



current and difference
centrations between
rrent, at the raft
; mean tide)

Harmful Algal Blooms

• Many Harmful Algal Blooms (HABs) clearly attributed to regional processes that occur well outside of the direct influences of salmon farms.

• At densities of salmon farms in BC and Norway, nutrient loading of farms might not alone be sufficient to initiate and sustain HABs.

BUT, in Chile, farms are more dense – little/no research.

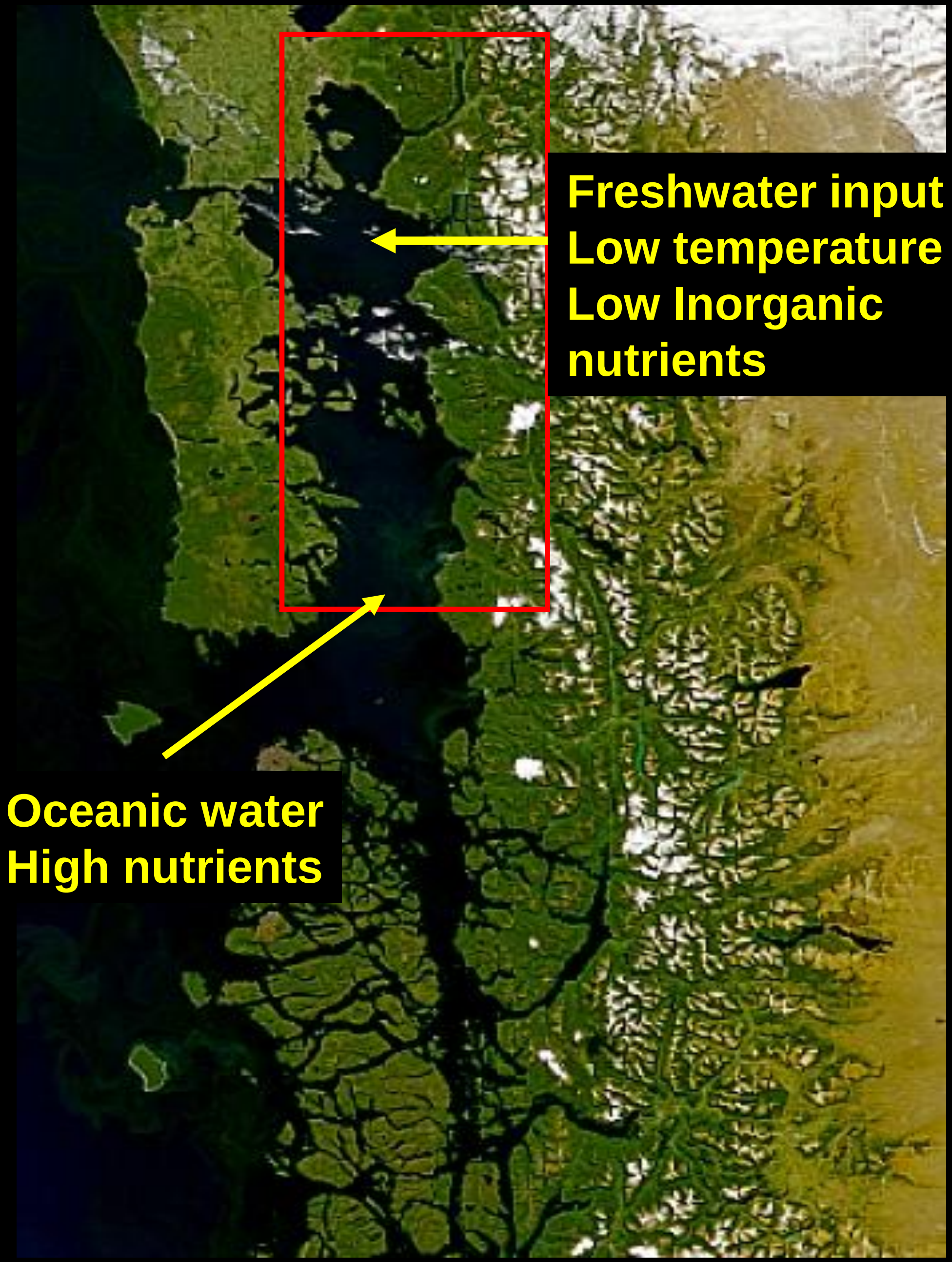
Chapter 5: Nutrient impacts of salmon aquaculture on Chilean lakes

