Changing adverse impacts into beneficial effects: Enrichment of west coast freshwater and marine aquatic food webs with aquaculture wastes

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Aquaculture Canada 2011 Plenary Session
Quebec City

Suppositions

- Supposition 1: aquaculture organic wastes are not "wasted" or do environmental damage when farms are optimally sited, sized and operated
- But rather: aquatic and wildlife food webs may be beneficiaries of these nutrients, but poorly described
- Supposition 2: benthic effects are documented near farms but standard techniques do not measure such effects at much greater distances from the pens.
- Examination of food web linkages through alternative types of measurement provides a means to evaluate such farther field effects

Atlantic Salmon
Womer 2001

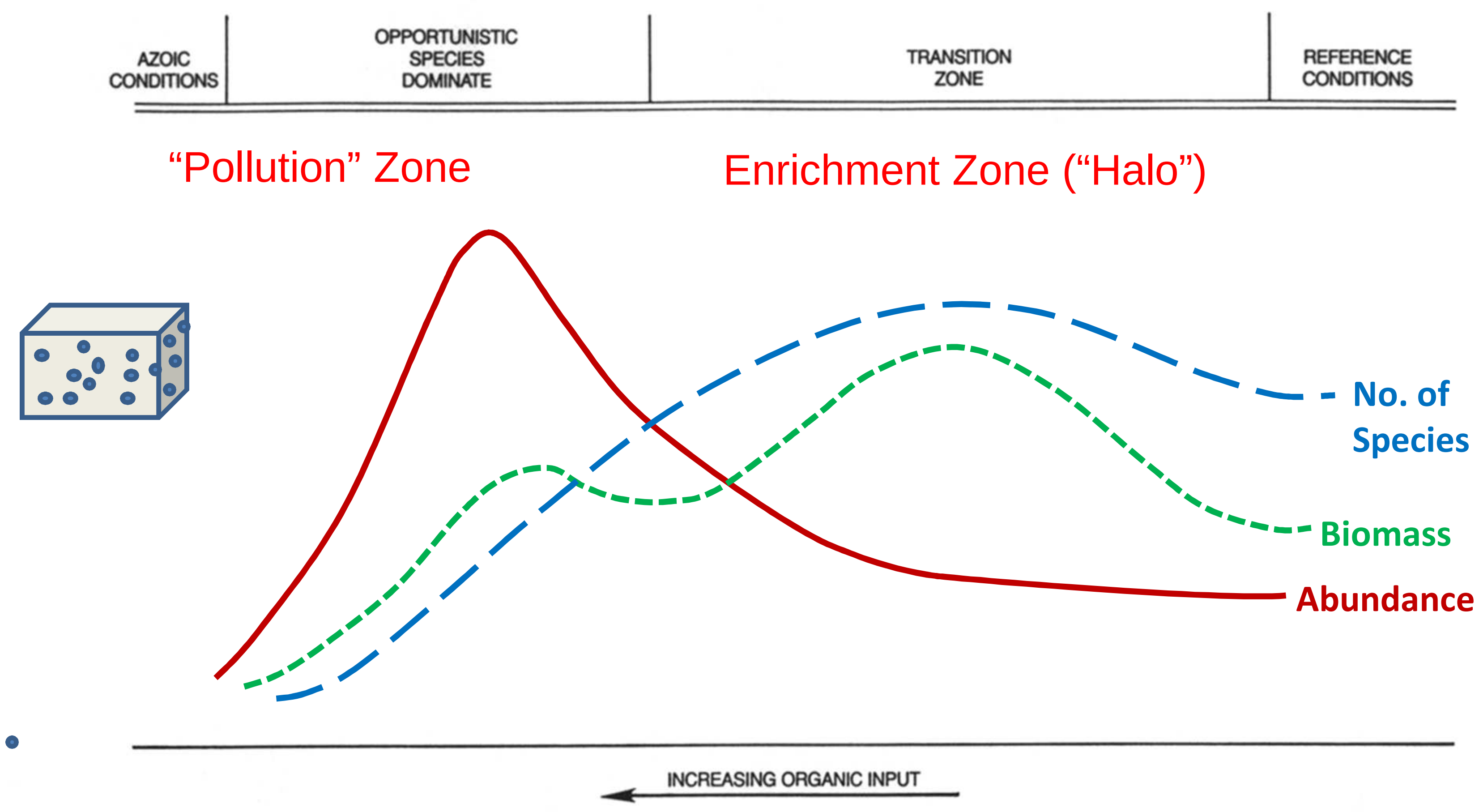
What we usually measure….

- Sediment chemistry: surrogate for sea or river bottom biota. These can be effective for defining adverse effects zones ….but static "snapshots" fail to tell us what is happening further away

… Why is that?

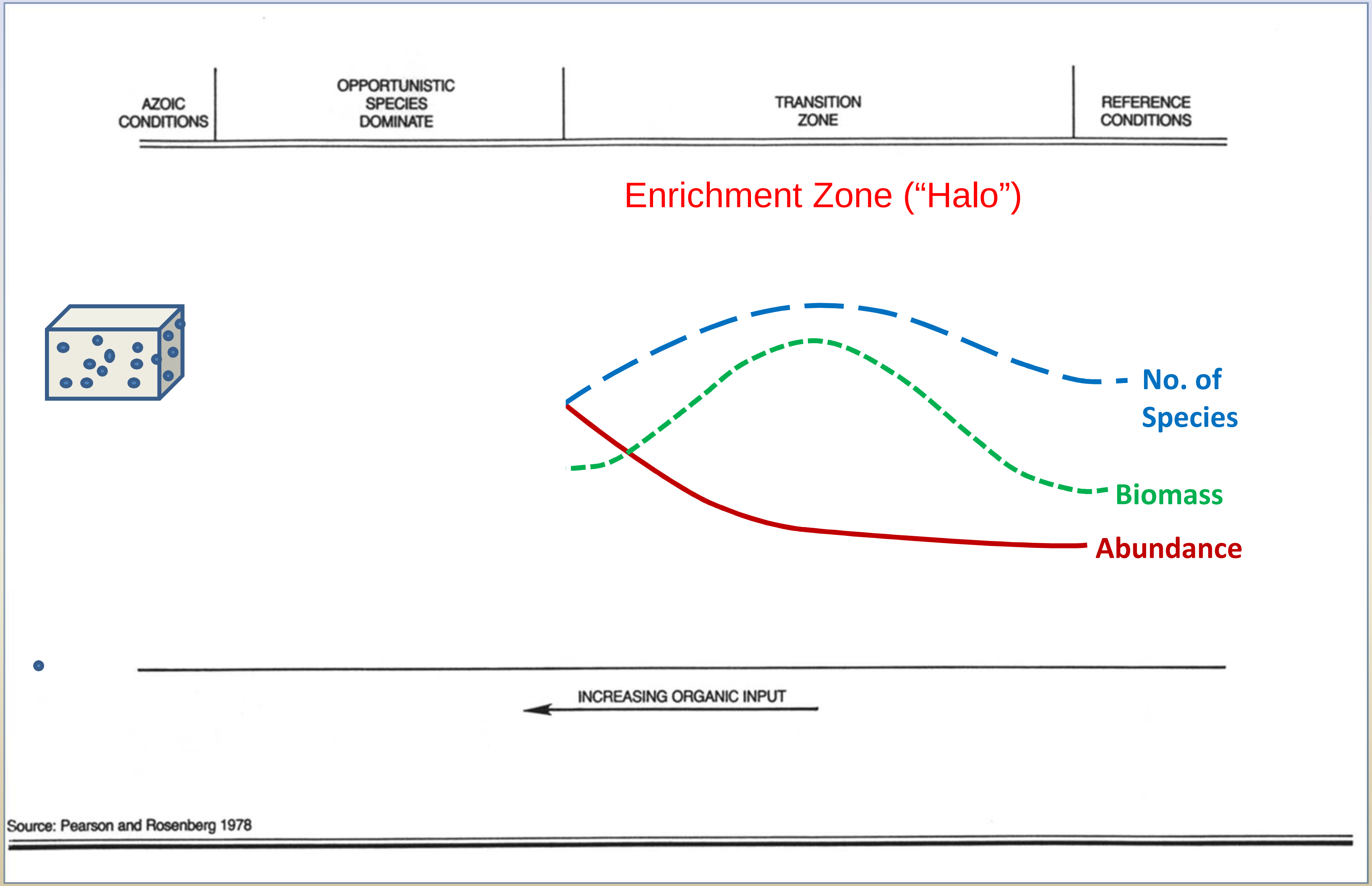
- Aquatic food webs are not divided into separate, exclusive compartments but regulatory focus is appropriately near-field oriented
- Higher organisms (macroinvertebrates, fish, marine mammals, sea birds) are interlinked into the system as are lower level organisms such as bacteria
- The media and some eNGO's have confused these issues by assuming all nutrients are pollutants in all situations.
- Earth's aquatic food webs dependent on nutrients…. the open ocean is actually becoming more nutrient and phytoplankton impoverished as are many now impounded great rivers.

Conceptual Model:
Organic Carbon Enrichment or Pollution Continuum

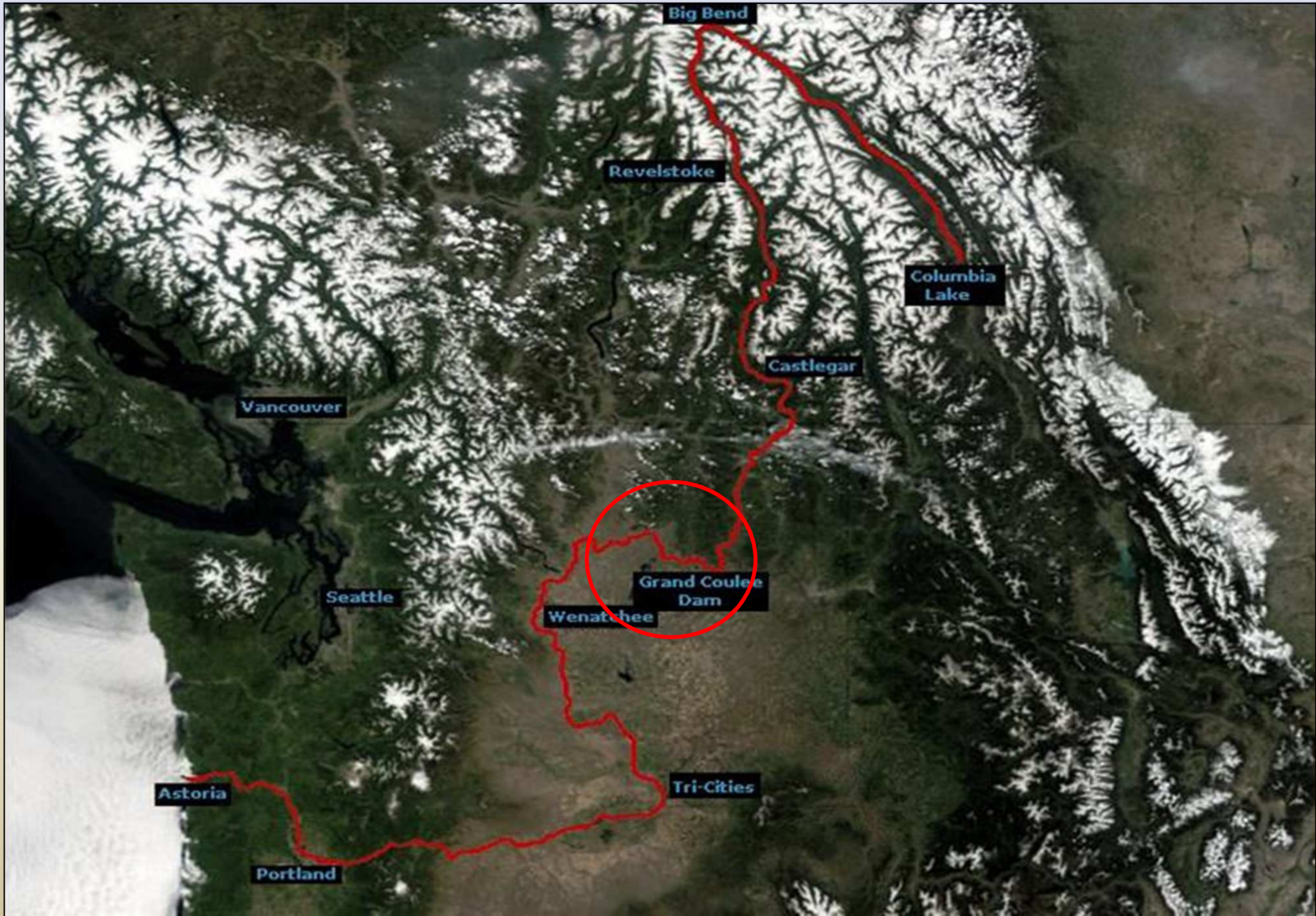


Source: Pearson and Rosenberg 1978

Conceptual Model:
Organic Carbon Enrichment or Pollution Continuum



Fish Farming in the Columbia River Example



- **No anadromous fish migration above Chief Joseph Dam**
- **No marine derived nitrogen upstream except fish farm inputs**
- **Unique experimental opportunities for stable isotope tracing**

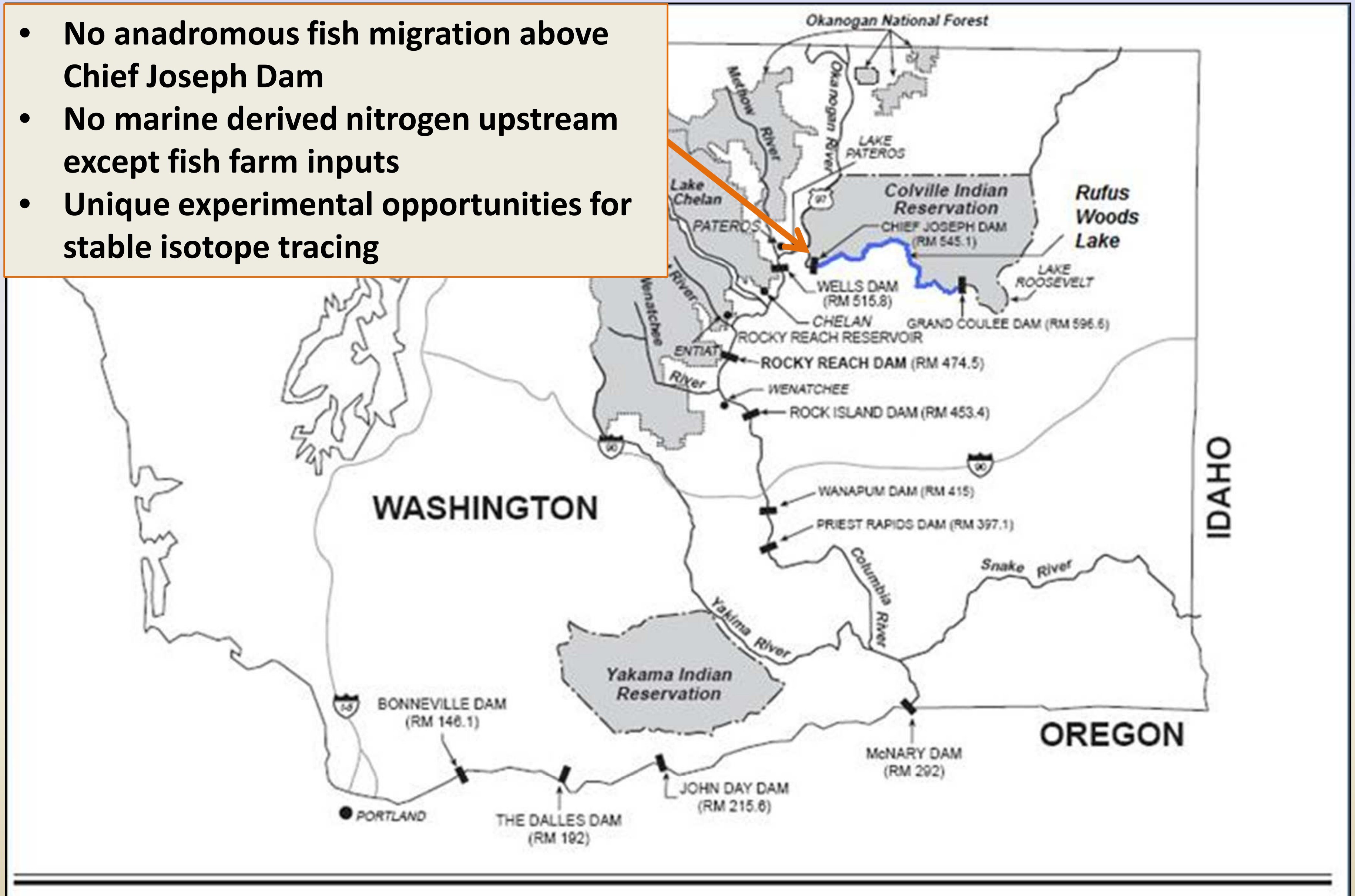
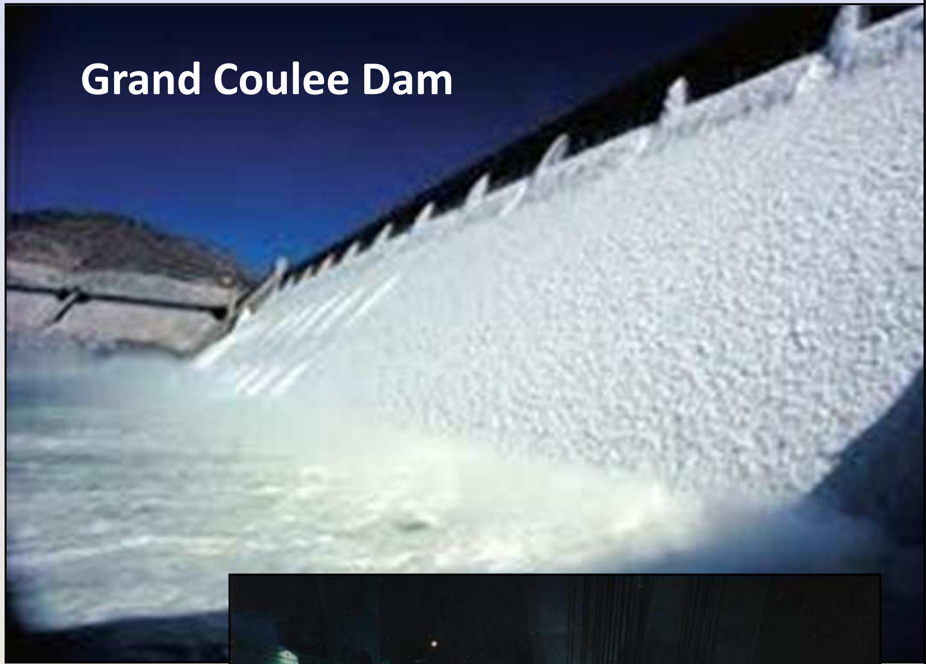
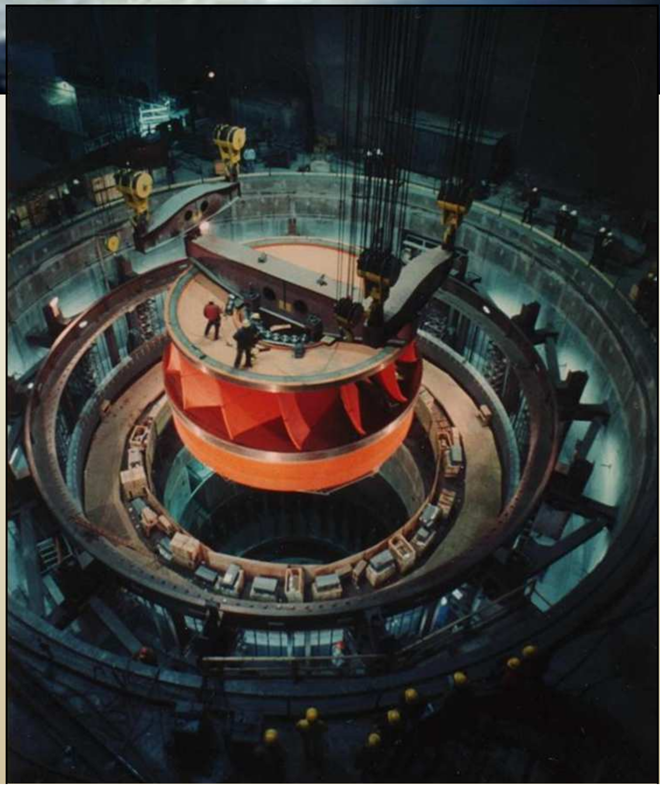
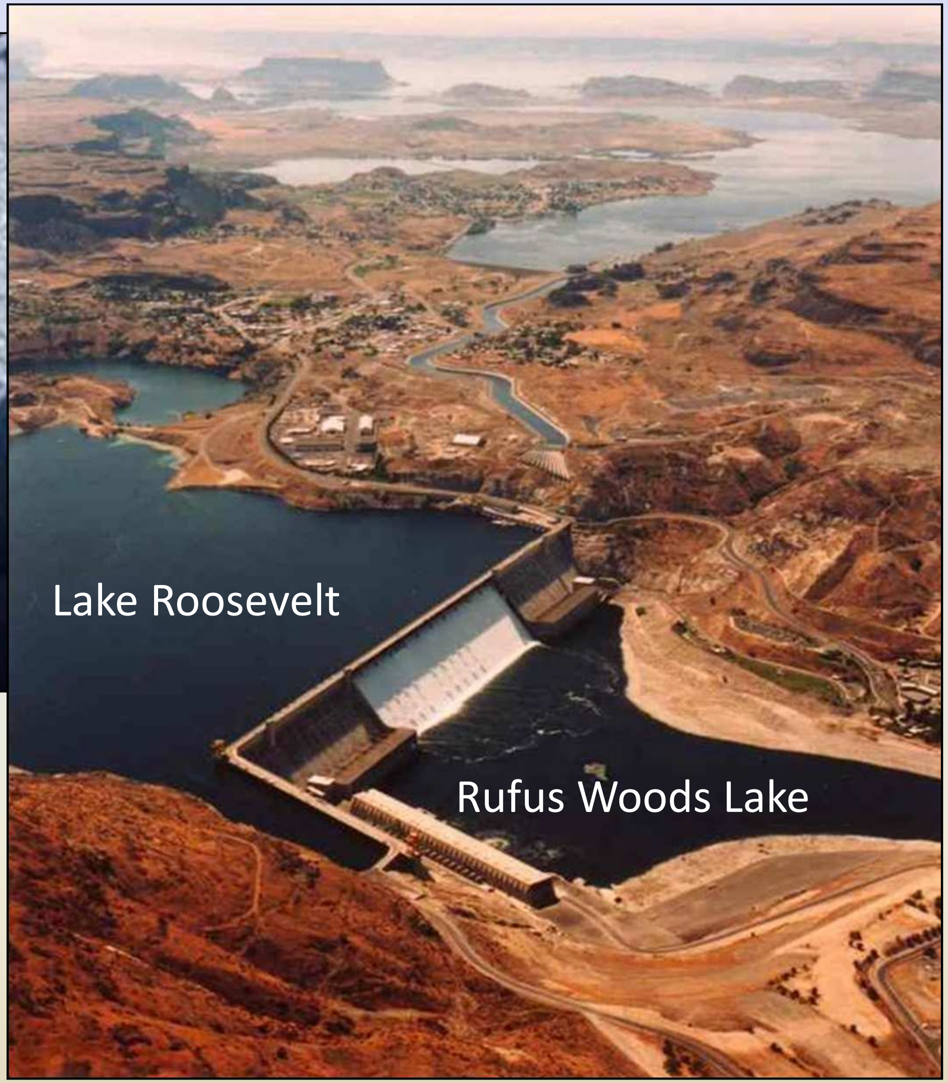