Dr. Jose Iriarte, Universidad Austral de Chile, Chile

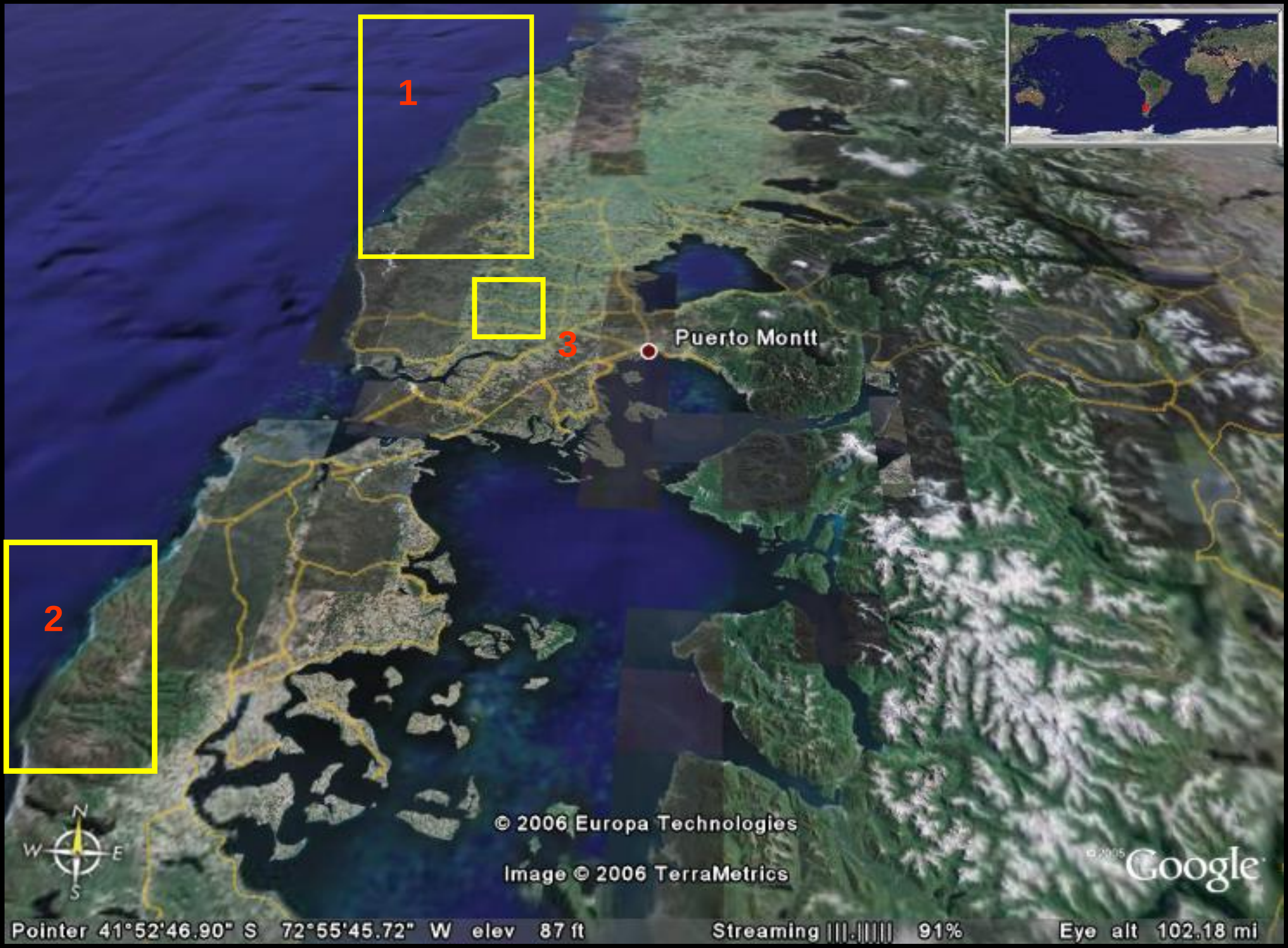
X Lake District
>80% national salmon production

Diversity of habitats:

Fjords
Estuaries
Lakes
Rivers
Bays
Channels
Islands



Main areas of smolt production in the X Lake District



Lake Llanquihue

Diverse Ecosystems

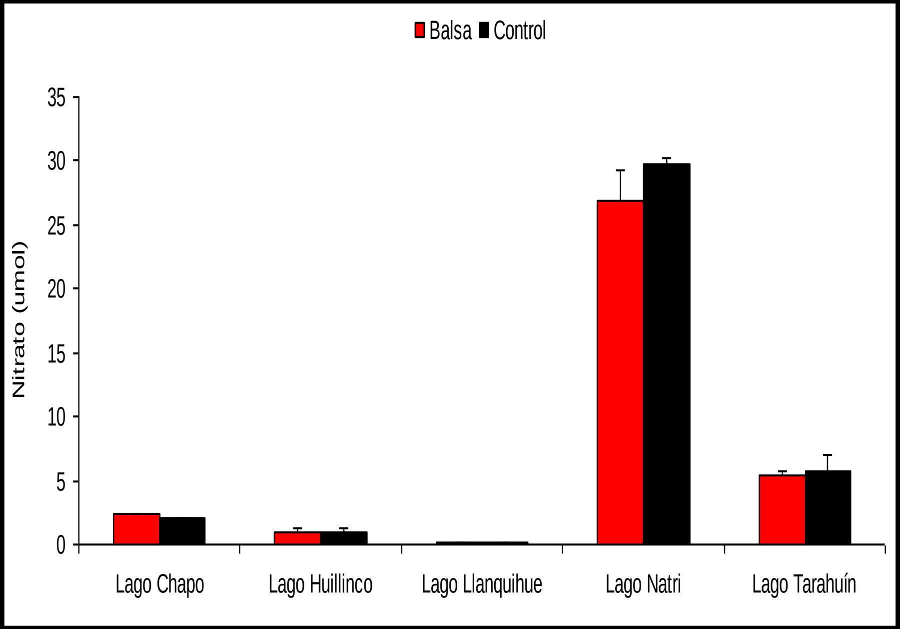
Lake Llanquihue

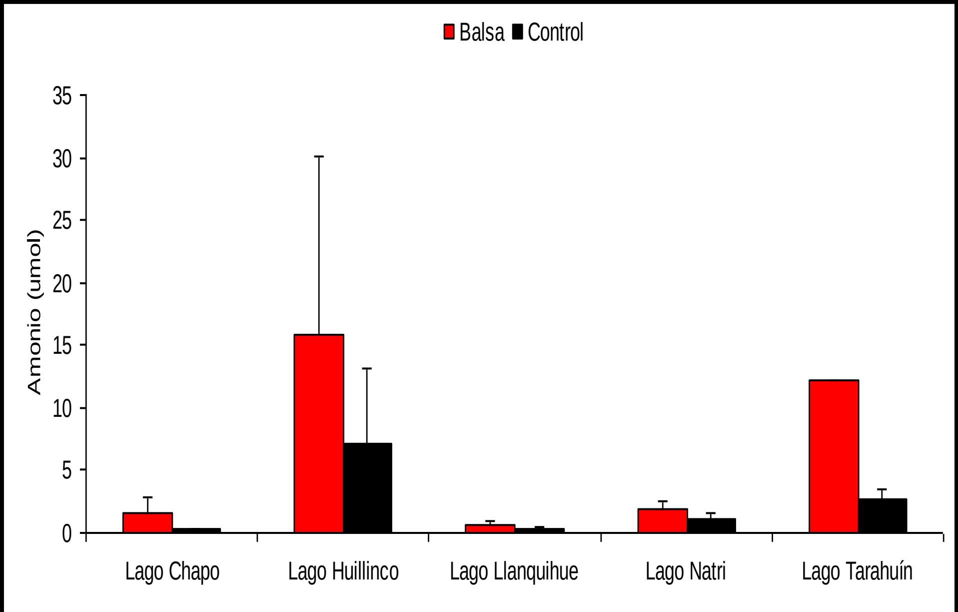
–one of the largest lakes in Chile
–Deep, oligotrophic, volcanic origin
–Tourist hot spot
–Recreational area (sport fishing, etc.)
–Salmon farming (water and land-based)
–Several cities surrounding

Lake Natri

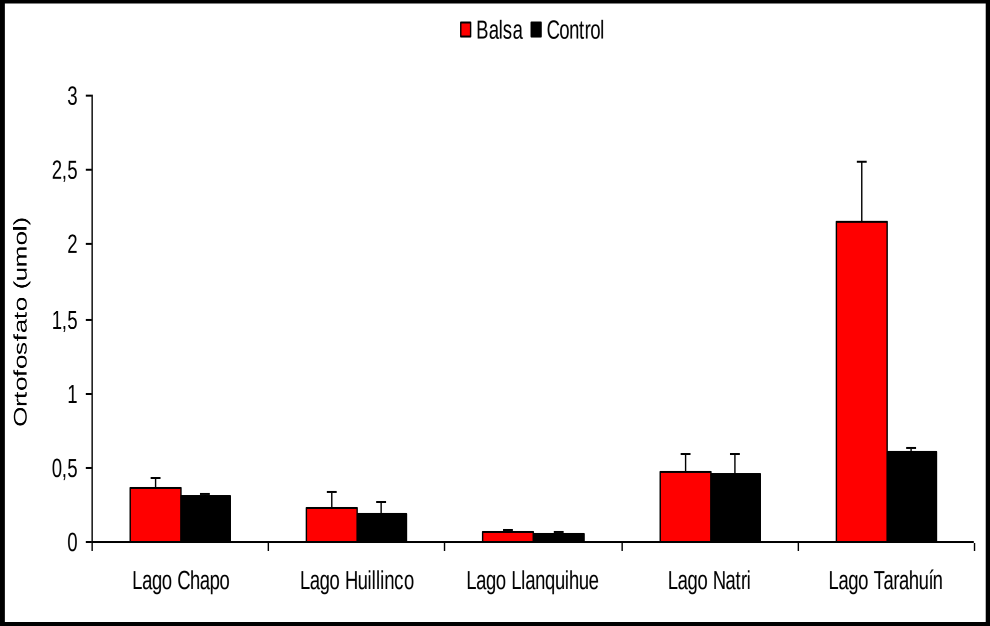
–Smaller than Llanquihue
–Shallow, eutrophic
–Salmon farming (smolt production)