Figure 1
General Locations of Columbia River Dams and Reservoirs

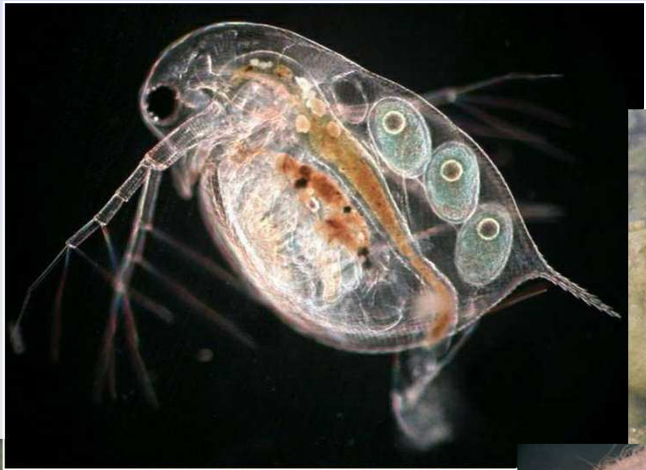

Grand Coulee Dam

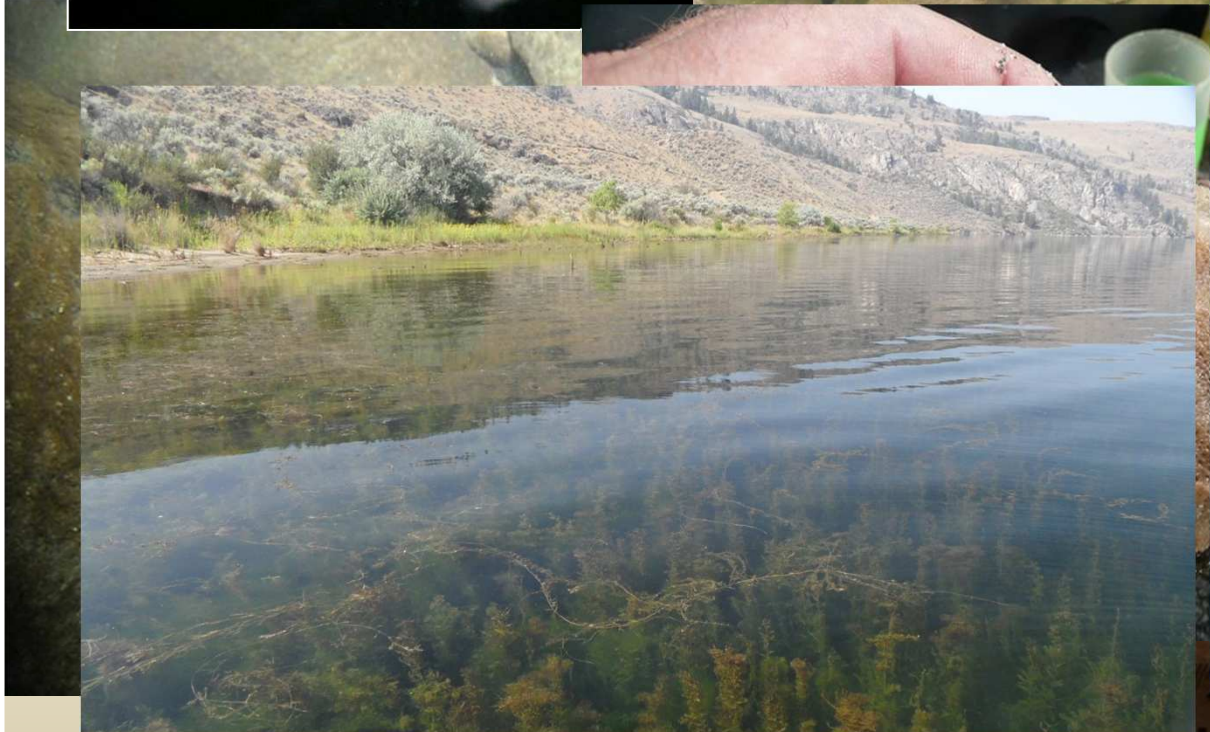


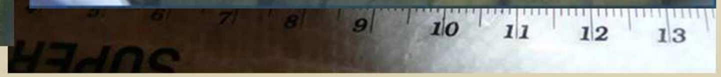

Lake Roosevelt
Rufus Woods Lake

Pacific Aquaculture steelhead trout
(sterile) fish farming
3,000 MT Annual Production
All new cages, equipment, processing plant

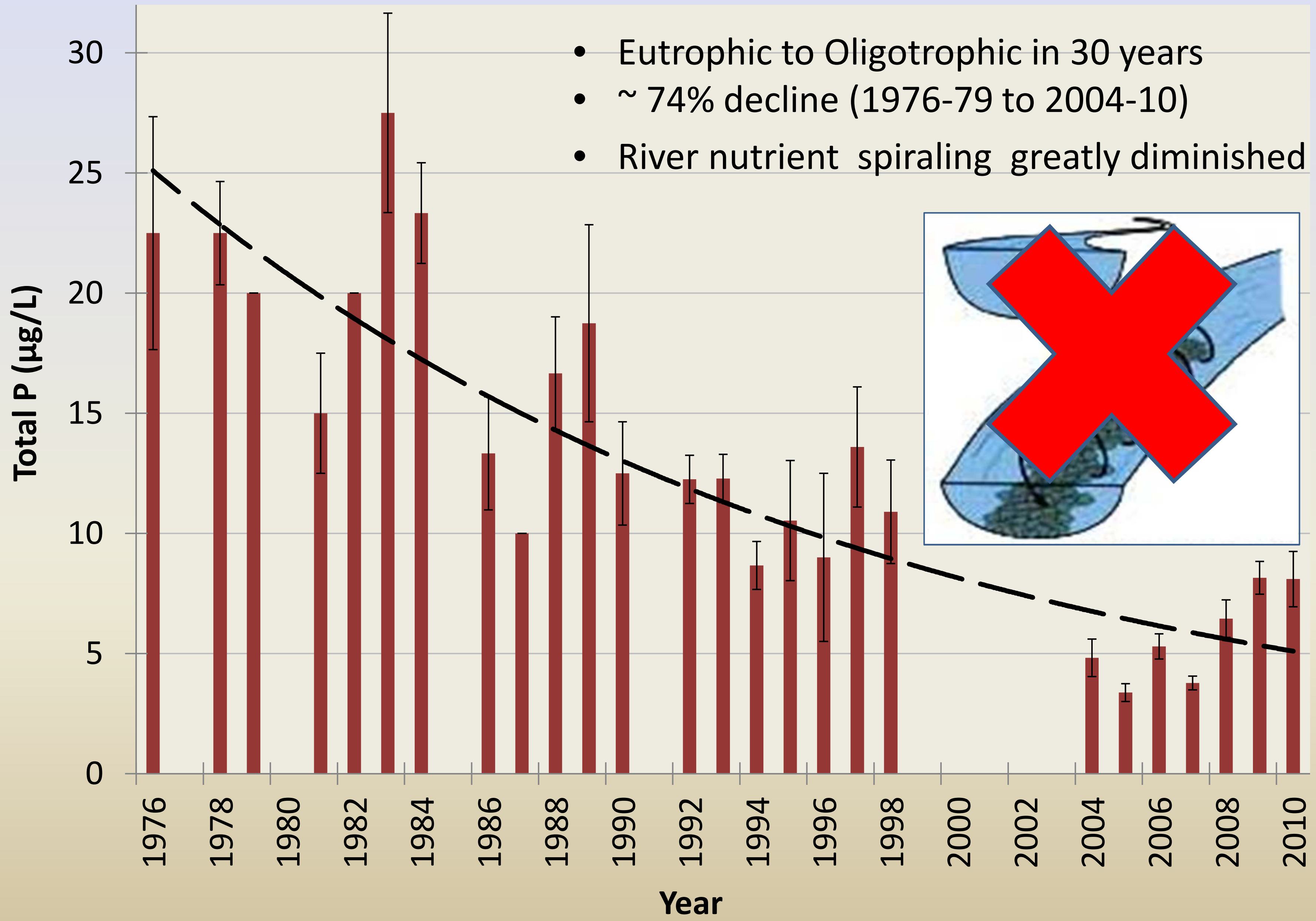
Rufus Woods Lake A

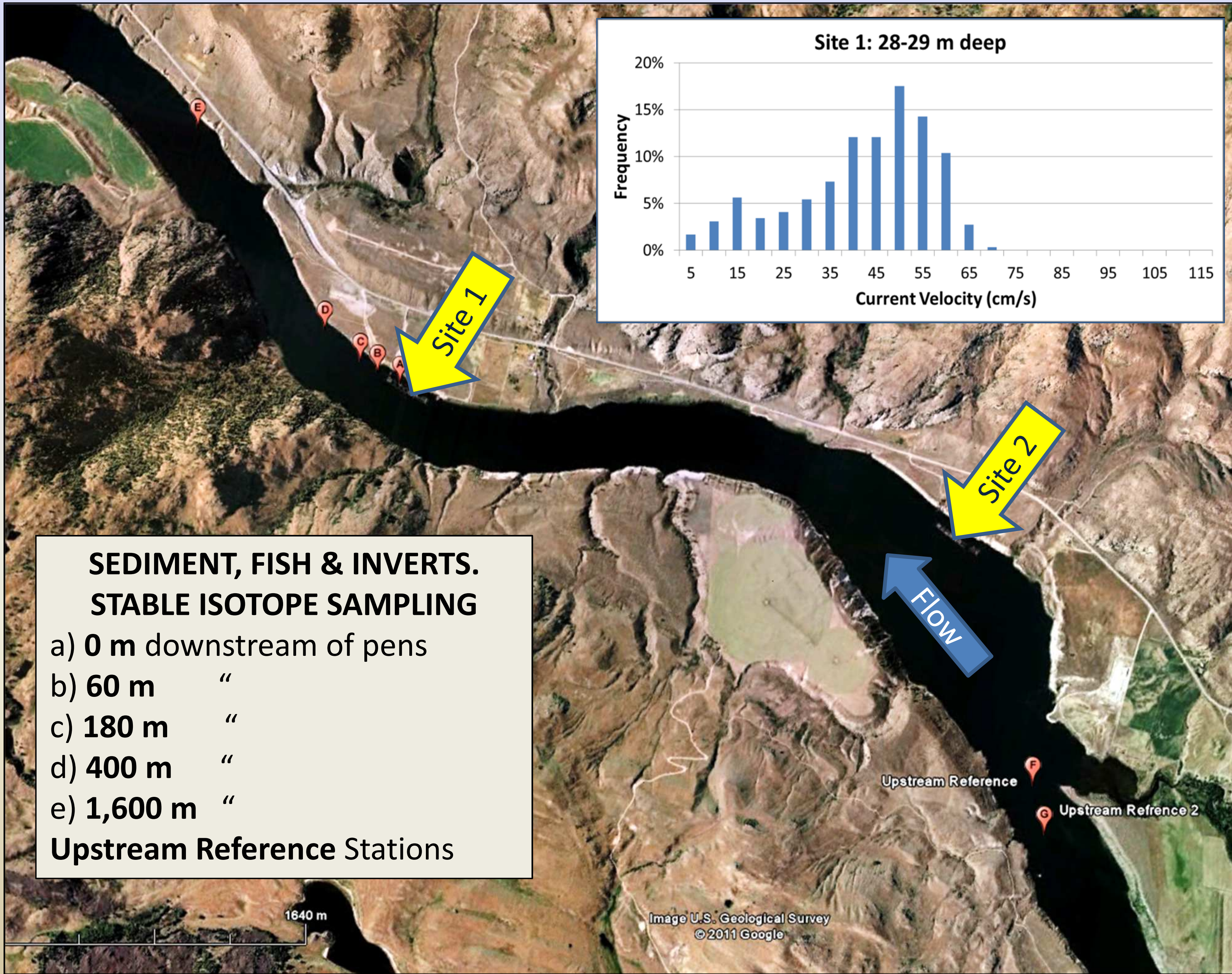






Columbia River Mean Summer Total Phosphorus (± SE)

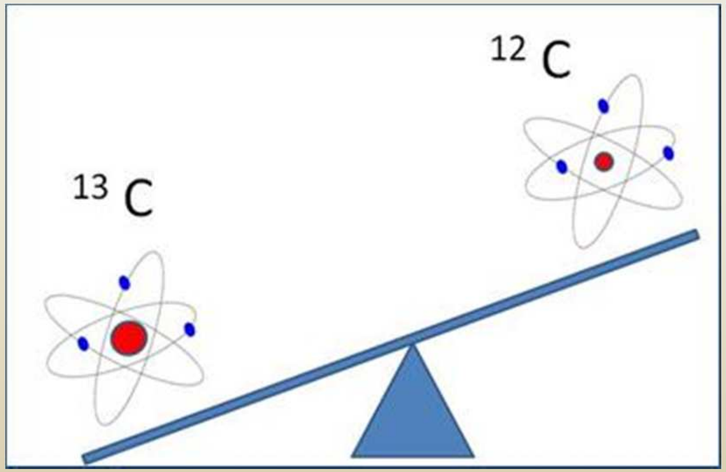




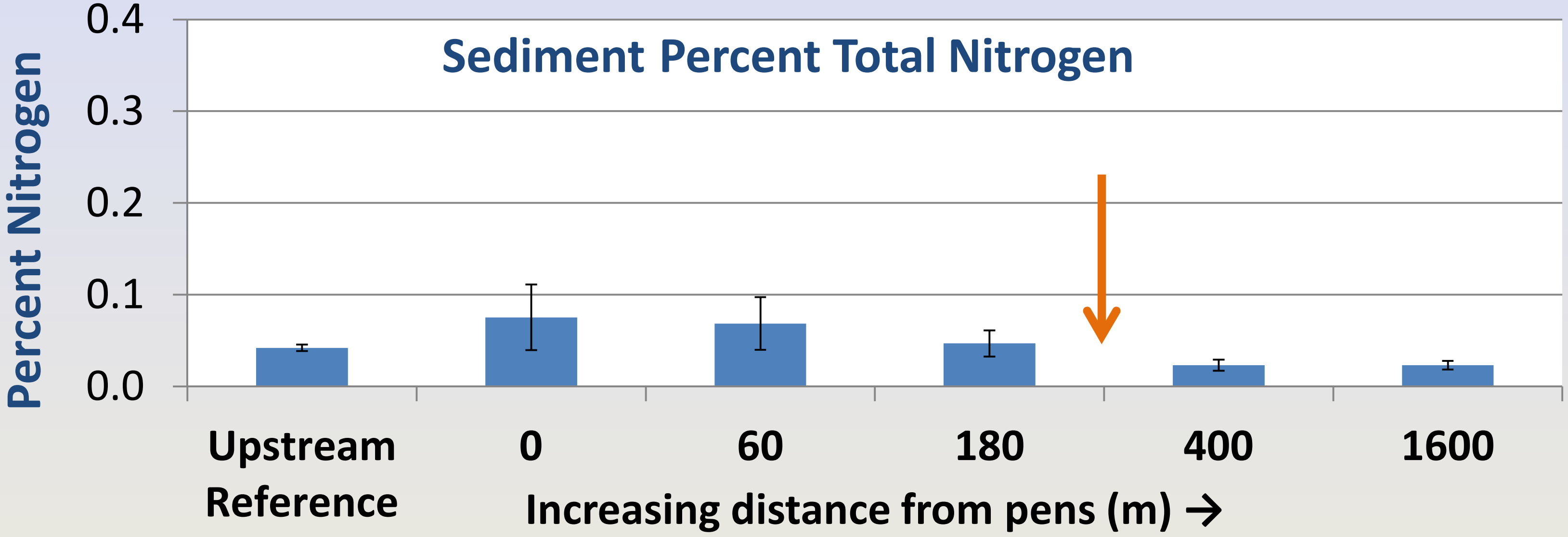
Site 1: 28-29 m deep
20%
15%
10%
5%
0%
Frequency
5
15
25
35
45
55
65
75
85
95
105
115
Current Velocity (cm/s)
Site 1
Site 2
Flow
SEDIMENT, FISH & INVERTS.
STABLE ISOTOPE SAMPLING
a) 0 m downstream of pens
b) 60 m “
c) 180 m “
d) 400 m “
e) 1,600 m “
Upstream Reference Stations
Upstream Reference
Upstream Refrence 2
1640 m
Image U.S. Geological Survey
© 2011 Google

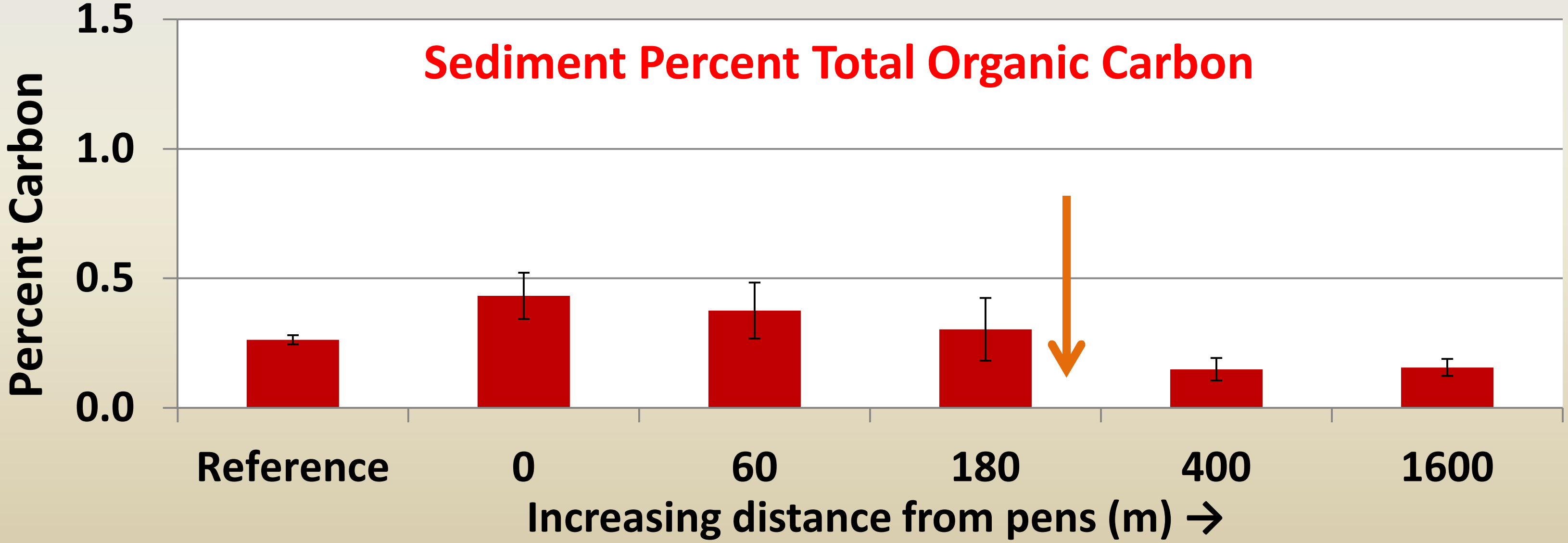
2 Minute Stable Isotope Primer

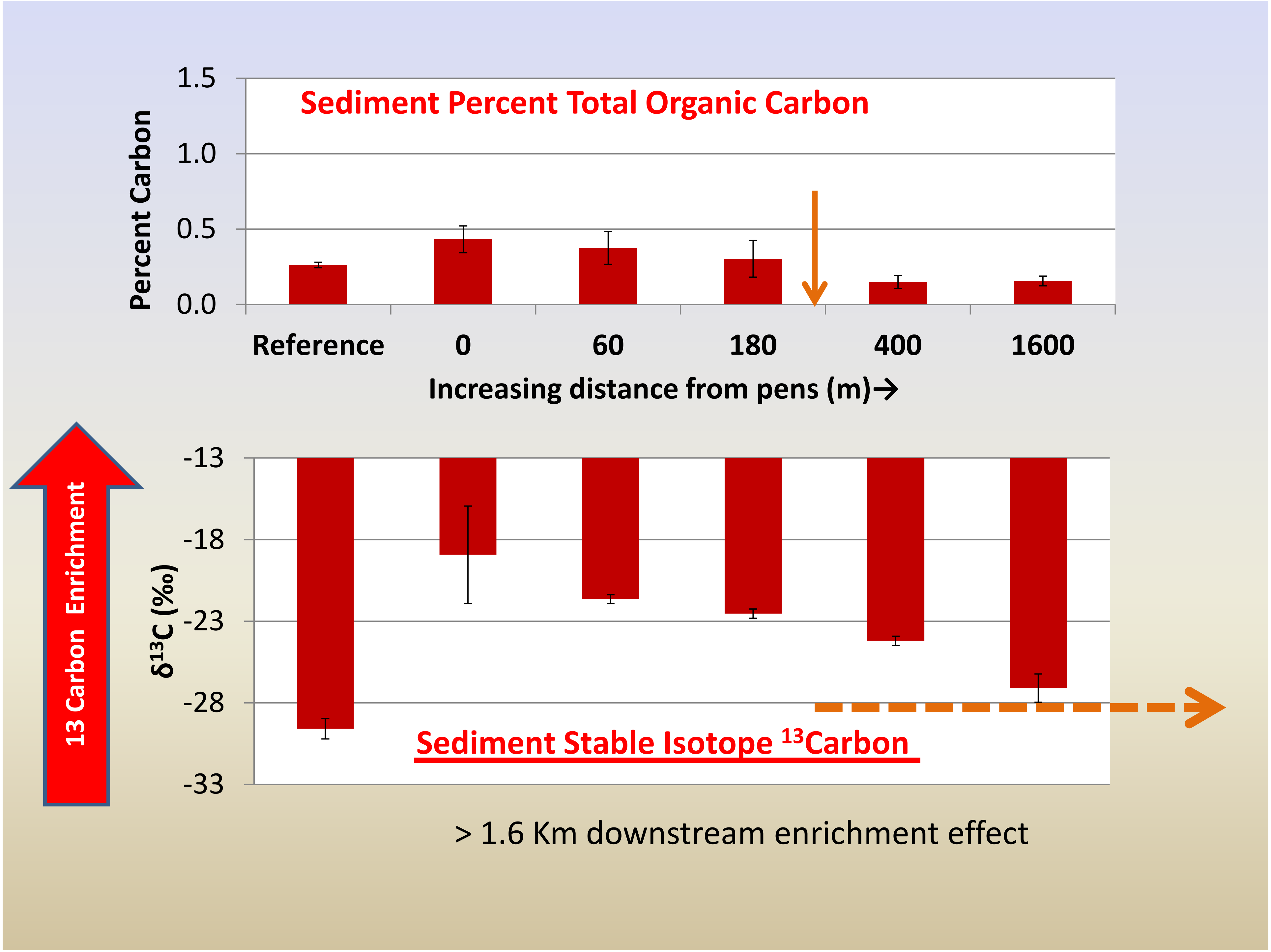
- Are fish wastes being taken up by the biota downstream or just feeding bacteria and using oxygen for respiration?   Stable isotope tracing of food source to consumer
- Stable isotopes are variants of atoms of specific elements with differing numbers of neutrons. (not radioactive): For example:
  12Carbon-13Carbon; 14Nitrogen -15Nitrogen
- Higher organisms consume and concentrate the heavy isotopes preferentially
- Respire the lighter carbon as CO2 and excrete the lighter nitrogen as urine
- Fish farms produce particulate C but mostly dissolved N, profound effect on results.



For Comparison to Stable Isotope Results

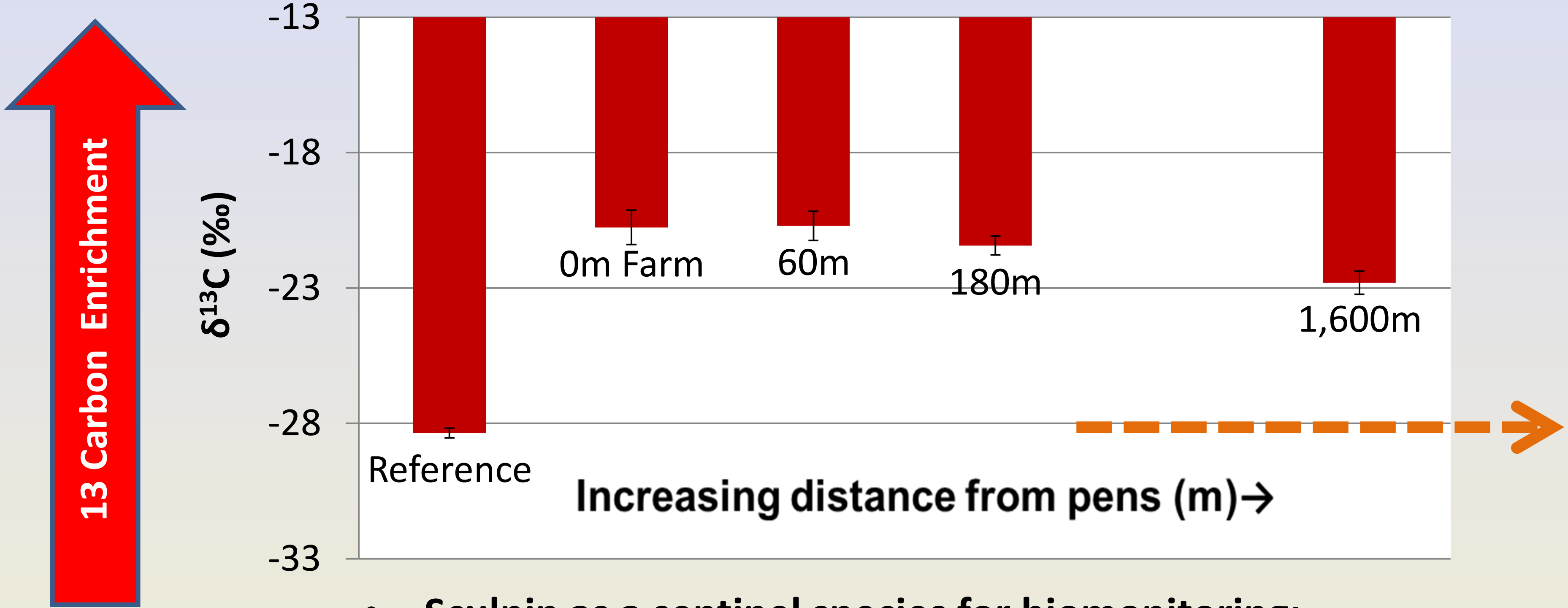






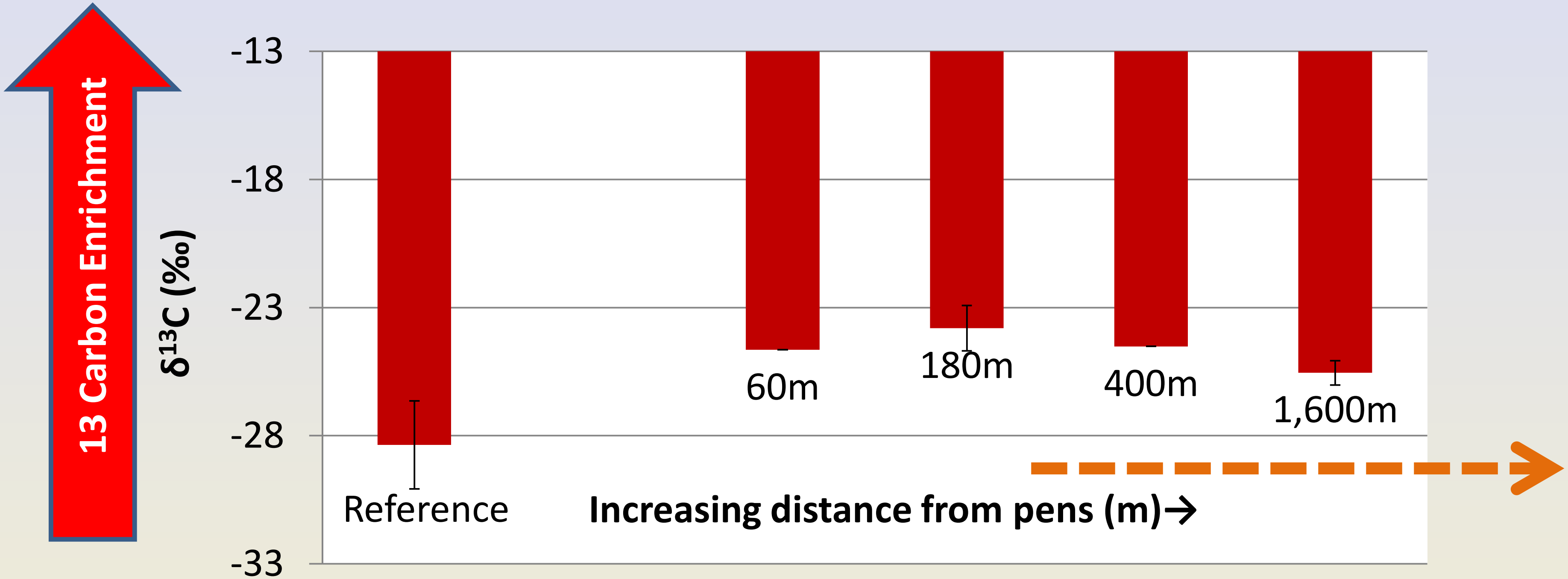
Sediment Percent Total Organic Carbon
Percent Carbon
1.5
1.0
0.5
0.0
Reference
0
60
180
400
1600
Increasing distance from pens (m)→
13 Carbon Enrichment
-13
-18
-23
-28
-33
δ13C (‰)
Sediment Stable Isotope 13Carbon
> 1.6 Km downstream enrichment effect

Sculpin Stable Isotope ^{13}Carbon

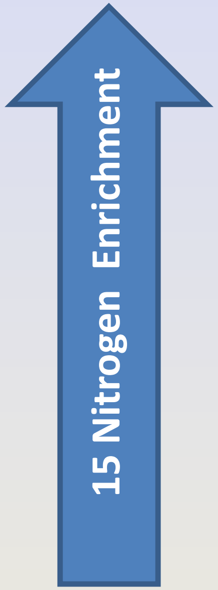


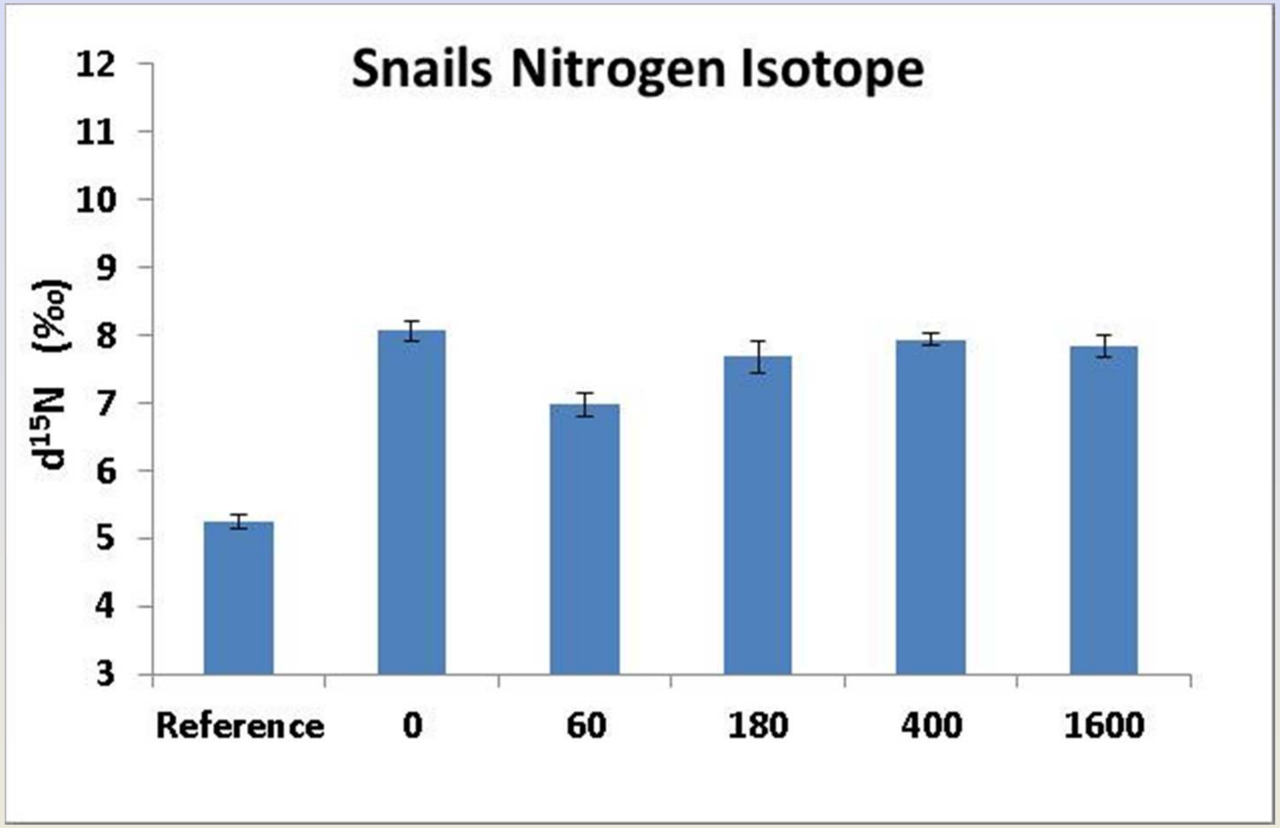
- **Sculpin as a sentinel species for biomonitoring:**
- **Small home range**
- **Consume waste feed and fish feces!**

Crayfish Stable Isotope ^{13}Carbon



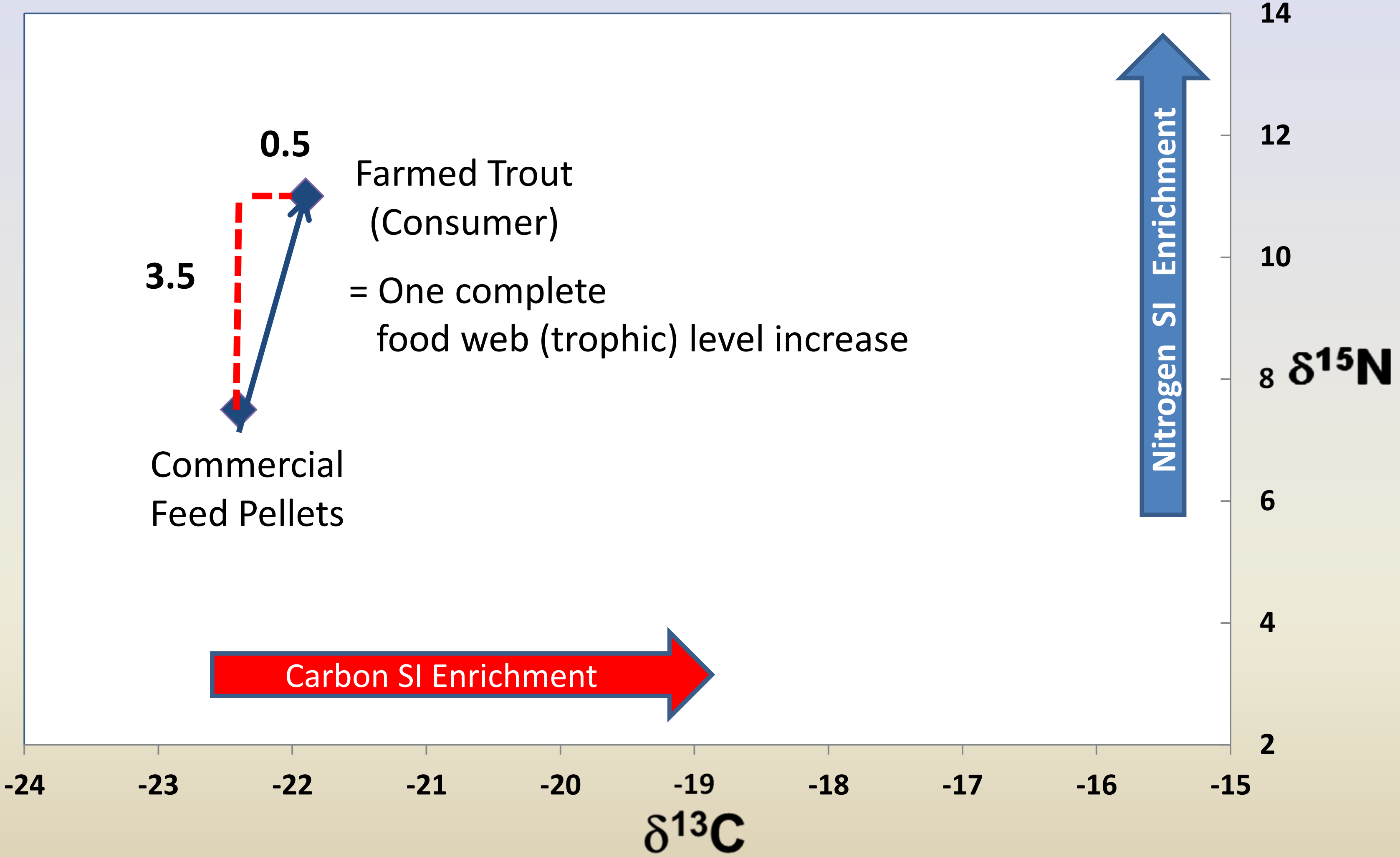
Omnivores (multiple food sources)
More complex food web





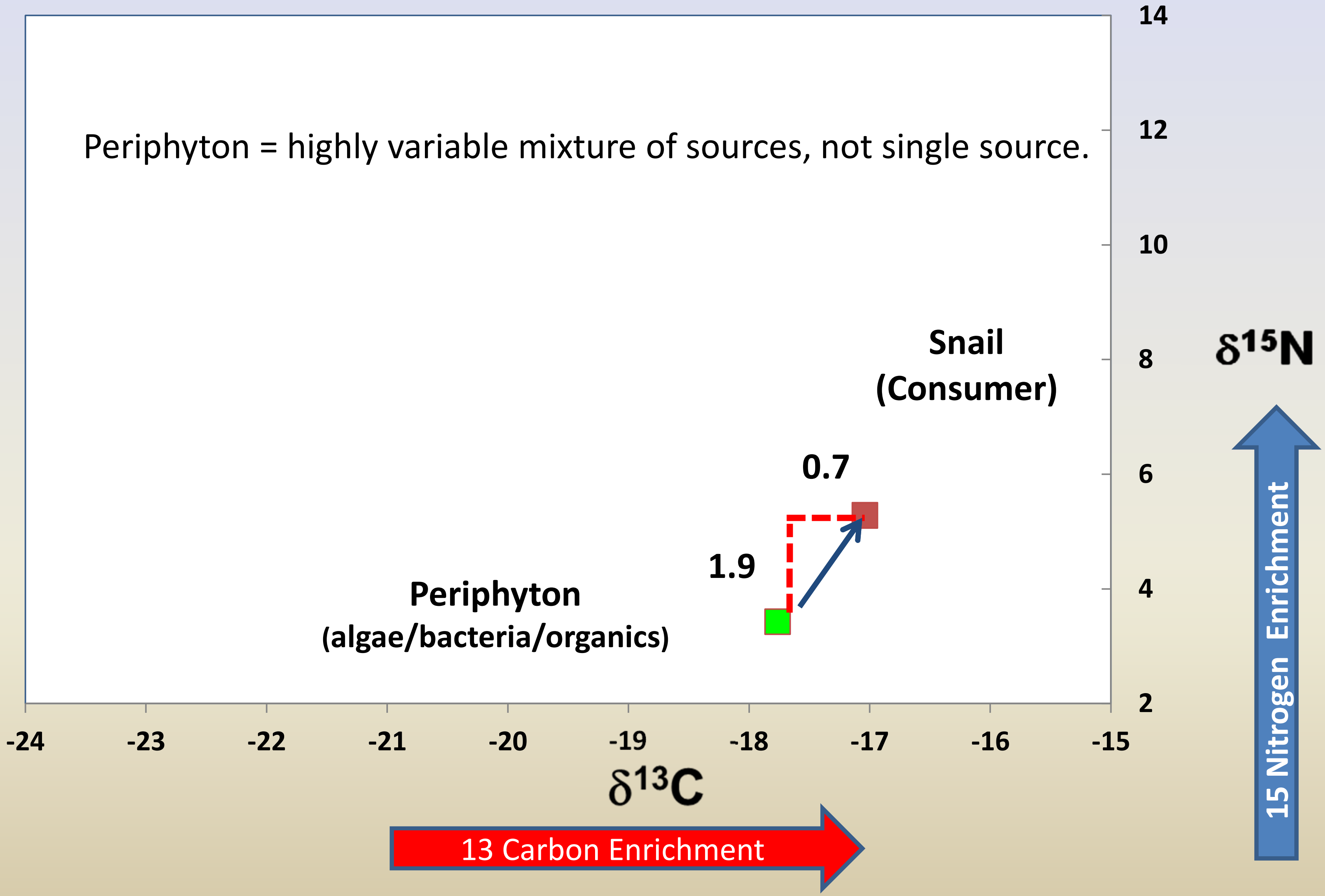
- **Significant increase in 15N for sediment, snails, sculpins, sponge but not crayfish.**

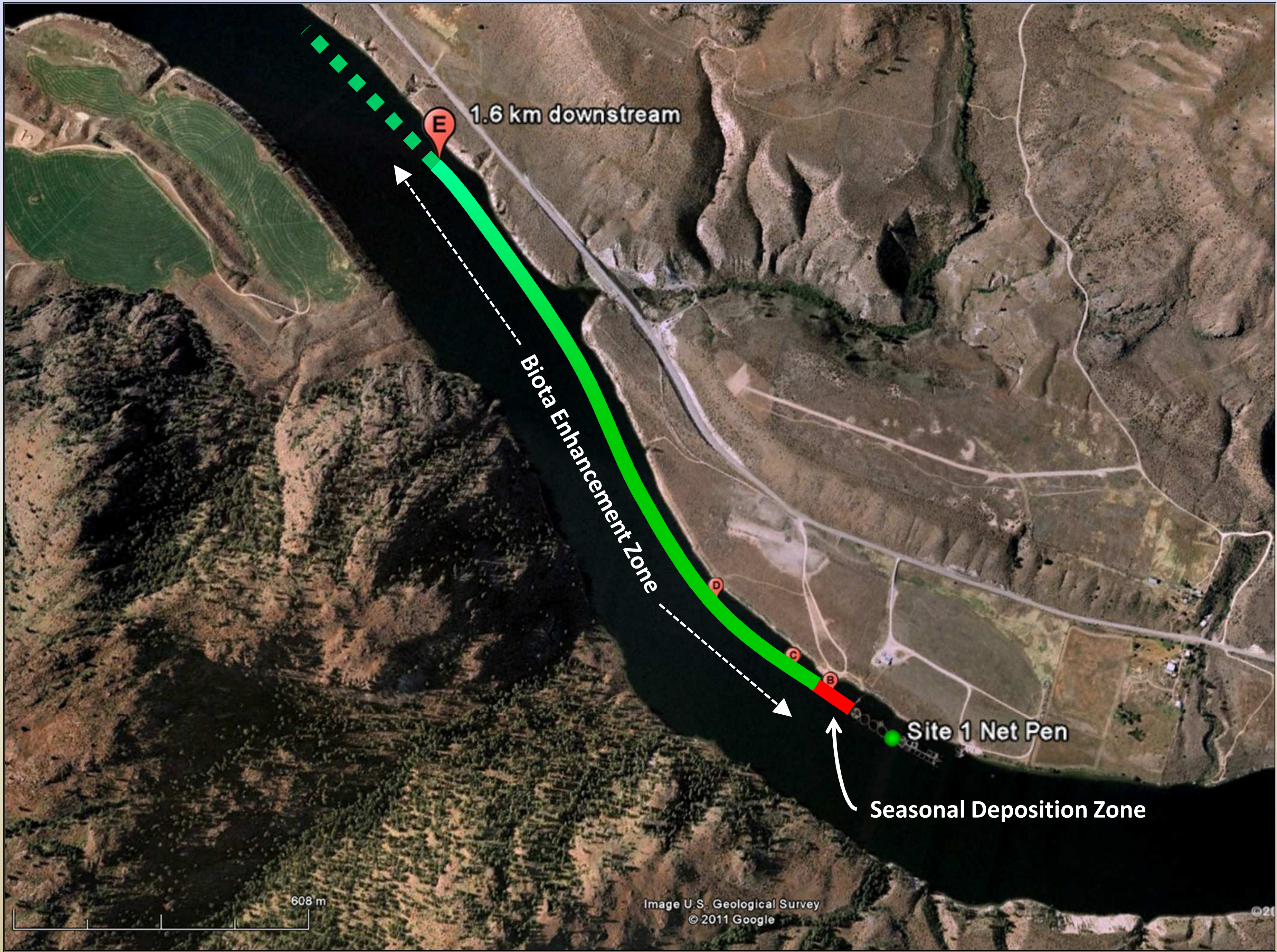
Dual Isotope (N and C) Analysis: One Food Source Example