Chilean Lakes: Water column

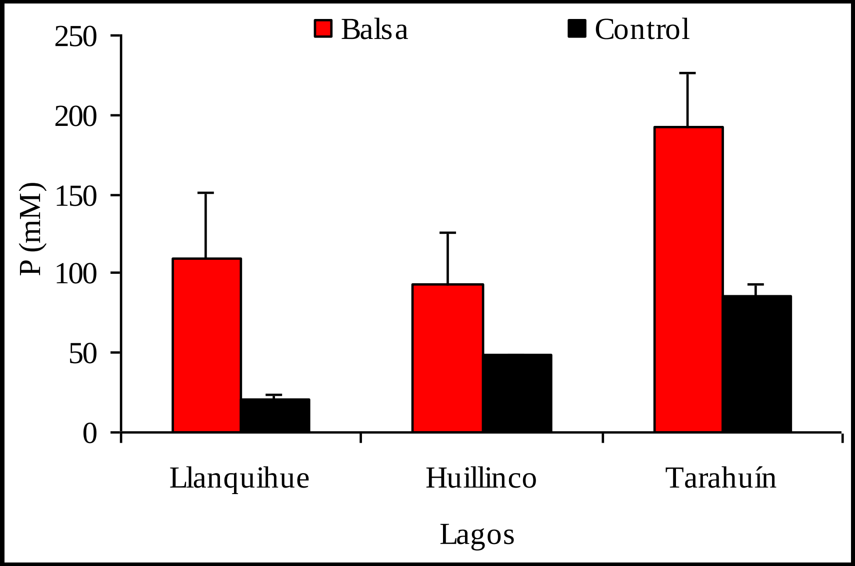


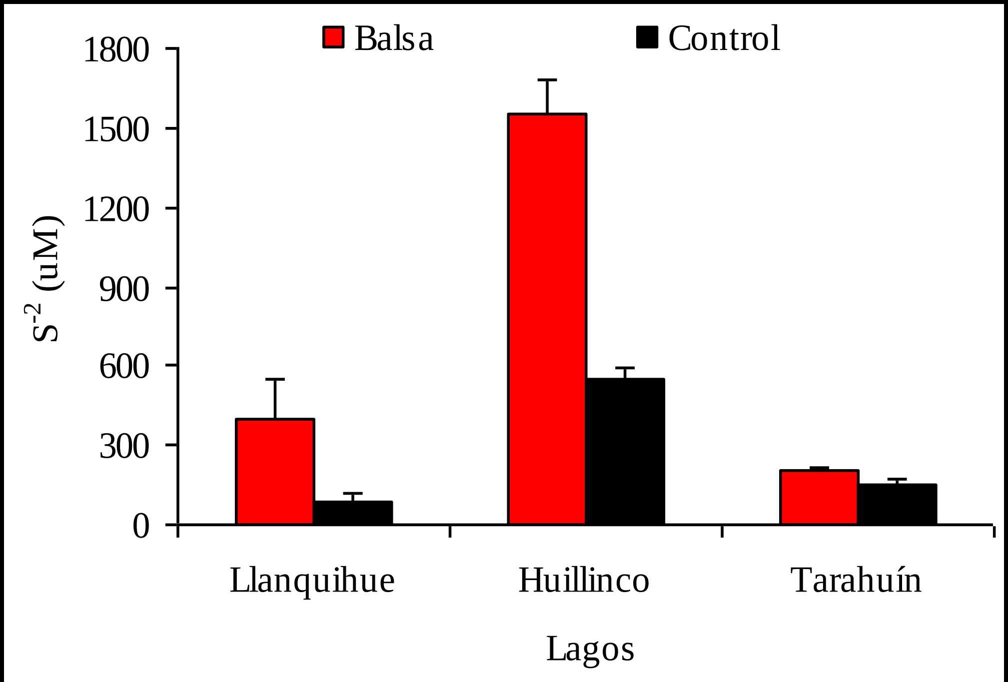


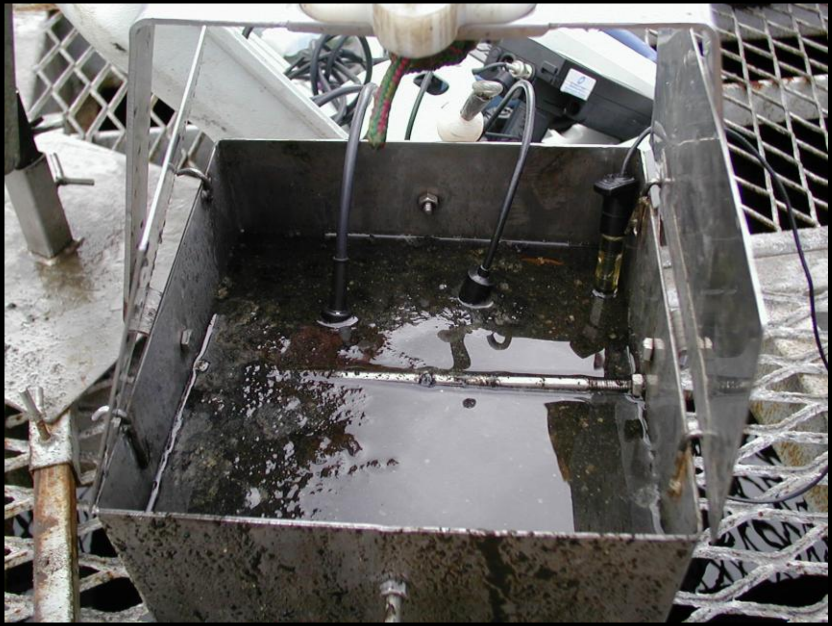
Chilean Lakes: water column



LAKE SEDIMENTS







Conclusions and Research Needs

Scientific concept for assessing impacts of nutrients in water column ecosystems

Two main mechanisms are important for the assimilation capacity of water column ecosystems:

✓*Nutrient assimilation by the planktonic food web components, with trophic transfers of energy and materials (e.g., nutrients) to higher trophic levels.*

There is a critical upper nutrient loading above which the water column ecosystem looses its integrity, resulting in algal blooms

✓*Hydrodynamic mediated dilution of nutrients and organisms at production sites and their surrounding water masses.*

Nutrient loads are diluted, the potential negative effects of high nutrient input are mitigated, because the critical level is not reached

The three most important factors determining the impact of salmon farming on water column nutrients, water quality, and pelagic ecosystems are the:

1. loading rate of inorganic nutrients, especially nitrogen for marine systems and phosphorus for freshwater ones; the hydrodynamics; and the water depths of cage sites,

2. morphometry and topography (degree of “openness”) of bays and the nearshore coastal areas,

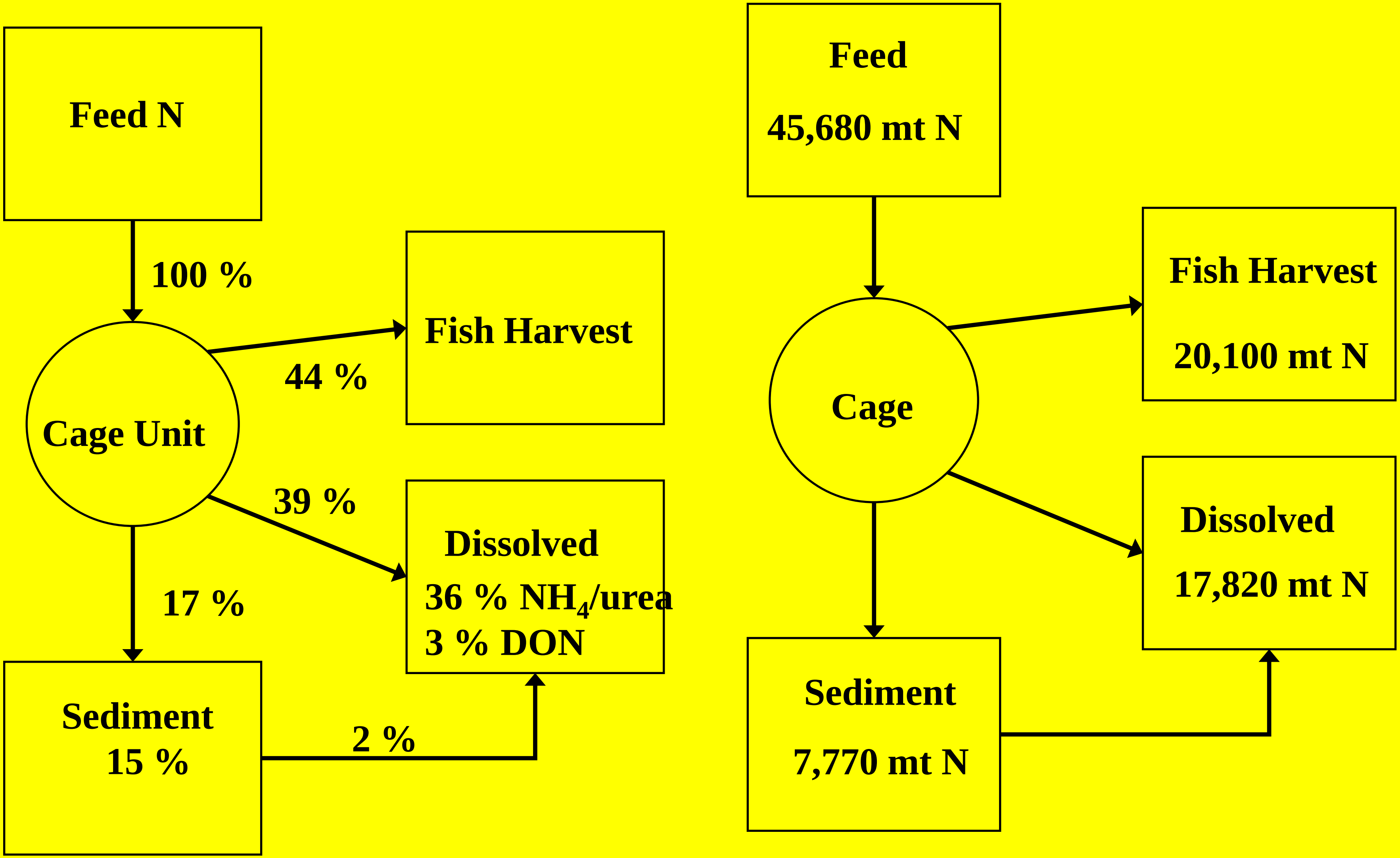
3. stocking density of fish (local scale) and the density of fish farms (regional scale).

Nutrient Impacts of Salmon Aquaculture on Chilean Lakes

- Preliminary reports indicate Chiloé lakes with salmon farming had impacts, while Northern Patagonian lakes including Lakes Llanquihue, Rupanco, Puyehue, Yelcho did not.