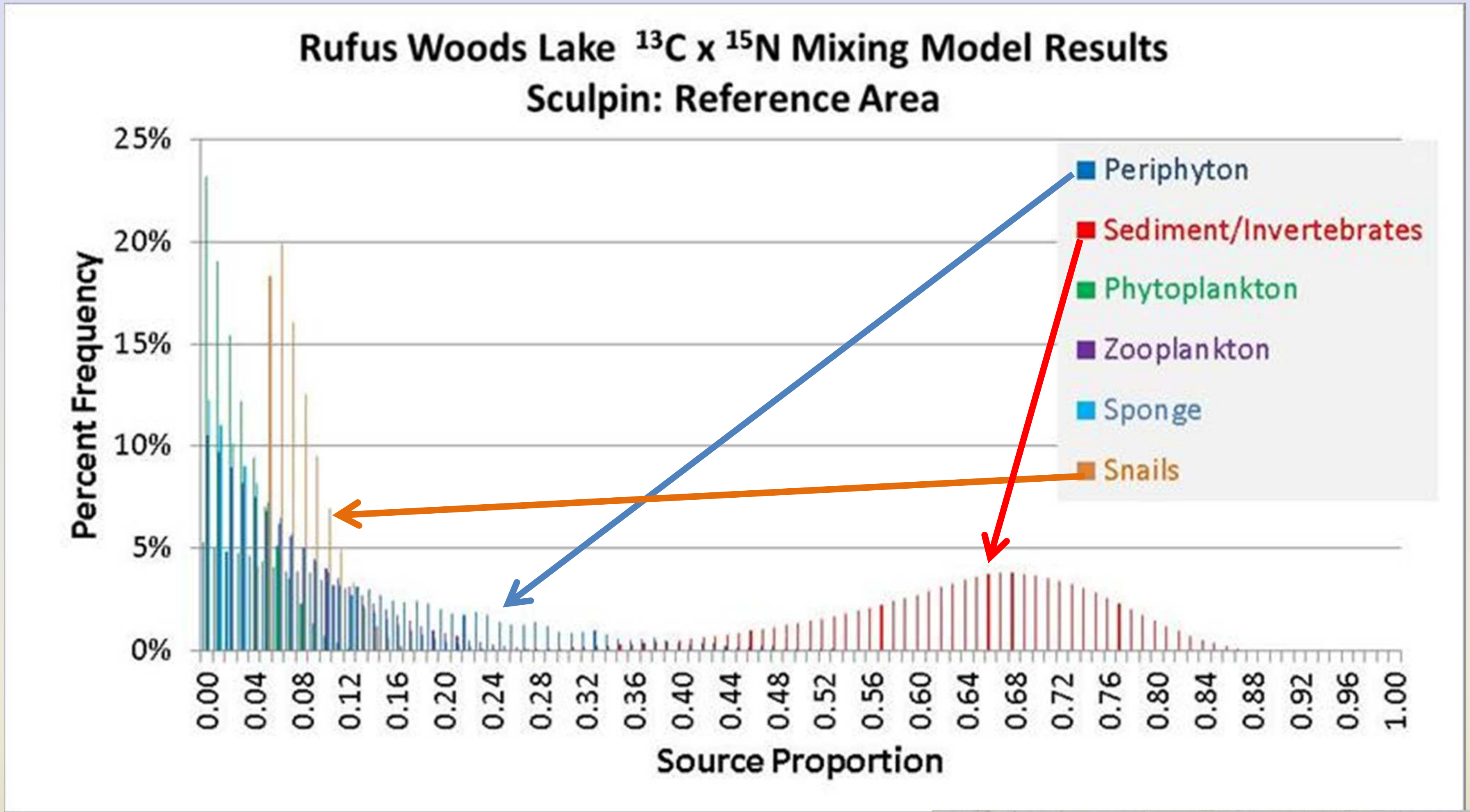
- **Carbon stable isotope: negative values, less negative is enrichment**
- **Nitrogen stable isotope: positive values, higher is enriched**

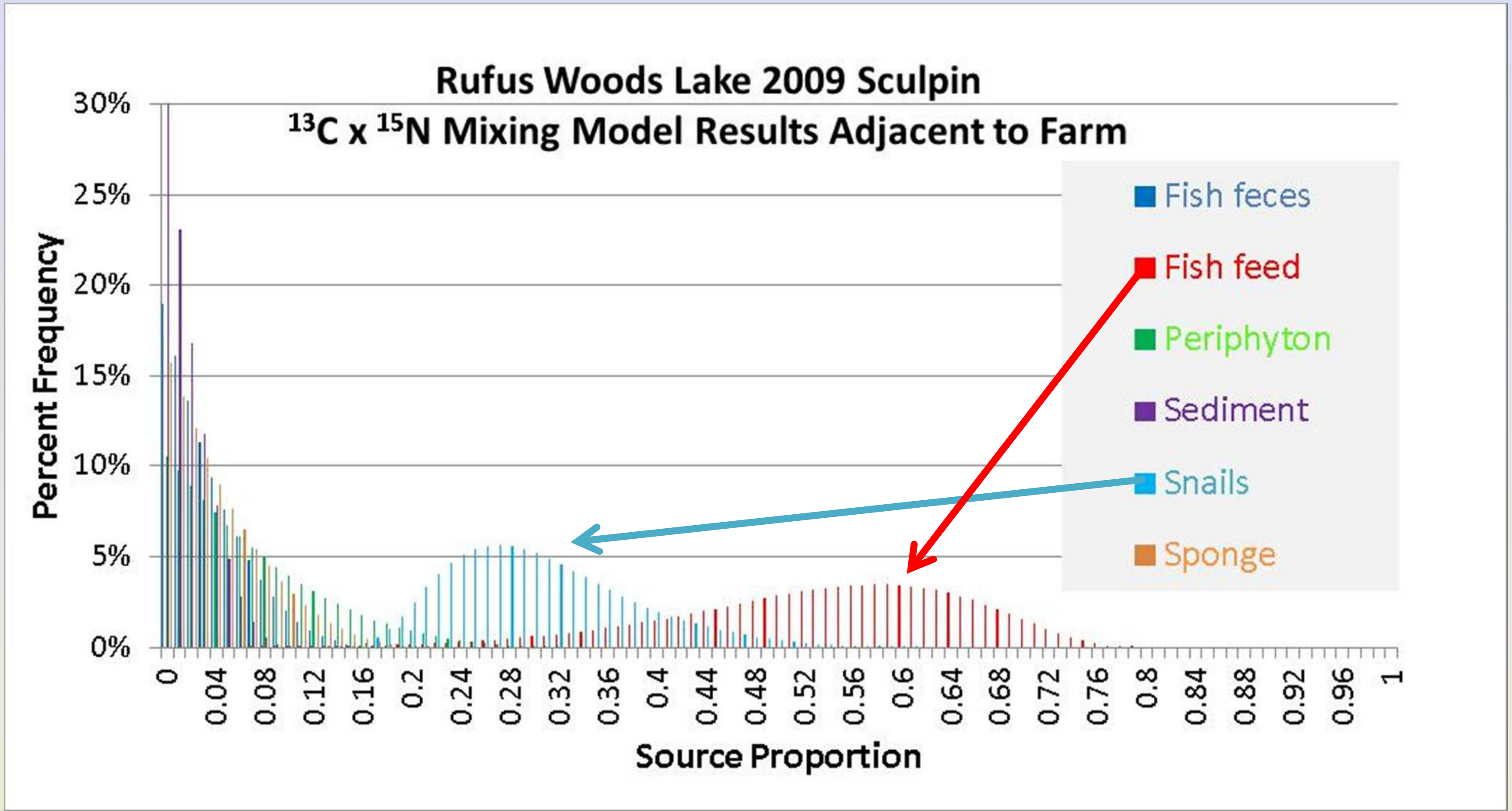
Dual Isotope (N and C) Analysis: Multiple Food Source



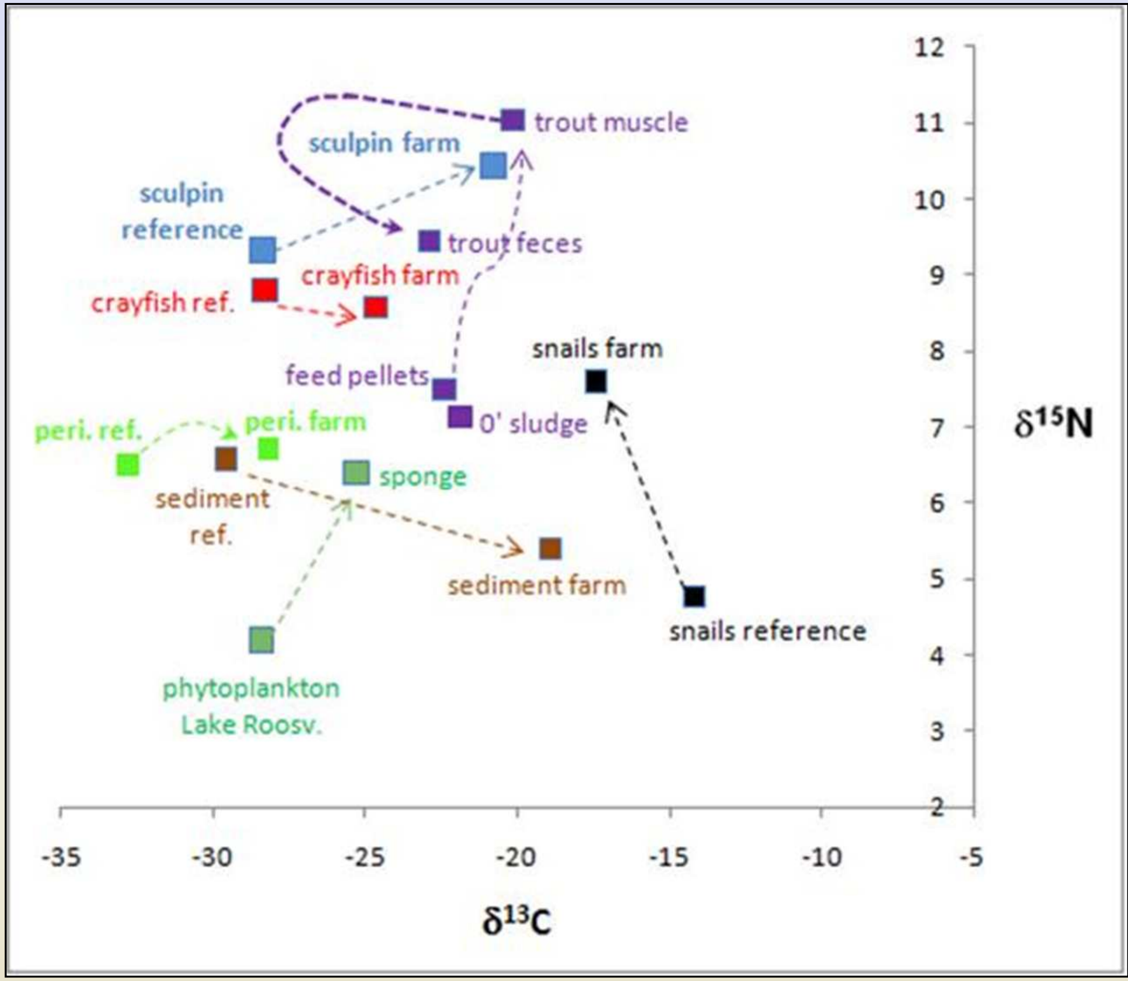


1.6 km downstream
E
Biota Enhancement Zone
D
C
B
Site 1 Net Pen
Seasonal Deposition Zone
608 m
Image U.S. Geological Survey
© 2011 Google


Rufus Woods Lake ¹³C x ¹⁵N Mixing Model Results
Sculpin: Reference Area
25%
20%
15%
10%
5%
0%
Percent Frequency
0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28 0.32 0.36 0.40 0.44 0.48 0.52 0.56 0.60 0.64 0.68 0.72 0.76 0.80 0.84 0.88 0.92 0.96 1.00
Source Proportion
Periphyton
Sediment/Invertebrates
Phytoplankton
Zooplankton
Sponge
Snails



- Overfeeding with prior, short-term ownership & management!
- Prickly sculpin serve as excellent biomonitoring (and prey) species
- Small home range and relatively easy to capture with slurp gun

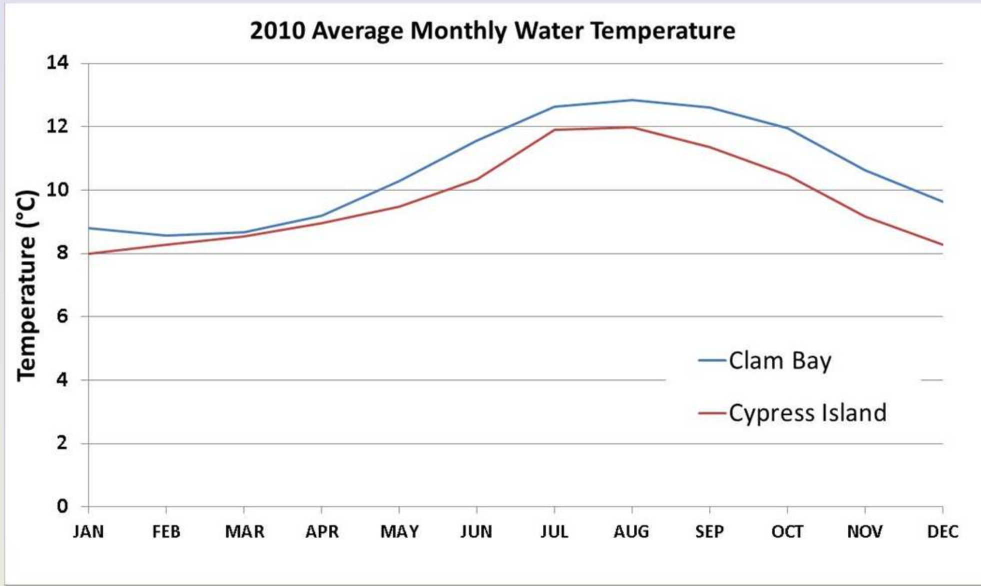


pen operation
d measurable

rtebrates and

out for 15N less
ed excretion
omplex and
Power

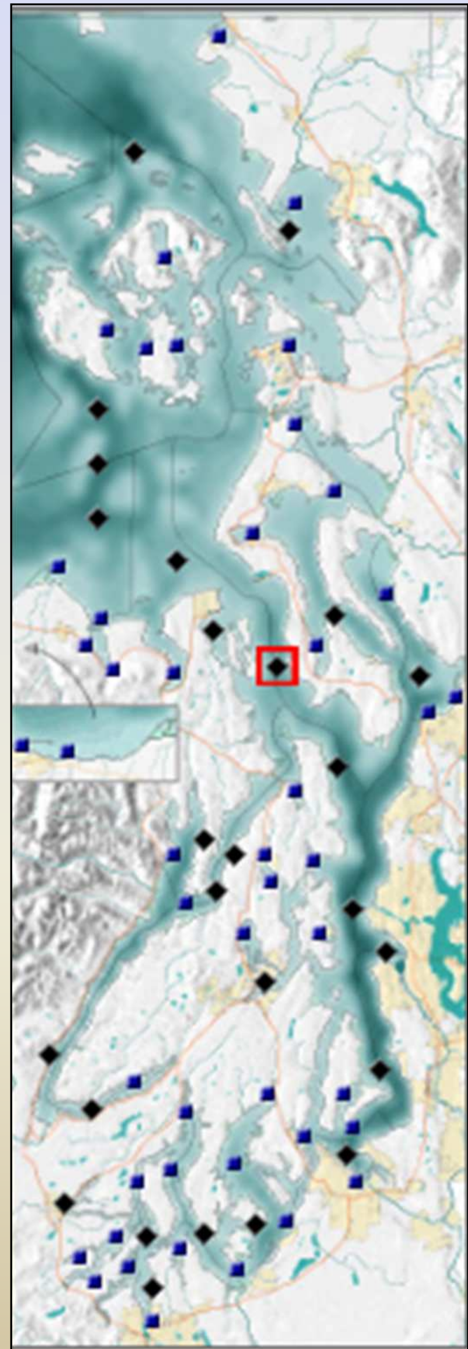
Puget Sound Net Pen Examples



- Highly scrutinized and regulated industry
- But science-based permit & appeals system
- The result of extensive research in 1980s & 1990s

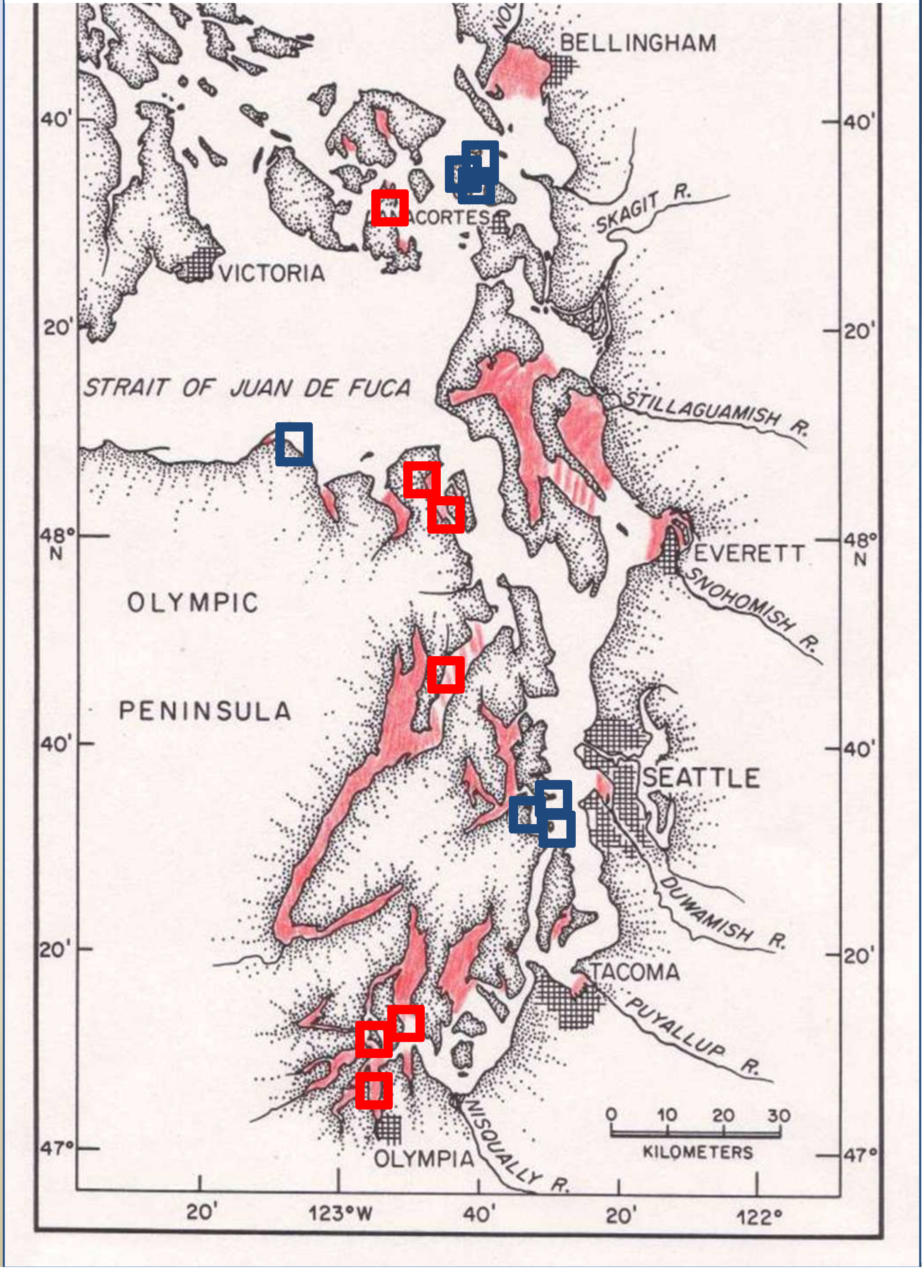
Ranking of nutrient sensitivity: Nutrient & subsurface dissolved oxygen monitoring