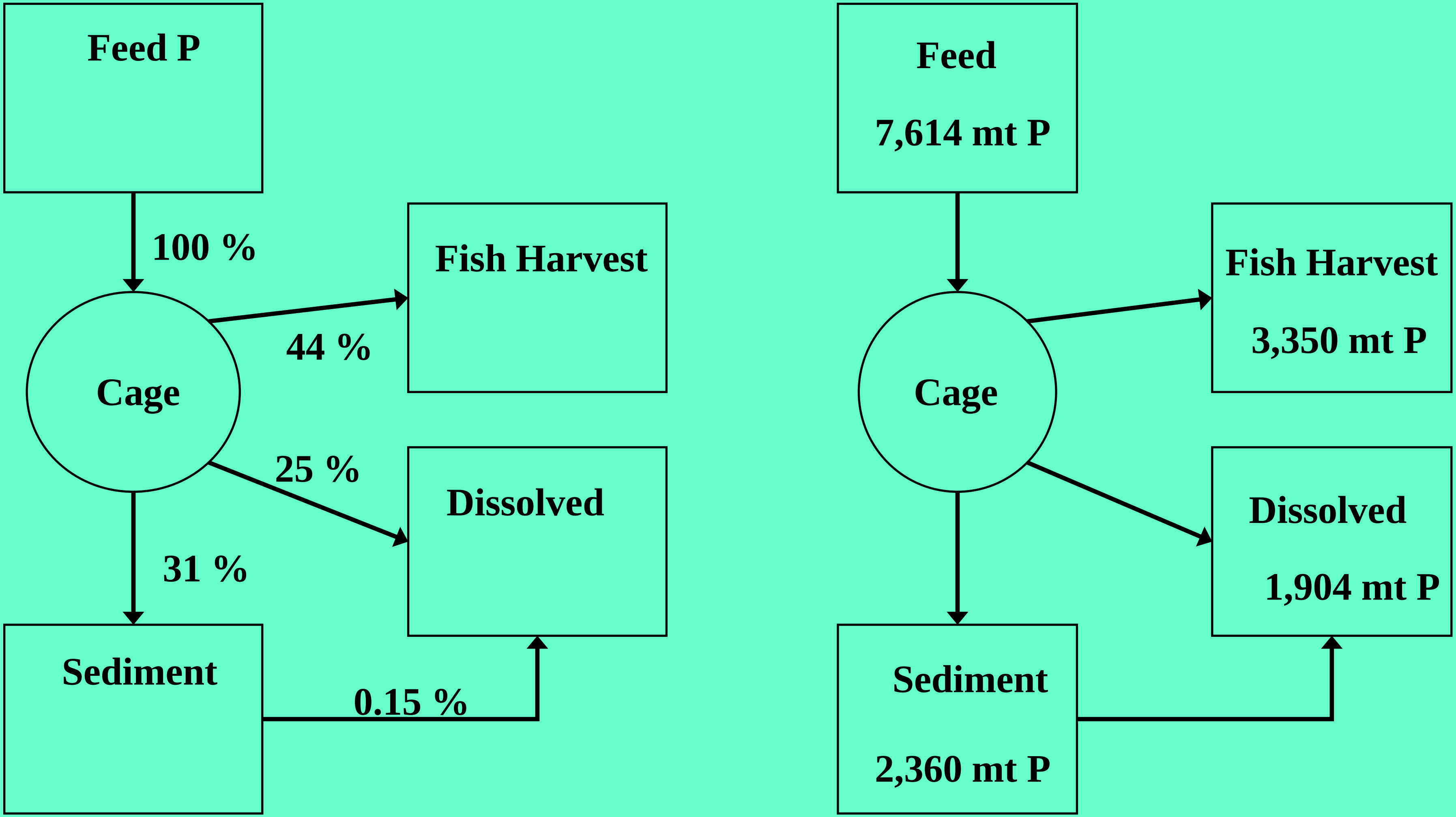
- Chiloé lakes were impacted because of small size/volume, shallow depth and low water exchange rates and intensive farming practices.

Nitrogen



Feed N
100 %
Cage Unit
Fish Harvest
44 %
39 %
Dissolved
36 % NH_4/urea
3 % DON
17 %
Sediment
15 %
2 %
Feed
45,680 mt N
Cage
Fish Harvest
20,100 mt N
Dissolved
17,820 mt N
Sediment
7,770 mt N

Phosphorous



Key Research Needs

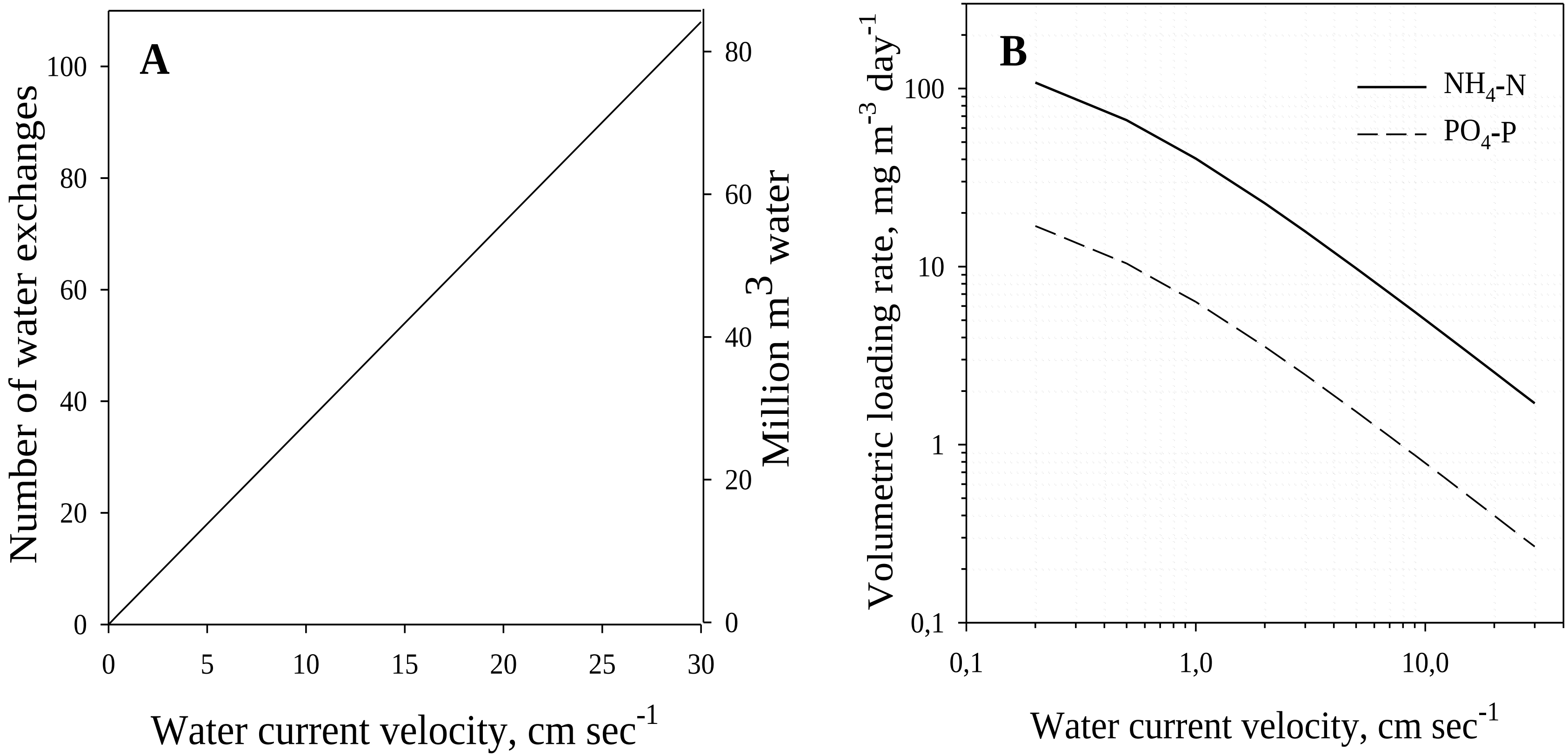
Sophisticated, connected modeling
(note advances, next slides)