Rensel (1991) for U.S. EPA

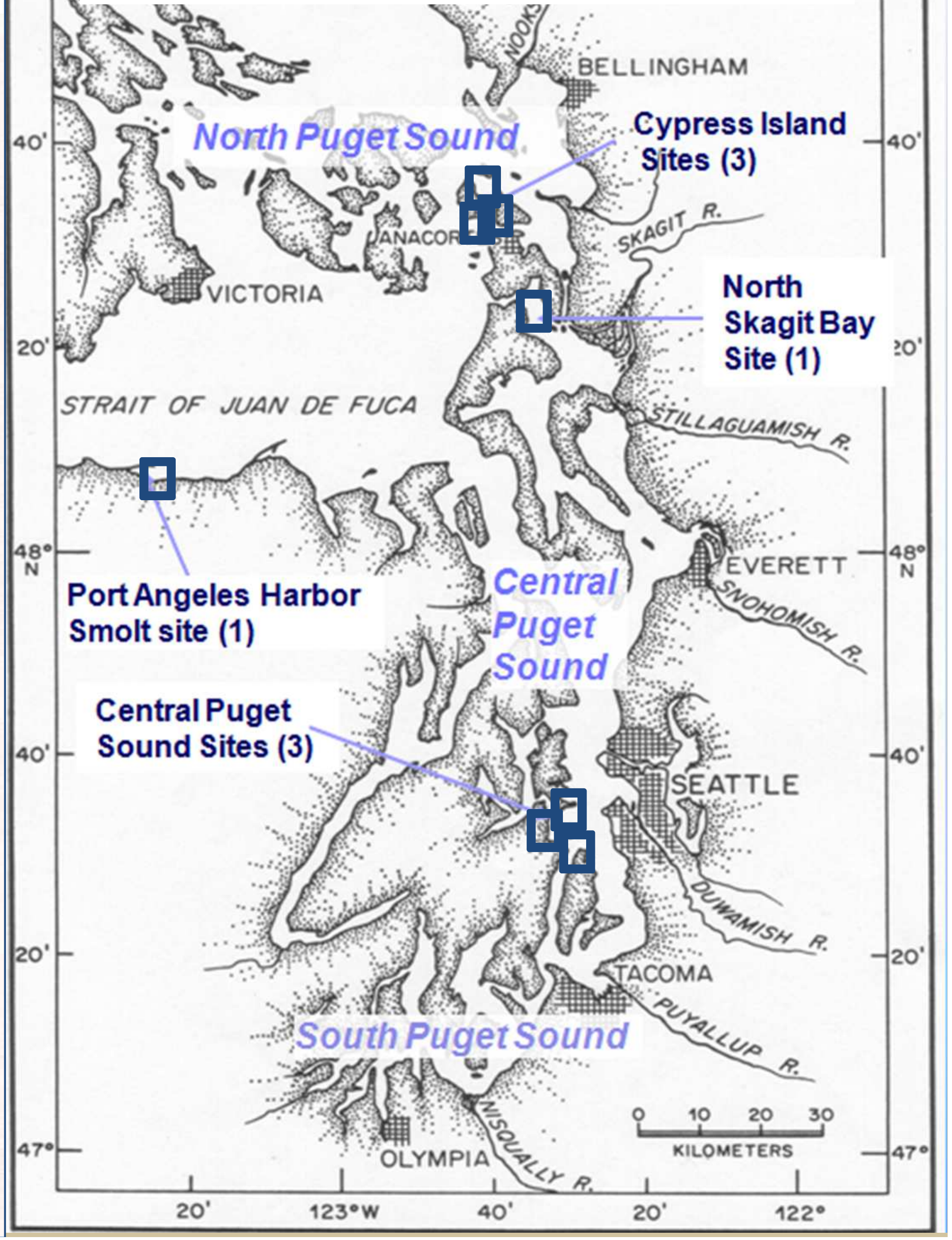


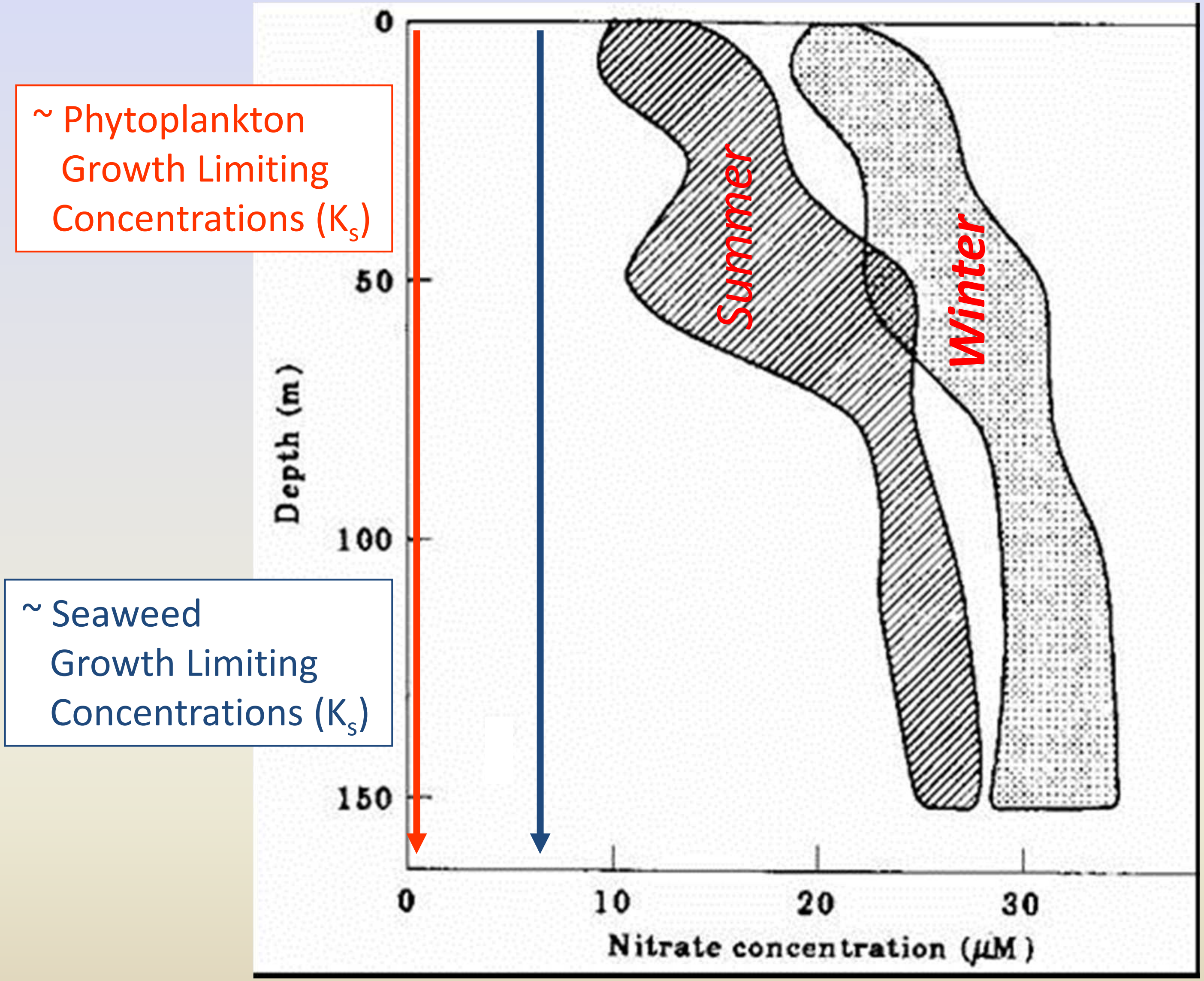
1969-85 Pens: Nutrient Sensitive Areas

1969-85 Pens: Non-Nutrient Sensitive Areas



2011 All Net Pens in Non Nutrient Sensitive Locations

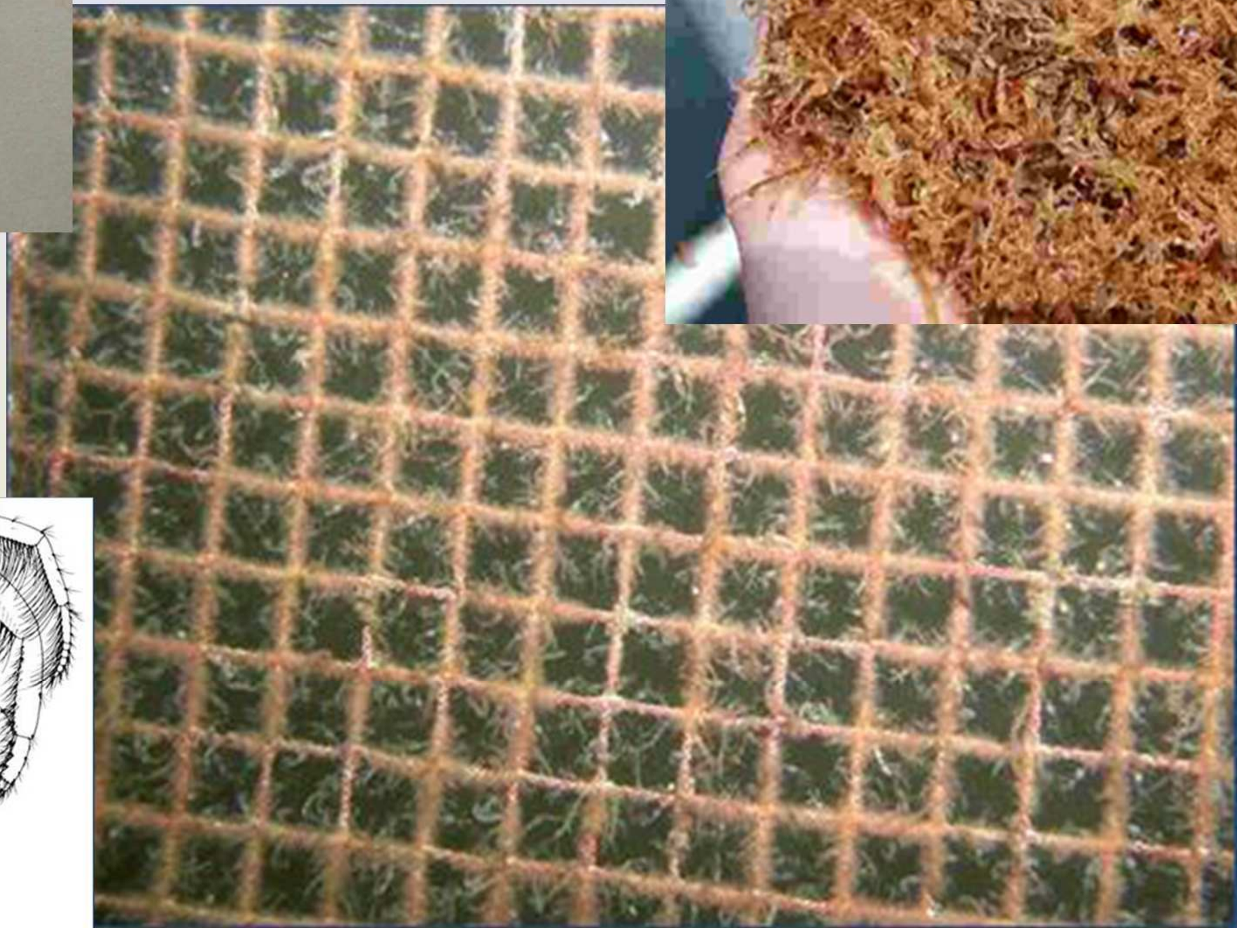


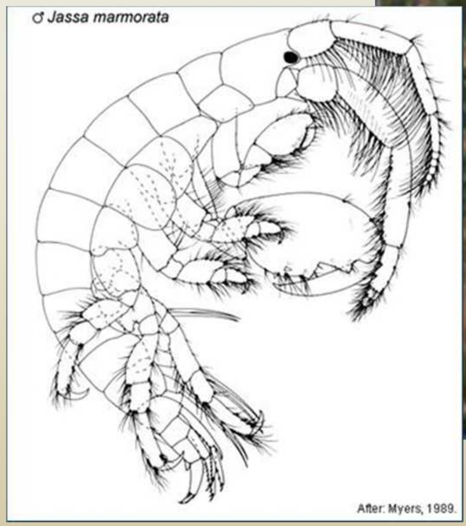


Sunlight, vertical mixing & advection limit algal growth, not nutrient supply, in main basins of Puget Sound and the Strait of Juan de Fuca. (after P. Harrison, UBC)

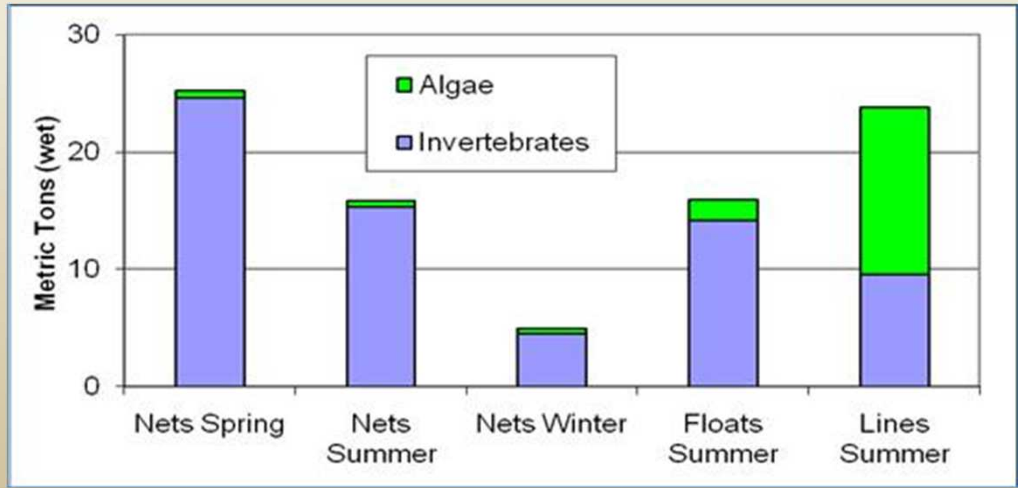
"Beneficial Effects" Study

Billions of
Amphipods



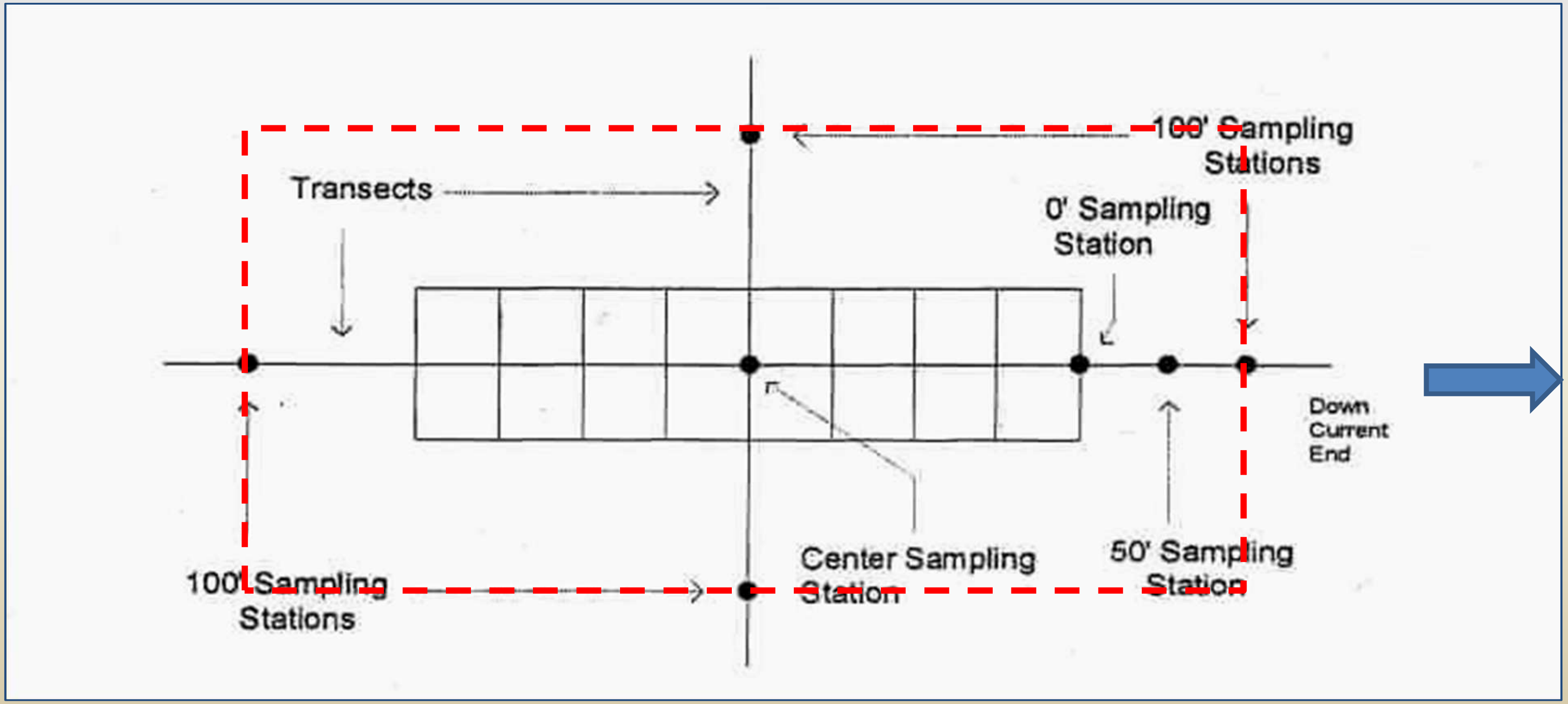



>100 species of macroinvertebrates
Cling fish
Many species of seaweeds
No exotic sea squirts


Metric Tons (wet)
30
20
10
0
Algae
Invertebrates
Nets Spring
Nets Summer
Nets Winter
Floats Summer
Lines Summer

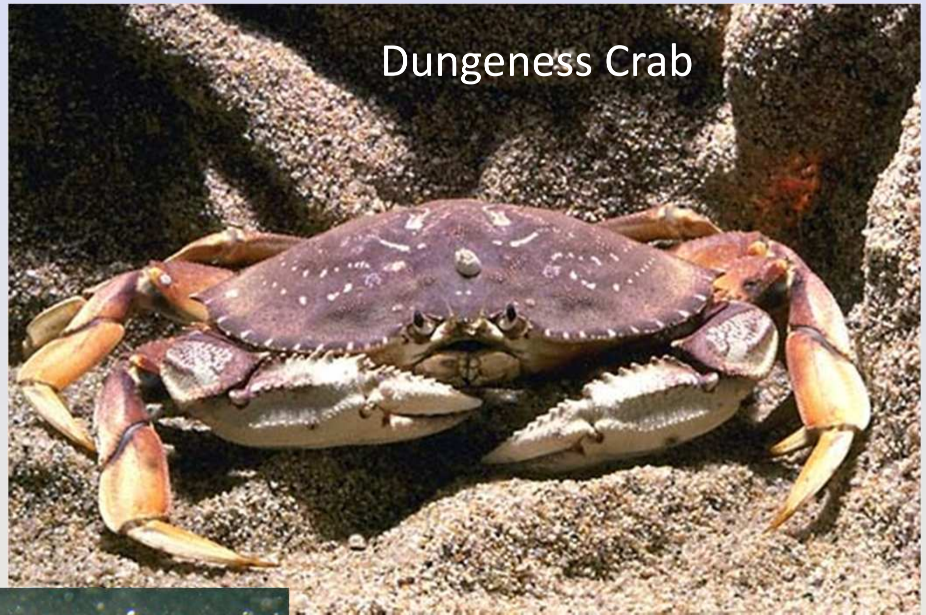
Limits of Adverse Effects & Where is the Halo Zone?

- Sediment impact zone: 30m from pens allowable effects
- Sampled for infauna, total organic carbon and sediment grain size
- Most pass, some have had to reconfigure or shift location slightly
- Infauna samples outside zone often show no enhancement. Why?