Further research on fecal mass faction settling rates and fates in marine ecosystems

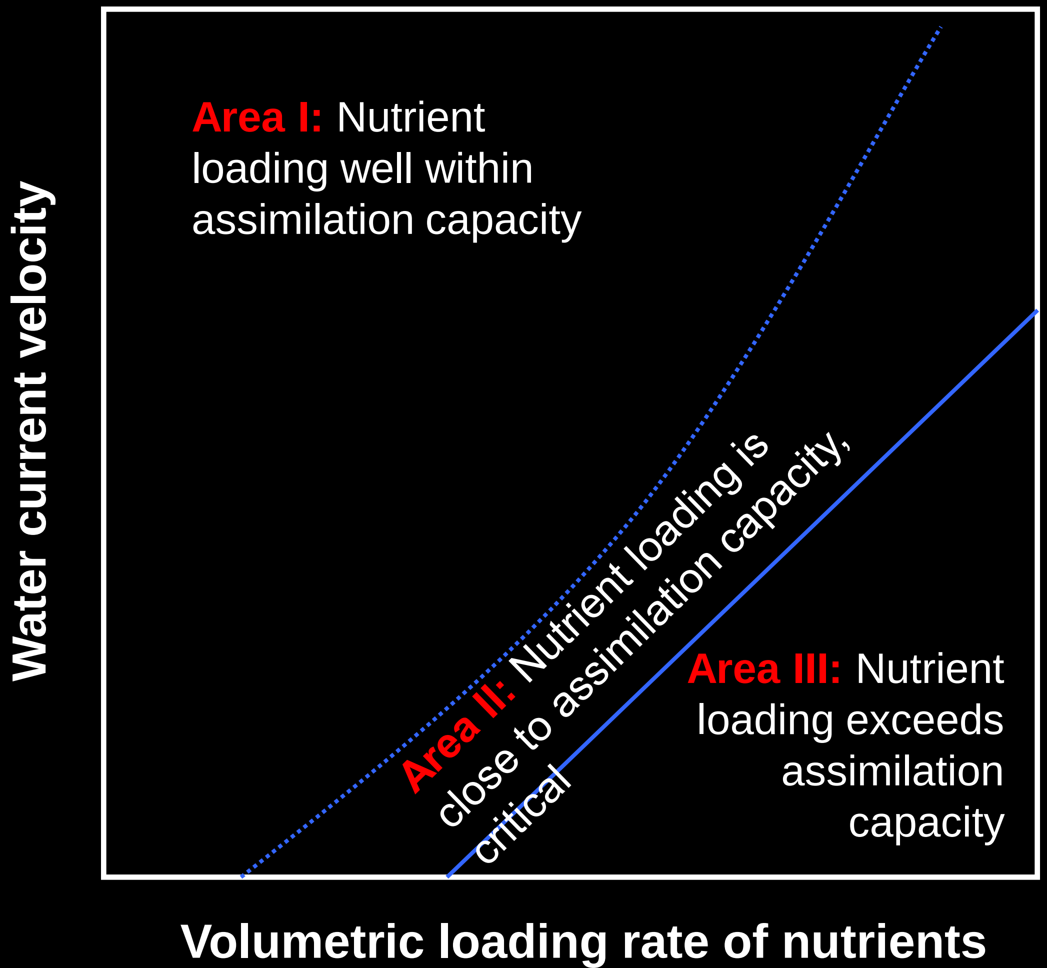
Advanced 3D hydrodynamic modeling to estimate volumetric loading rates and spreading patterns of excess nutrients; particularly important for nutrient assessments where multiple farms are in the same water body…

Estimation of water exchange (A) and volumetric inorganic nutrient loading rate (B) as a function of water current velocity

Assumes: Production of 1000 MT salmon/year, plug flow pattern, no dilution of water downstream of the farm



Integrated scientific concept for assessing assimilation capacity of water column ecosystems



Area I: Water dynamics are strong enough to maintain nutrient loading within the limits of the assimilation capacity of the water column ecosystems

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Area III: Nutrient loading exceeds the limits of the assimilation capacity, the water column ecosystem can loos its integrity, which may cause harmful coastal eutrophication

Key Research Needs

Continued development of nutrient dense feeds (continue to decrease fines and to improve FCR's)

Further research on improving the digestibilities of feeds

Much more research needed on aquaculture loading within the context of cage densities, esp. for Chile where the research database appears weak (Reloncavi estuary)

Reloncavi Estuary

- **Narrow and deep**
- **High concentration of salmon farming**
- **Hypoxia events in water column**
- **High freshwater discharge from 3 rivers**
- **Land use**
- **Hydroelectric power**
- **installations**

Key Research Needs

Can HABs be related in the field to wastes from salmon farms?