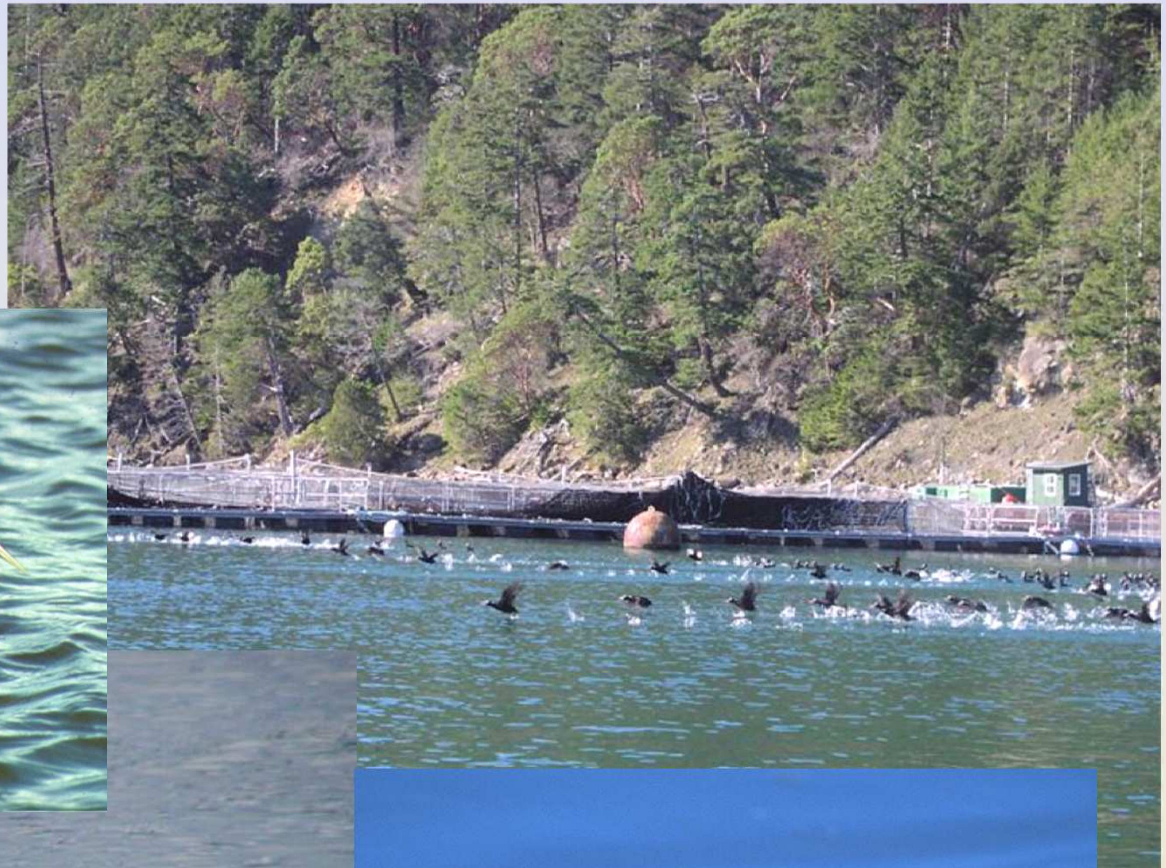
Higher Food Web Effects

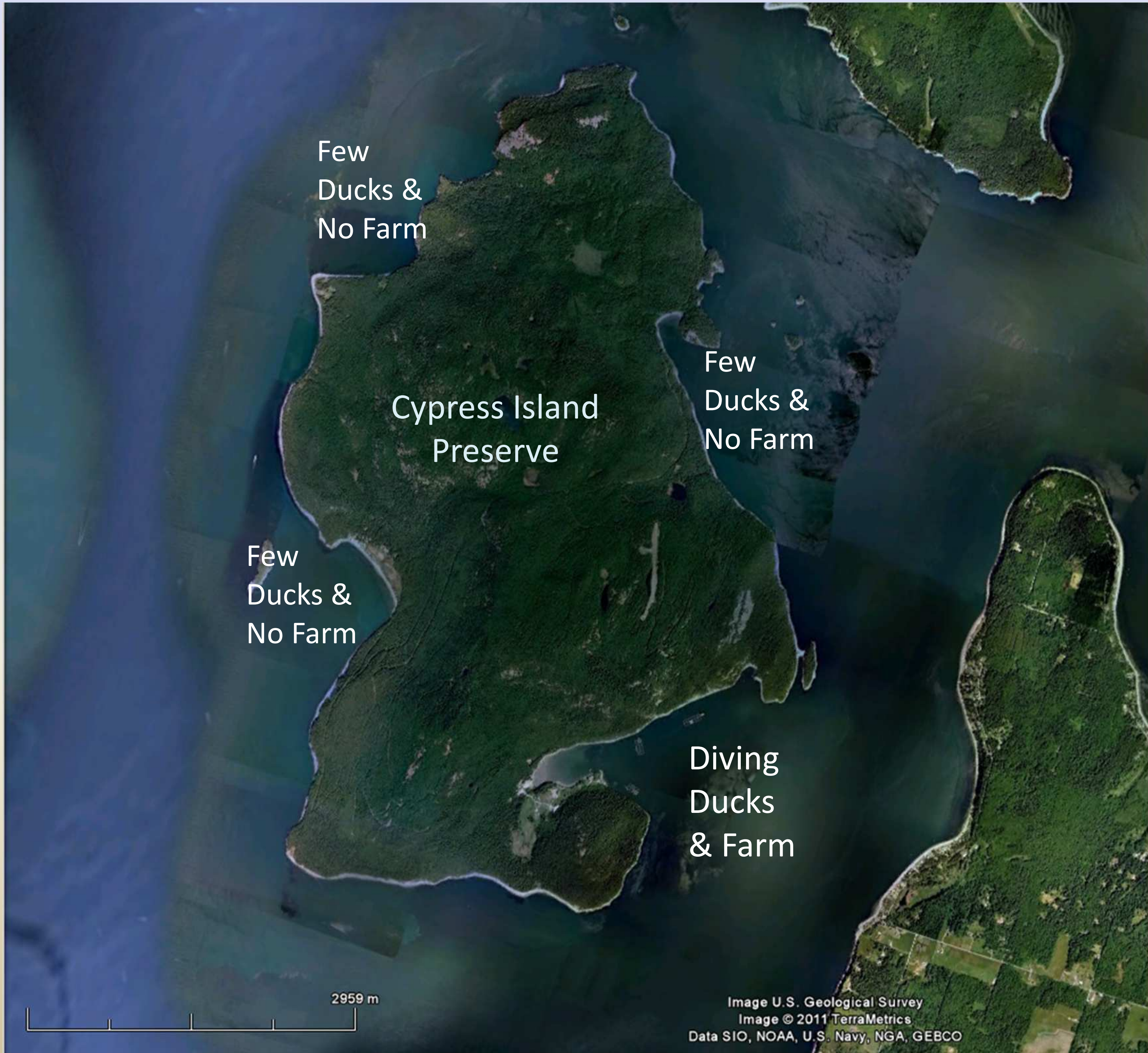
Sport & Commercial Species
Abundant Near PS Net Pens



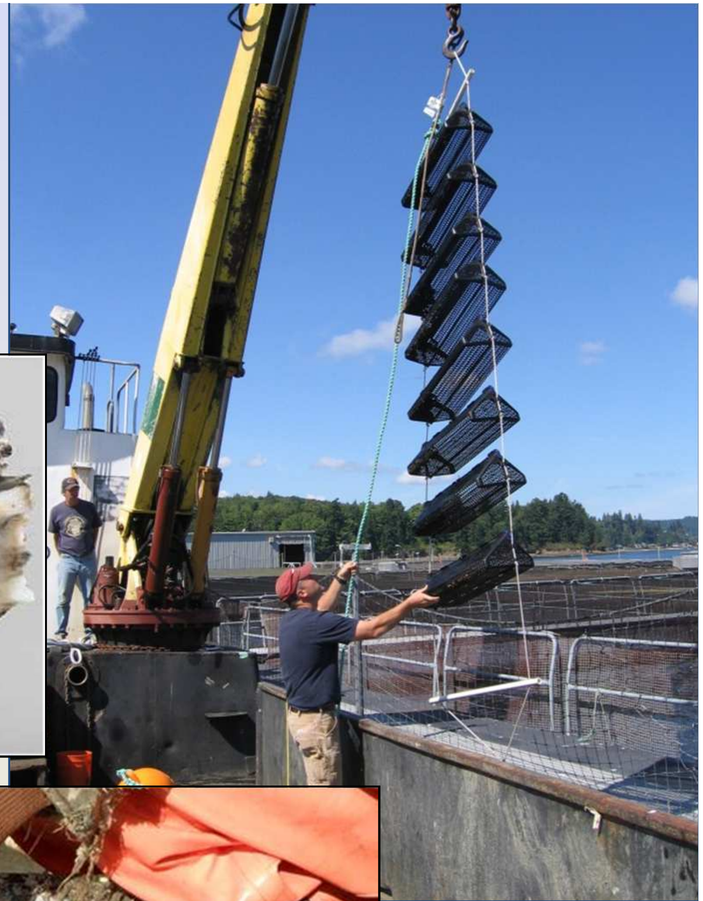
Higher Food Web Effects

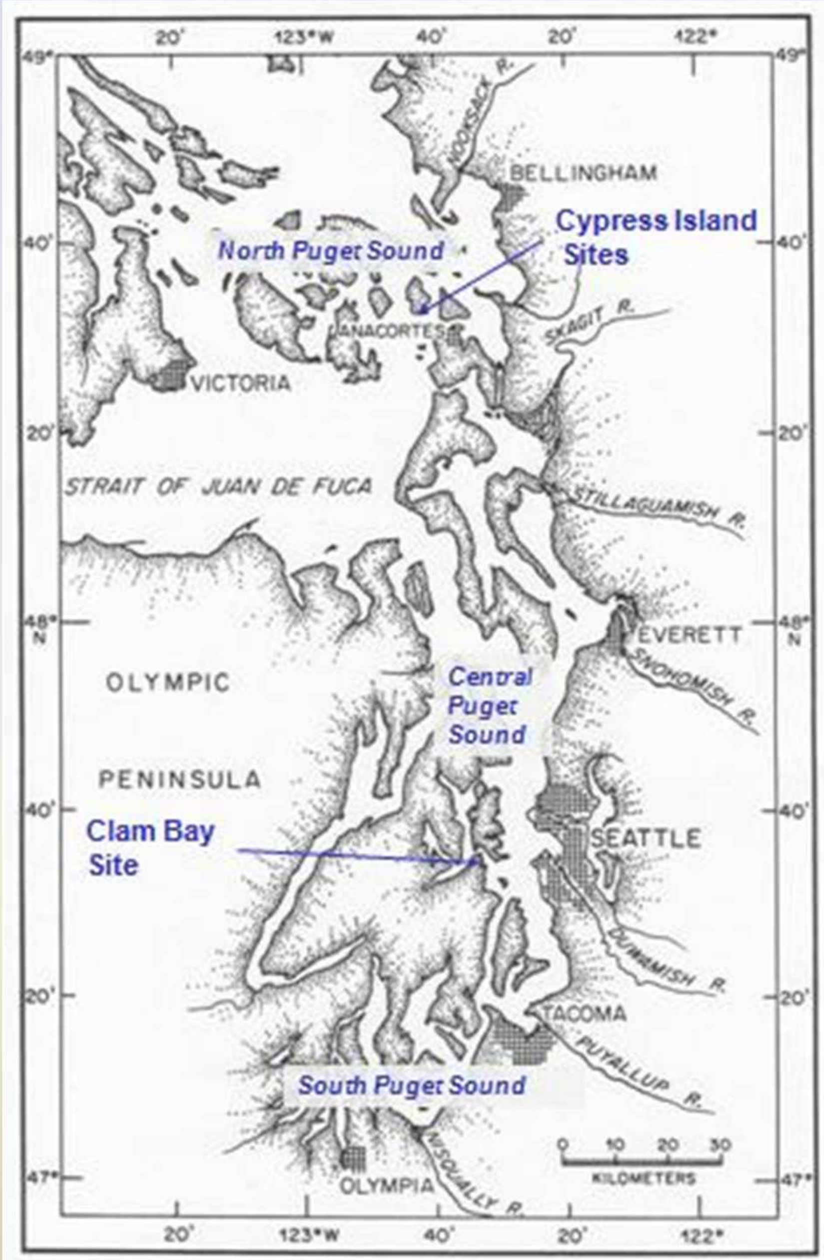
Seabirds in Net Pen Areas




Few
Ducks &
No Farm
Cypress Island
Preserve
Few
Ducks &
No Farm
Few
Ducks &
No Farm
Diving
Ducks
& Farm
2959 m
Image U.S. Geological Survey
Image © 2011 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Oyster/Mussel/Salmon Aquaculture IMTA in Puget Sound

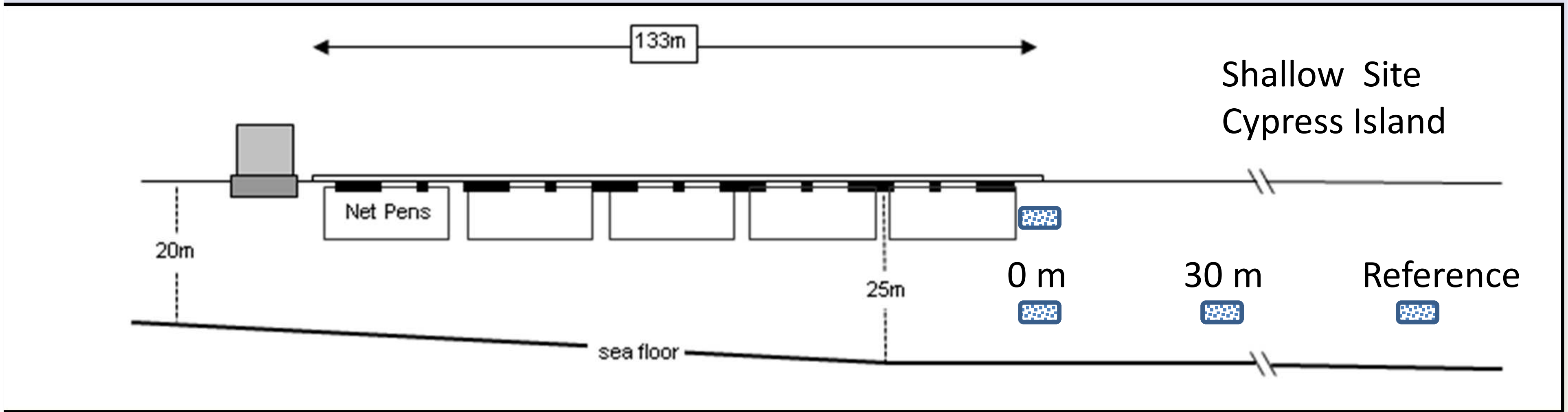


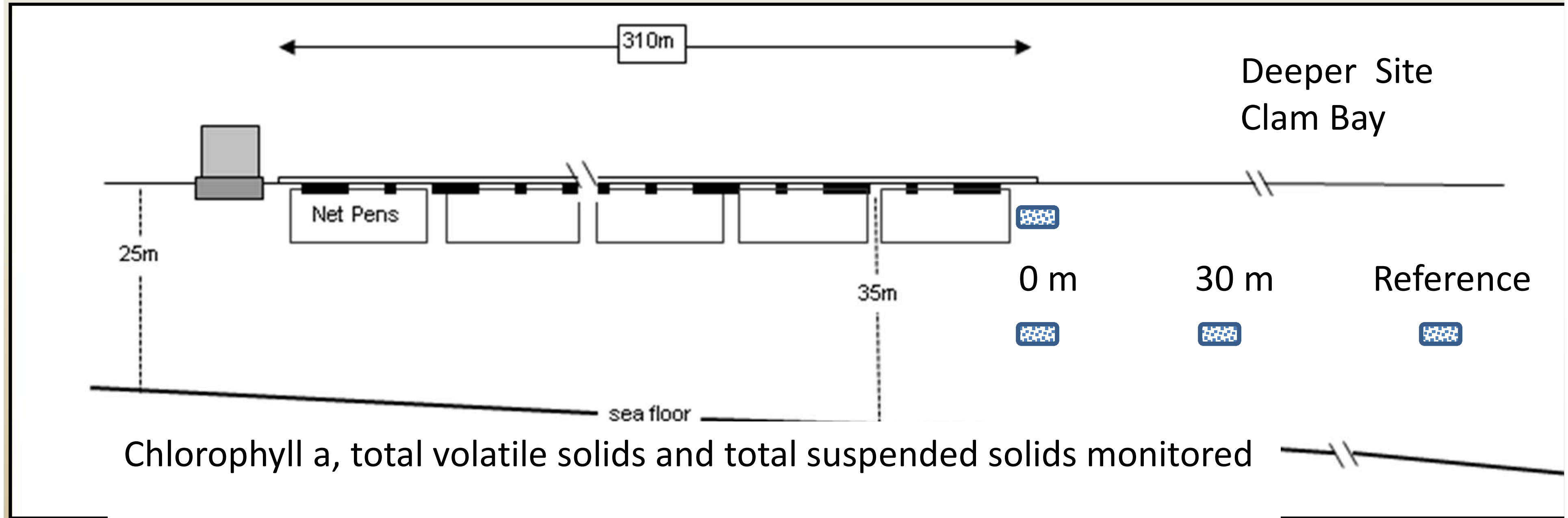


North Puget Sound
Cypress Island Sites
BELLINGHAM
ANACORTES
VICTORIA
STRAIT OF JUAN DE FUCA
NOOKSACK R.
SKAGIT R.
STILLAGUAMISH R.
EVERETT
SNOHOMISH R.
OLYMPIC PENINSULA
Central Puget Sound
Clam Bay Site
SEATTLE
DUWAMISH R.
TACOMA
PUYALLUP R.
South Puget Sound
OLYMPIA
NISQUALLY R.
0 10 20 30
KILOMETERS
123°W
122°
49°
48° N
47°

Pacific Oysters & Gallo Mussels
5 replicates of each at four locations

American Gold Seafoods (Icicle Seafoods)
Taylor Shellfish Farms



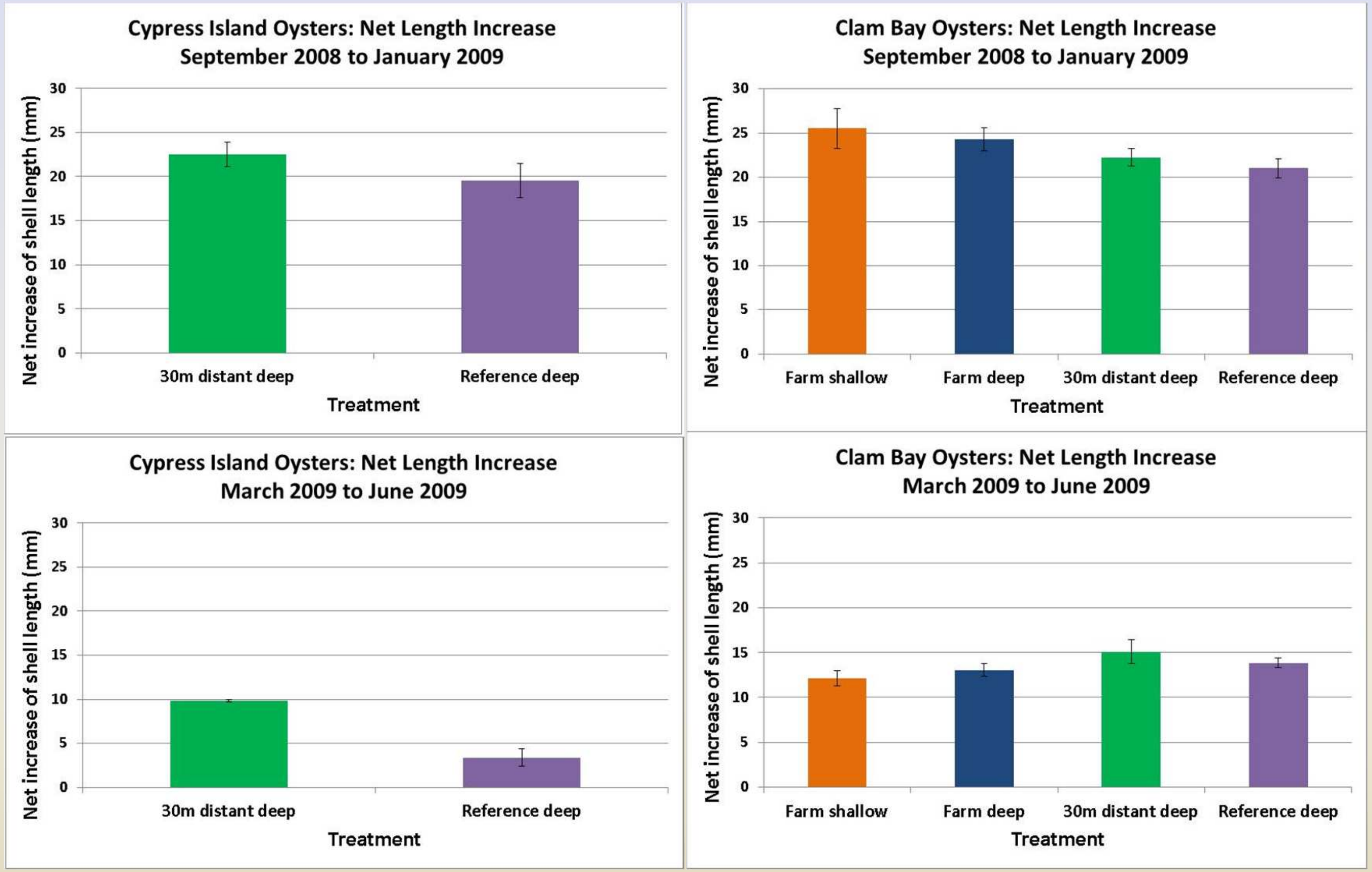


Chlorophyll a, total volatile solids and total suspended solids monitored

Pacific Oyster Growth

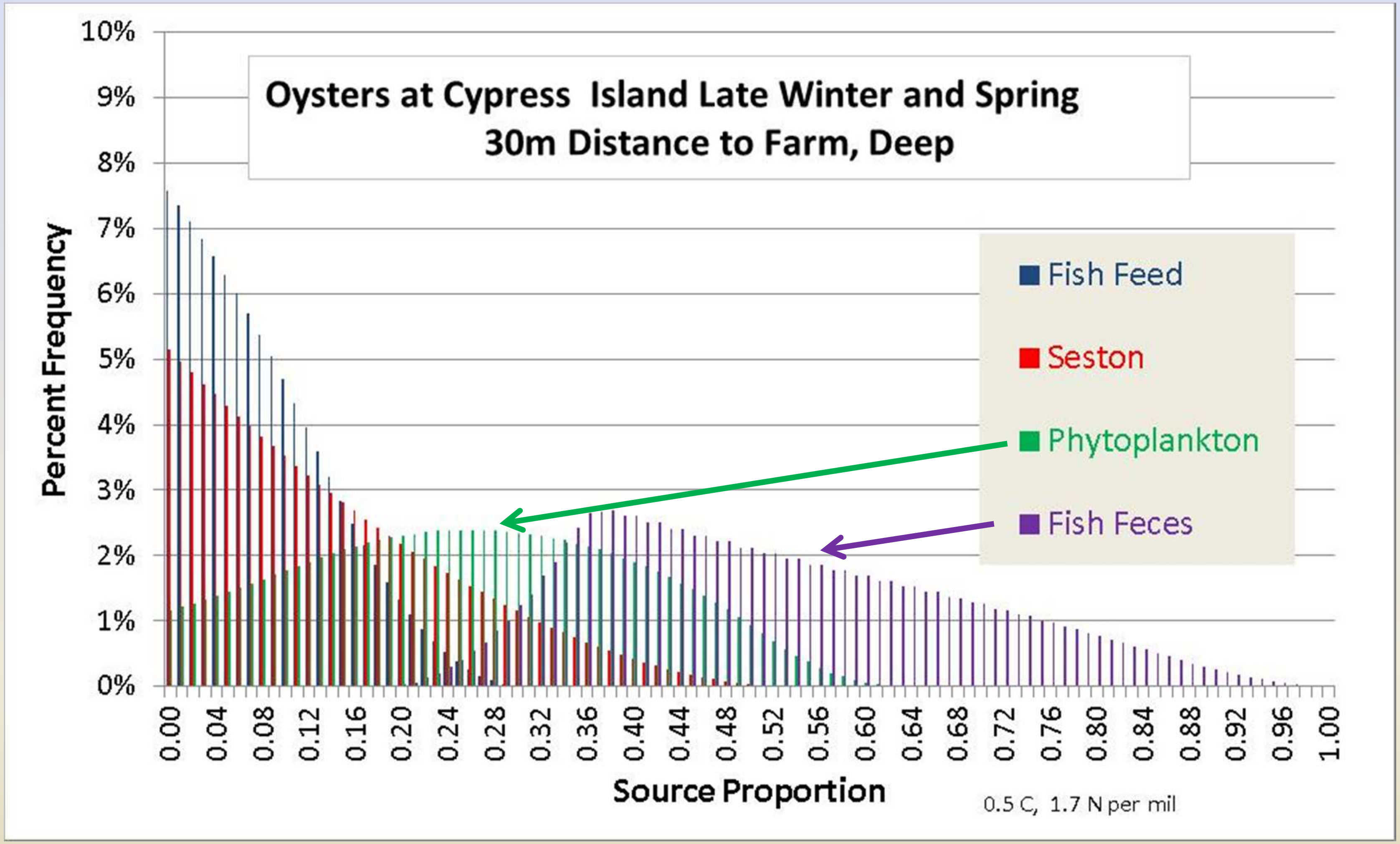
Fall & Early Winter

Spring

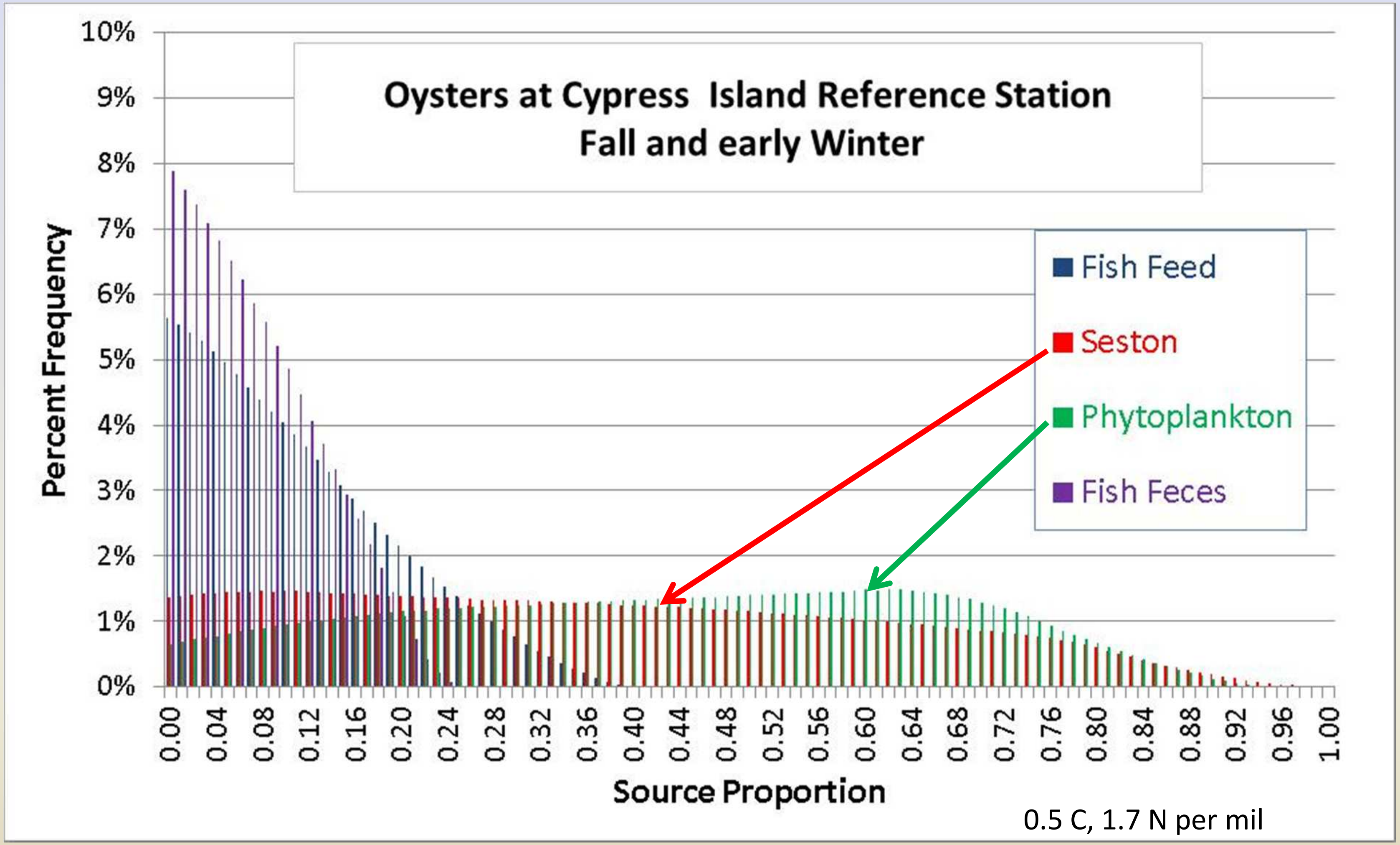


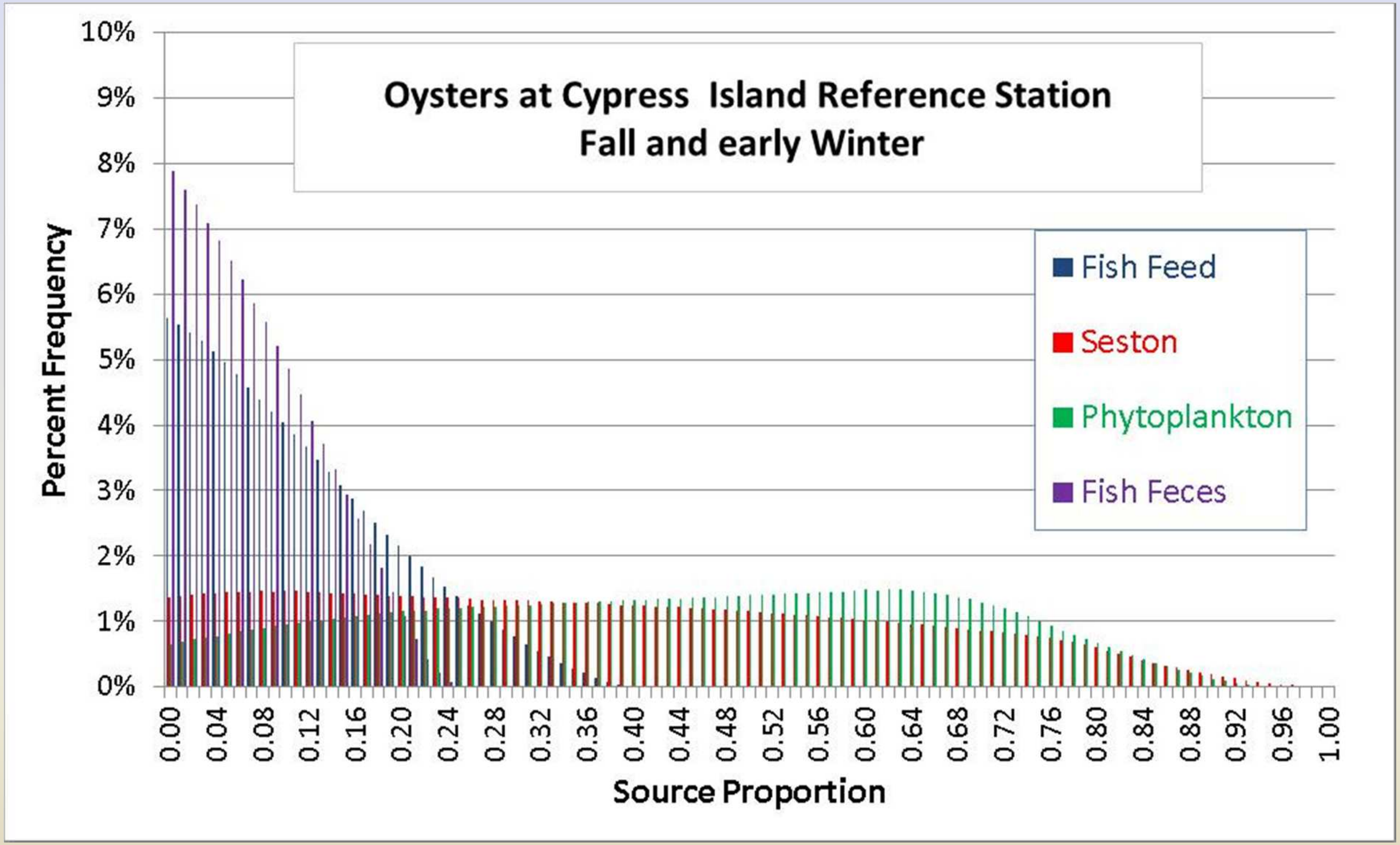
But…… Mussels: No significant growth effects !

Literature IMTA growth documentation is limited



Oysters at Cypress Island Late Winter and Spring
30m Distance to Farm, Deep
Percent Frequency
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Fish Feed
Seston
Phytoplankton
Fish Feces
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
0.68
0.72
0.76
0.80
0.84
0.88
0.92
0.96
1.00
Source Proportion
0.5 C, 1.7 N per mil


Oysters at Cypress Island Reference Station
Fall and early Winter
Percent Frequency
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
0.68
0.72
0.76
0.80
0.84
0.88
0.92
0.96
1.00
Source Proportion
Fish Feed
Seston
Phytoplankton
Fish Feces
0.5 C, 1.7 N per mil



Oysters at Cypress Island Reference Station
Fall and early Winter
Percent Frequency
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Fish Feed
Seston
Phytoplankton
Fish Feces
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
0.68
0.72
0.76
0.80
0.84
0.88
0.92
0.96
1.00
Source Proportion

IMTA Puget Sound Synthesis

	Experiment 1: 2009-2010							
	Oysters				Mussels			
Ranking Factor	Clam Bay		Cypress Island		Clam Bay		Cypress Island	
	Fall	Winter - Spring	Fall	Winter - Spring	Fall	Winter - Spring	Fall	Winter - Spring
Growth	+	-	+	+	-	-	-	-
Mixing Model	+	+	+	+	-	-	-	-
Survival	-	-	-	-	+	+	-	-
Cummulative	Yes	Maybe	Yes	Yes	No	No	No	No

- **Net pen wastes affected oysters positively, but not mussels**
- **Mussel experiment repeated another year….. Same results**
- **Oyster feeding ecology different, less specialized (" oysters better at sorting useful and not useful particles")**

Macroinvertebrates Epicureans

Metridium senile anemones
mostly eat small zooplankton

Spot prawns only eat fresh food
including their brethren

How to understand and predict the distribution of beneficial effects with such complicated circulation and biological factors in marine waters?

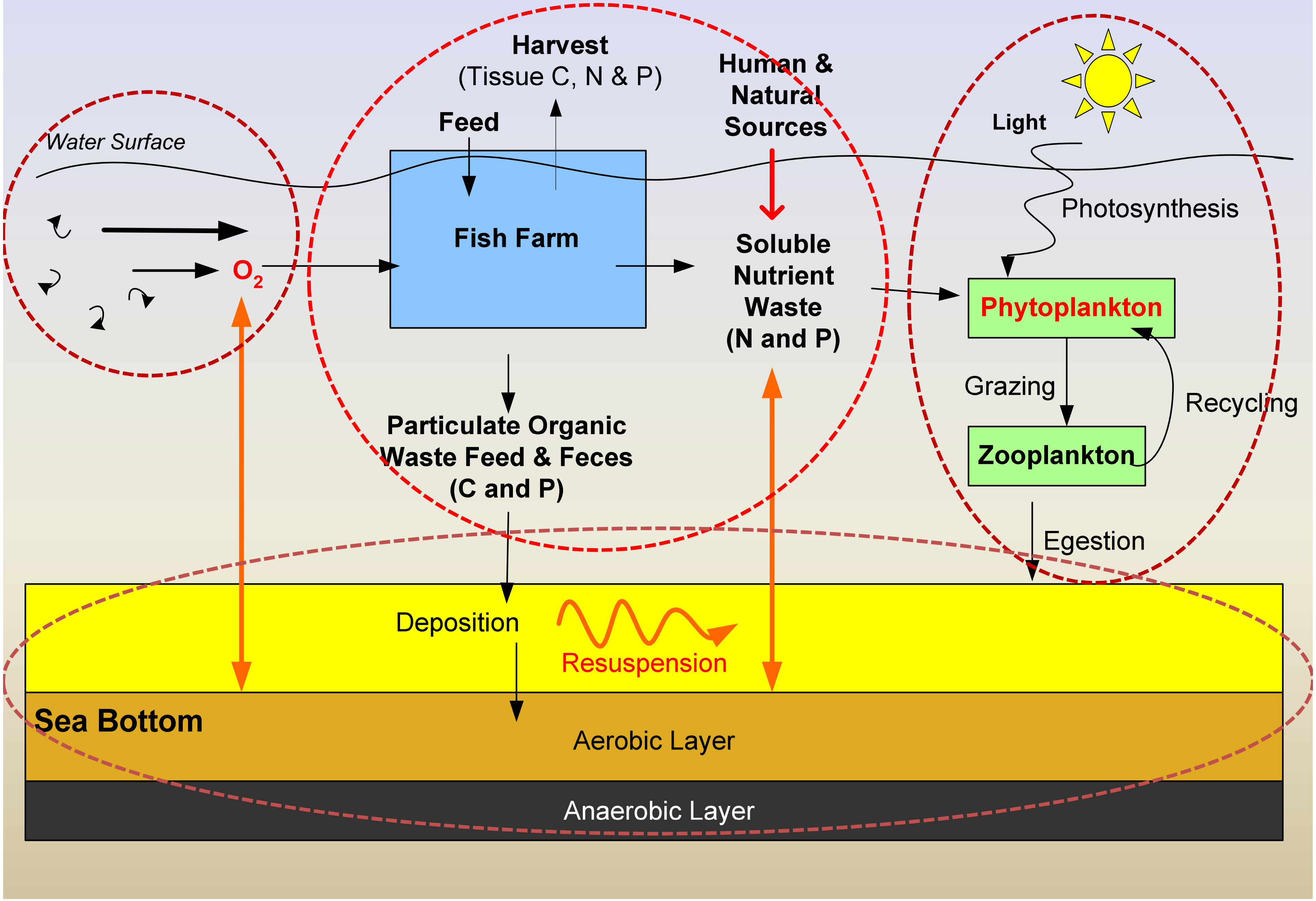
…… Computer simulation is the only alternative

Existing models provide static snapshots, but processes described here are highly dynamic

12 years ago our GIS modeling team began assembling software to meet this challenge.

Testing, applying, revising, sharing (but not selling) our software as we chewed off a giant chunk and wanted to get it right.

AquaModel Components

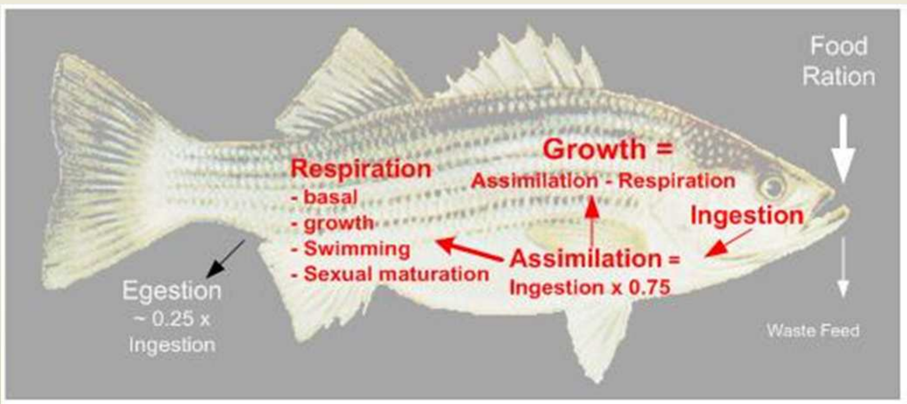


Physics Rules! (Biology)

- **Depositional ~ (<5 cm/s)**
- **Transitional ~ (5-15 cm/s)**
- **Erosional ~ (> 15 cm/s)**
- To maintain aerobic benthic community:
  strong currents throughout water column,
  secondarily variable direction of flow for dispersion
- Impossible to predict results without computer simulation
- Industry has used iterative approach in fitting farms to sites:
  many examples of inadequate currents and occasionally too much current, need for reconfiguration, re-sizing, relocation, closure, fish health problems, DO problems, etc.
- Goal is to link physics and biology in the simulations

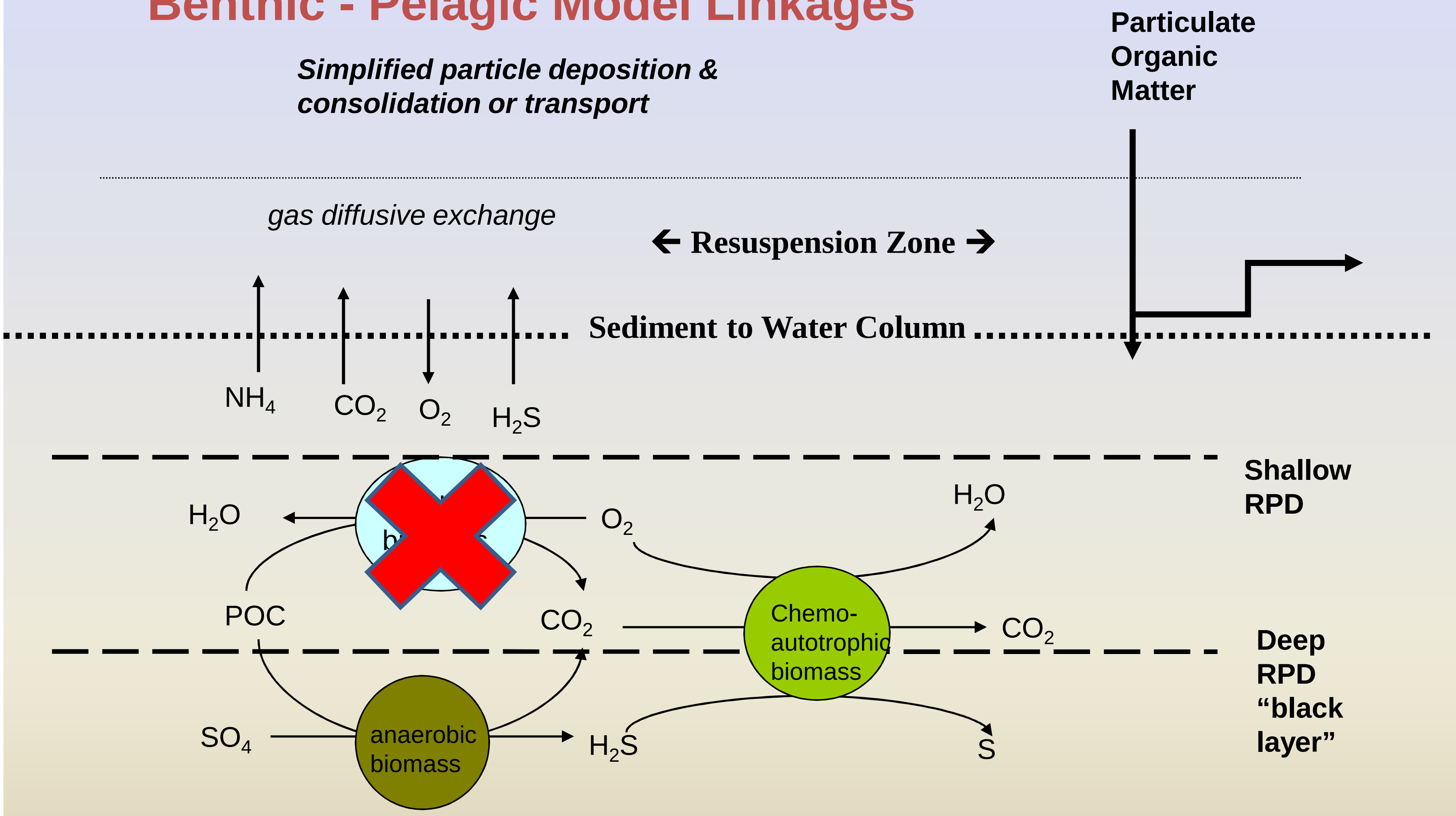
Bioenergetics Component of AquaModel

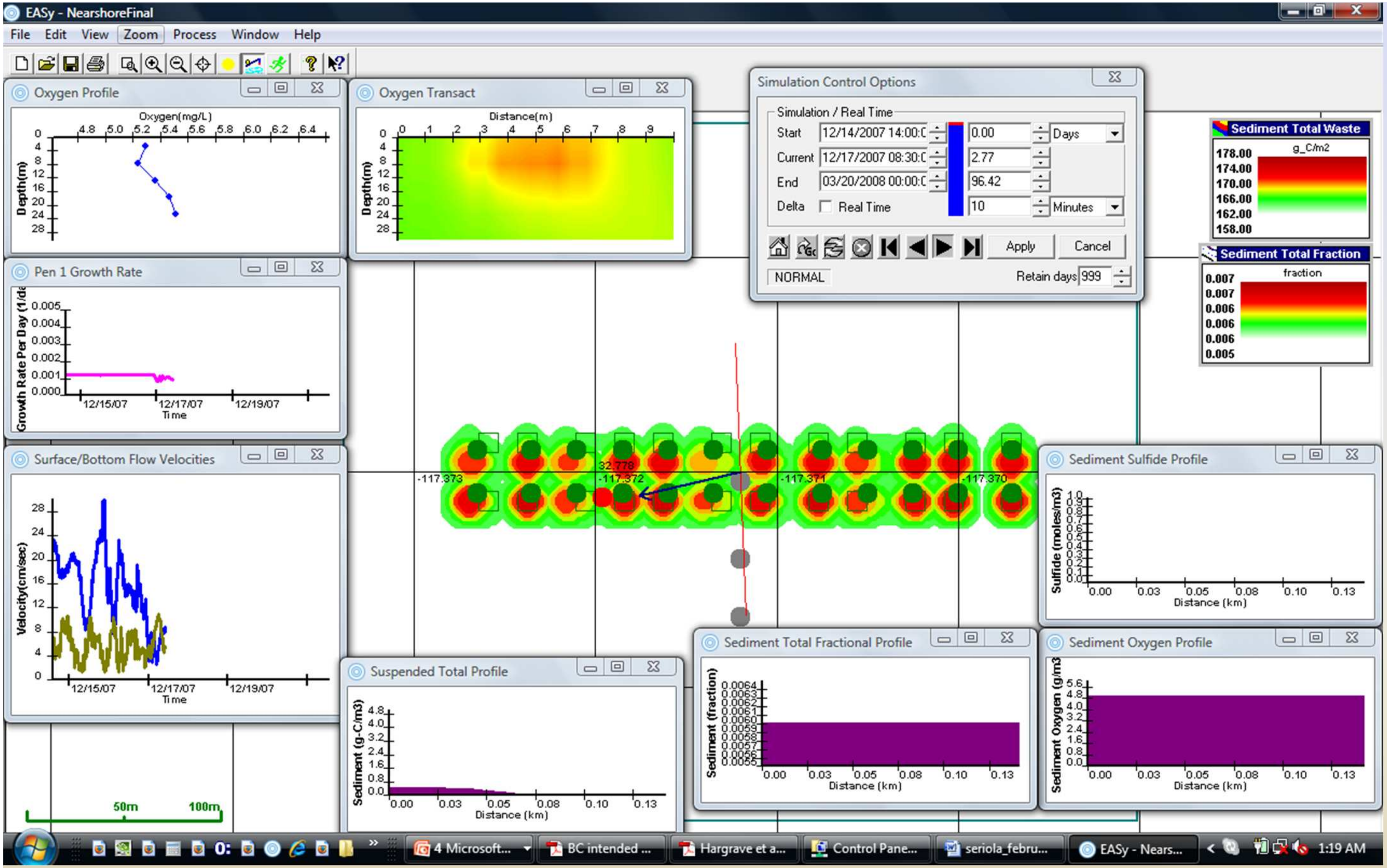
- Virtual fish population living in “mass balance” system
- Fish eat, grow, swim, metabolize, respire, excrete, egest
- Carbon, nitrogen and oxygen stoichiometry for marine waters
- Holistic water column + benthic system - interlinked
- “Submodels” salmon, striped bass, cobia, moi, sablefish
- Constants & rates vary – literature & our own physiology studies