HAB species near salmon farms

Triggers

Can nutrient conditions within farming areas promote establishment of *new* HAB seed areas?

How do the variations of nutrients from farm wastes affect the population dynamics of the various HAB spp?

How does phytoplankton community structure, inter-specific competition and uptake preferences for available nutrients affect 'triggers' for HAB blooms?

How does farm site physiography and oceanography affect nutrient availability to HABs?

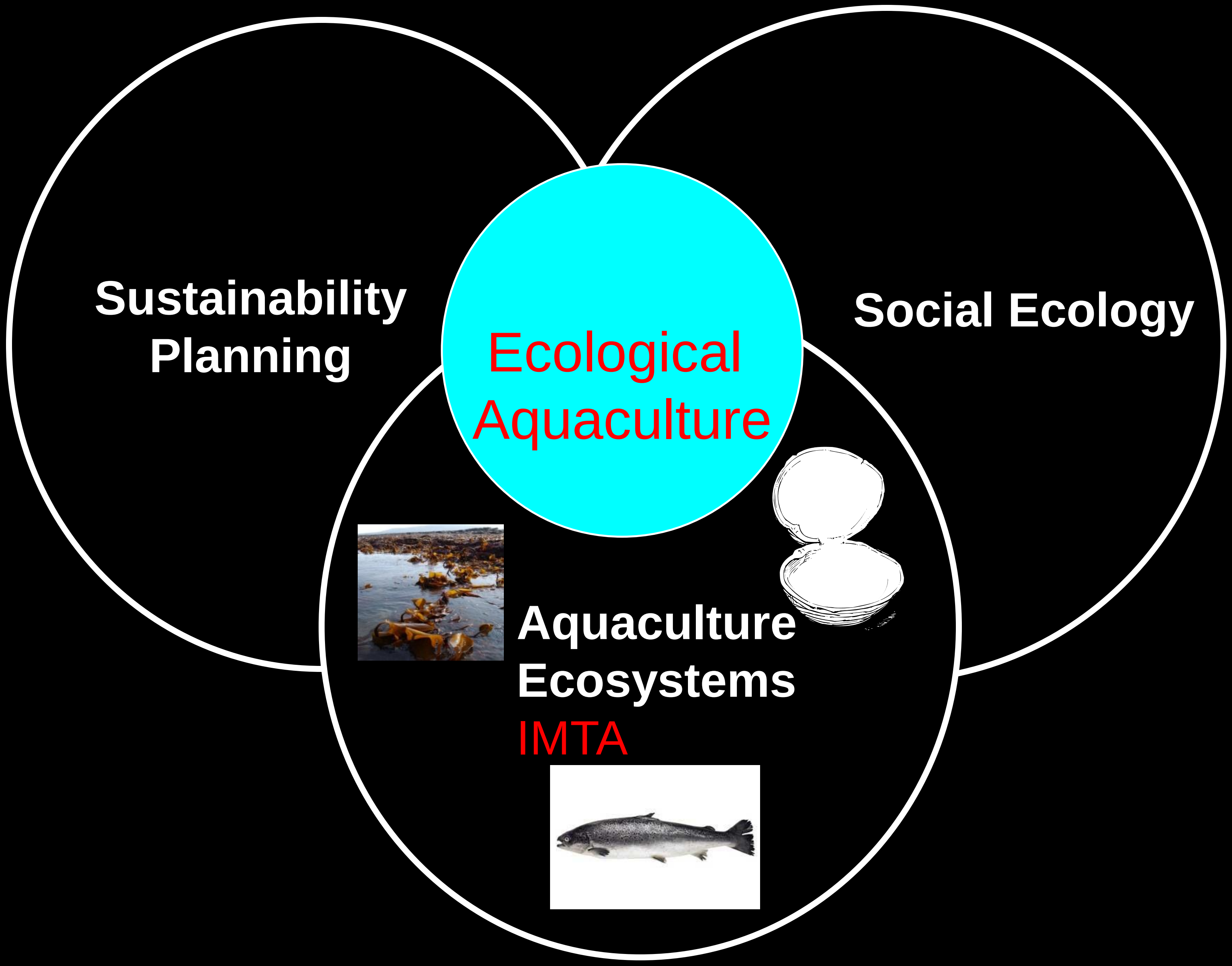
Other Recommendations

Chile Scientific/Monitoring Capacity
540 references – 12 in Chile

Ecological Aquaculture/IMTA
The evolution of the blue revolution!

1. Commercial Scale Collaborative SEA (Sustainable Ecological Aquaculture) Labs

Partnering Universities/Governments/Industries/NGOs to develop learning communities


Sustainability
Planning
Social Ecology
Ecological
Aquaculture
Aquaculture
Ecosystems
IMTA