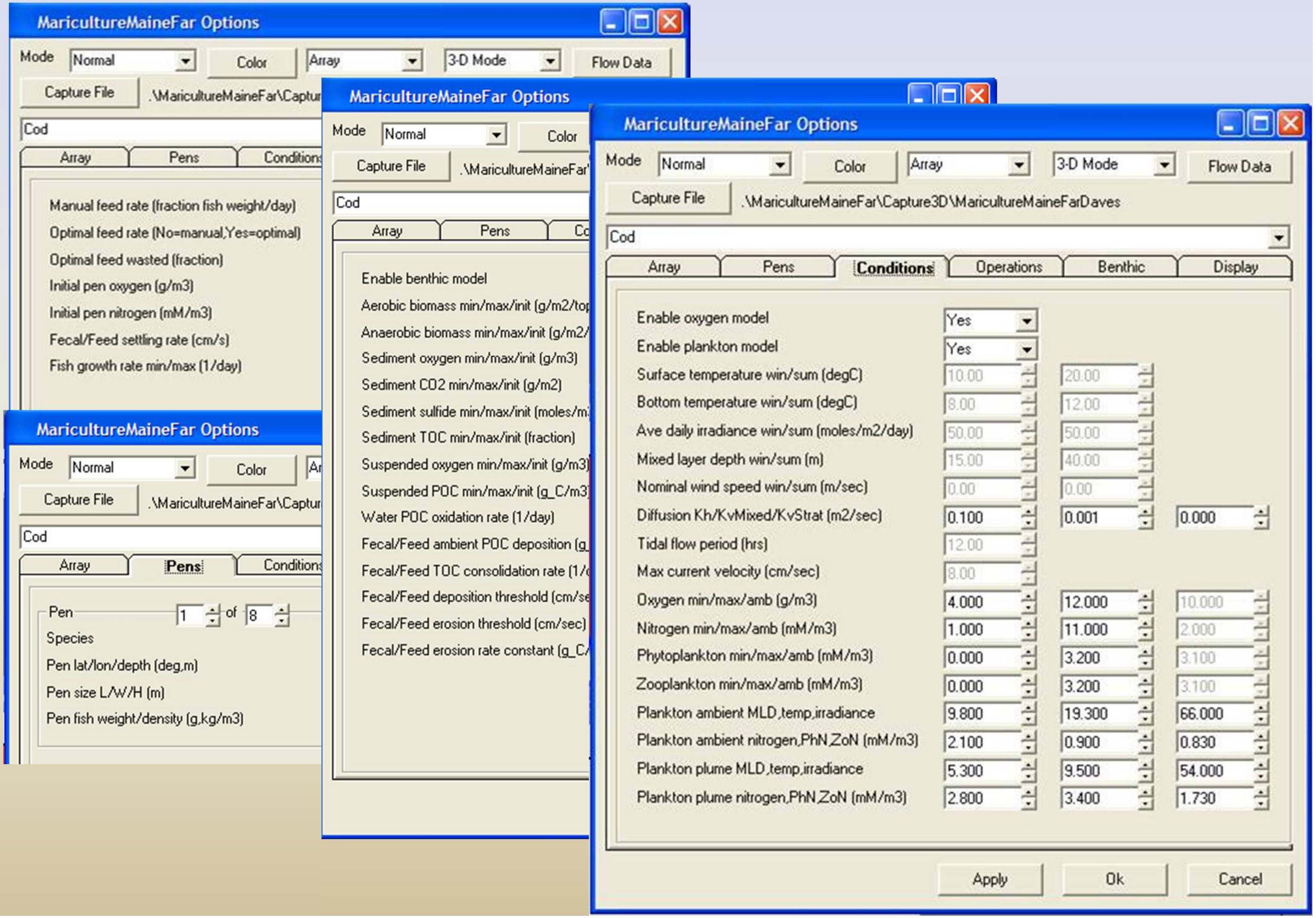
Benthic - Pelagic Model Linkages

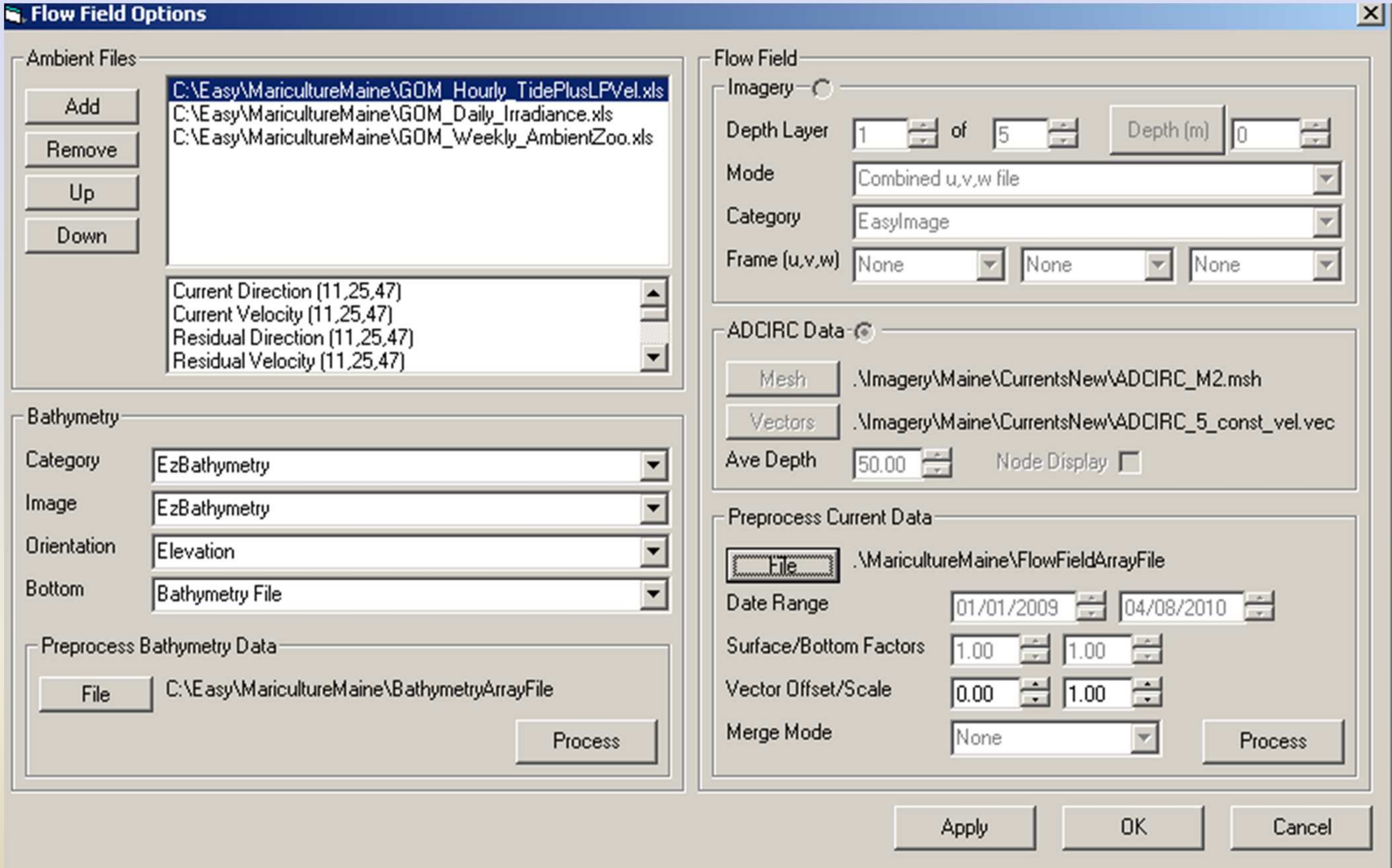
Simplified particle deposition & consolidation or transport



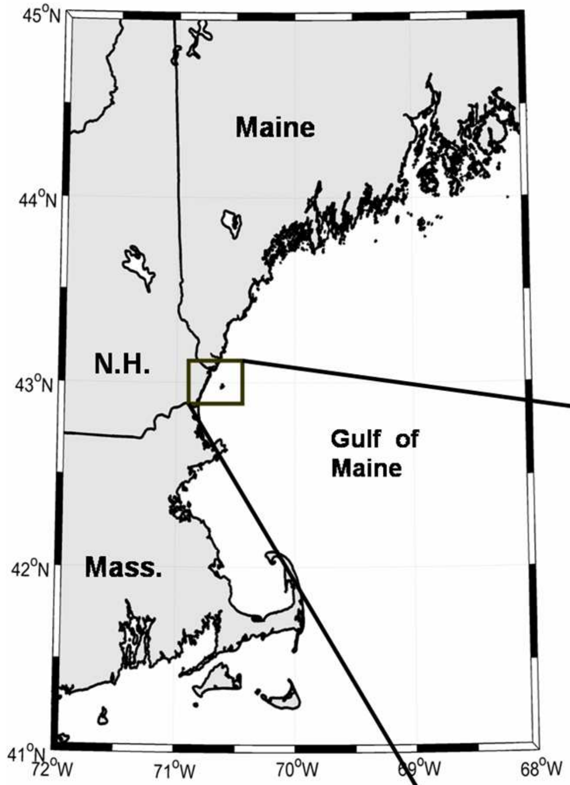

EASy - NearshoreFinal
File Edit View Zoom Process Window Help
Oxygen Profile
Oxygen(mg/L)
Depth(m)
Oxygen Transact
Distance(m)
Simulation Control Options
Simulation / Real Time
Start 12/14/2007 14:00 0.00 Days
Current 12/17/2007 08:30 2.77
End 03/20/2008 00:00 96.42
Delta Real Time 10 Minutes
Apply Cancel
NORMAL
Retain days 999
Sediment Total Waste
g_C/m2
178.00
174.00
170.00
166.00
162.00
158.00
Sediment Total Fraction
fraction
0.007
0.007
0.006
0.006
0.006
0.005
Pen 1 Growth Rate
Growth Rate Per Day (1/d
Time
Surface/Bottom Flow Velocities
Velocity(cm/sec)
Time
Sediment Sulfide Profile
Sulfide (moles/m3)
Distance (km)
Suspended Total Profile
Sediment (g-C/m3)
Distance (km)
Sediment Total Fractional Profile
Sediment (fraction)
Distance (km)
Sediment Oxygen Profile
Sediment Oxygen (g/m3)
Distance (km)
50m 100m
1:19 AM

Examples of Some AquaModel User Controls



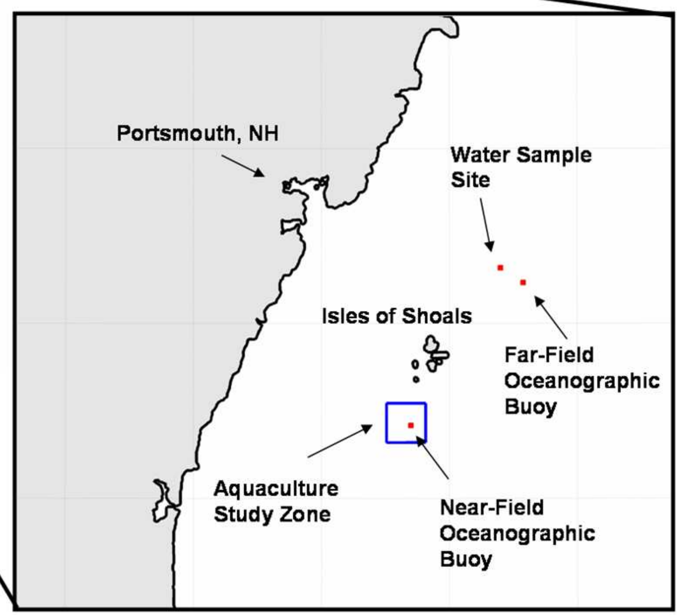

Flow Field Options
Ambient Files
Add
Remove
Up
Down
C:\Easy\MaricultureMaine\GOM_Hourly_TidePlusLPVel.xls
C:\Easy\MaricultureMaine\GOM_Daily_Irradiance.xls
C:\Easy\MaricultureMaine\GOM_Weekly_AmbientZoo.xls
Current Direction (11,25,47)
Current Velocity (11,25,47)
Residual Direction (11,25,47)
Residual Velocity (11,25,47)
Bathymetry
Category
EzBathymetry
Image
EzBathymetry
Orientation
Elevation
Bottom
Bathymetry File
Preprocess Bathymetry Data
File
C:\Easy\MaricultureMaine\BathymetryArrayFile
Process
Flow Field
Imagery
Depth Layer
1
of
5
Depth (m)
0
Mode
Combined u,v,w file
Category
EasyImage
Frame (u,v,w)
None
None
None
ADCIRC Data
Mesh
.\Imagery\Maine\CurrentsNew\ADCIRC_M2.msh
Vectors
.\Imagery\Maine\CurrentsNew\ADCIRC_5_const_vel.vec
Ave Depth
50.00
Node Display
Preprocess Current Data
File
.\MaricultureMaine\FlowFieldArrayFile
Date Range
01/01/2009
04/08/2010
Surface/Bottom Factors
1.00
1.00
Vector Offset/Scale
0.00
1.00
Merge Mode
None
Process
Apply
OK
Cancel

Modeling and Data Collection Site



University of New Hampshire Open Ocean Aquaculture Study Zone

Data rich model operations testing



University of New Hampshire Open Ocean Aquaculture Study Zone (OOA) within the model domain

AquaModel 2D – 3 Depth Near Field

Single Farm Simulation

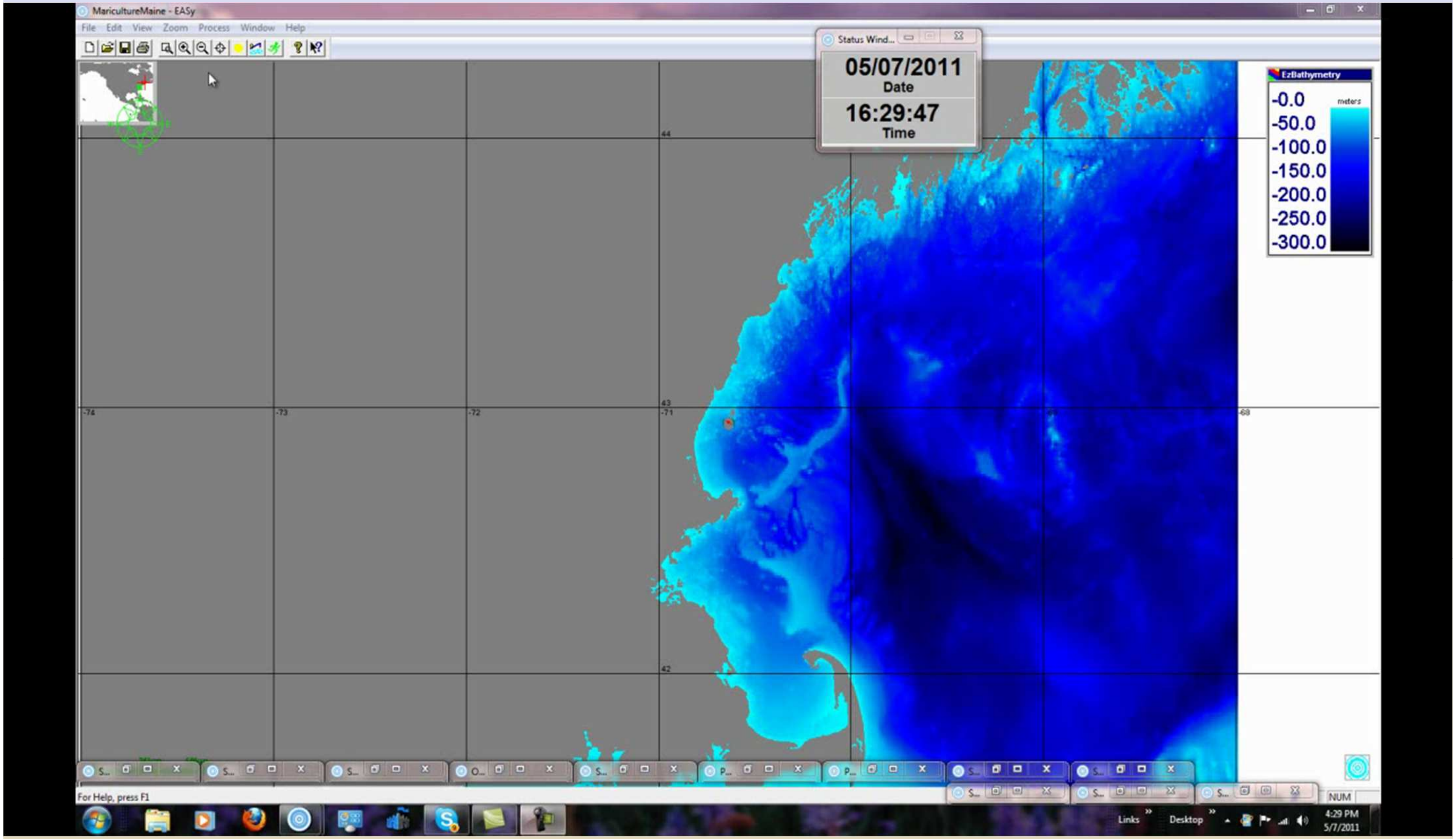
Gulf of Maine: University of New Hampshire OOA Site

12 Large (75m Dia) Cages Each

Hourly current meter and water quality data inputs

Total 18 Month Production 12,000 MT

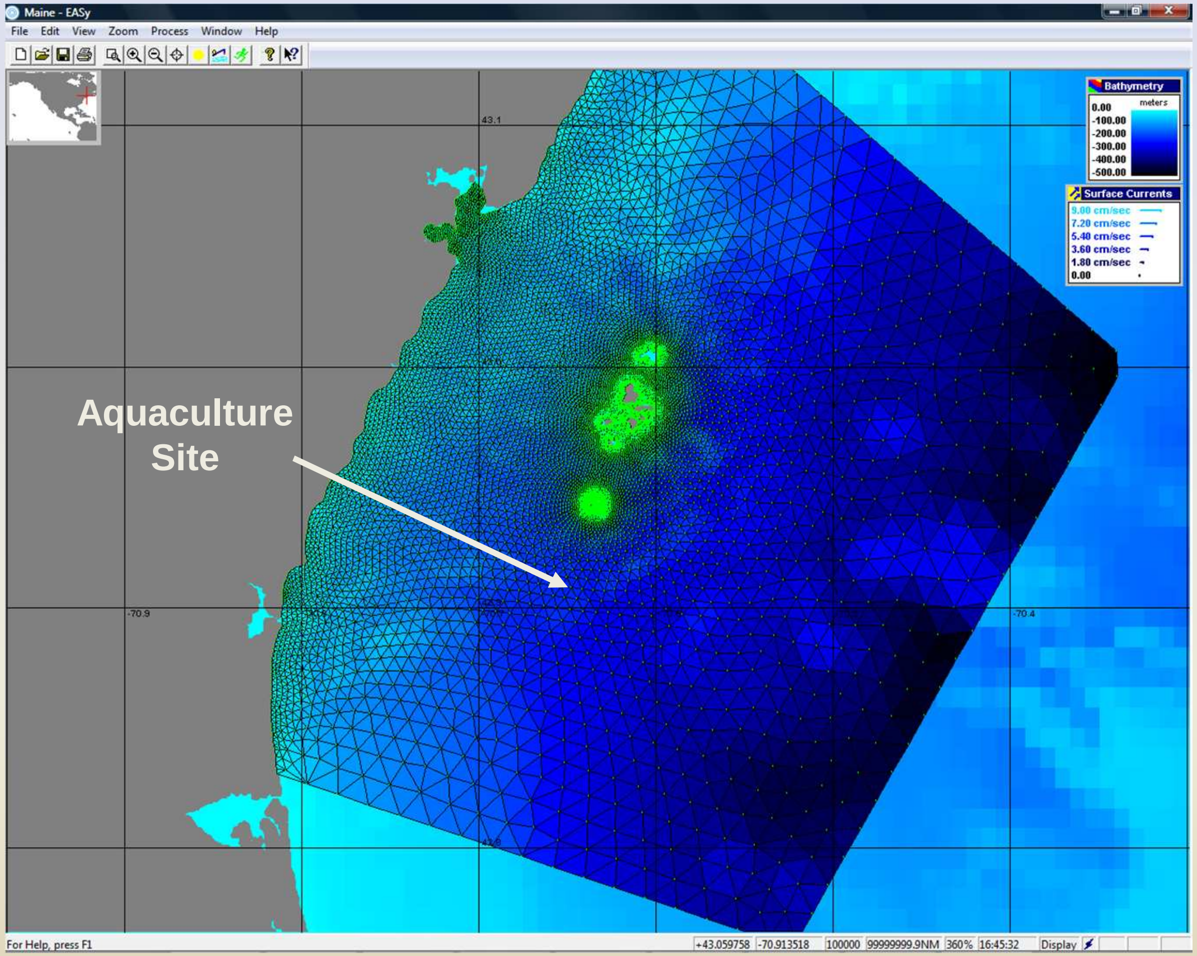
Over the top large to test site capacity!


MaricultureMaine - EASy
File Edit View Zoom Process Window Help
Status Wind...
05/07/2011
Date
16:29:47
Time
EzBathymetry
meters
-0.0
-50.0
-100.0
-150.0
-200.0
-250.0
-300.0
44
43
42
-74
-73
-72
-71
-68
For Help, press F1
NUM
Links
Desktop
4:29 PM
5/7/2011

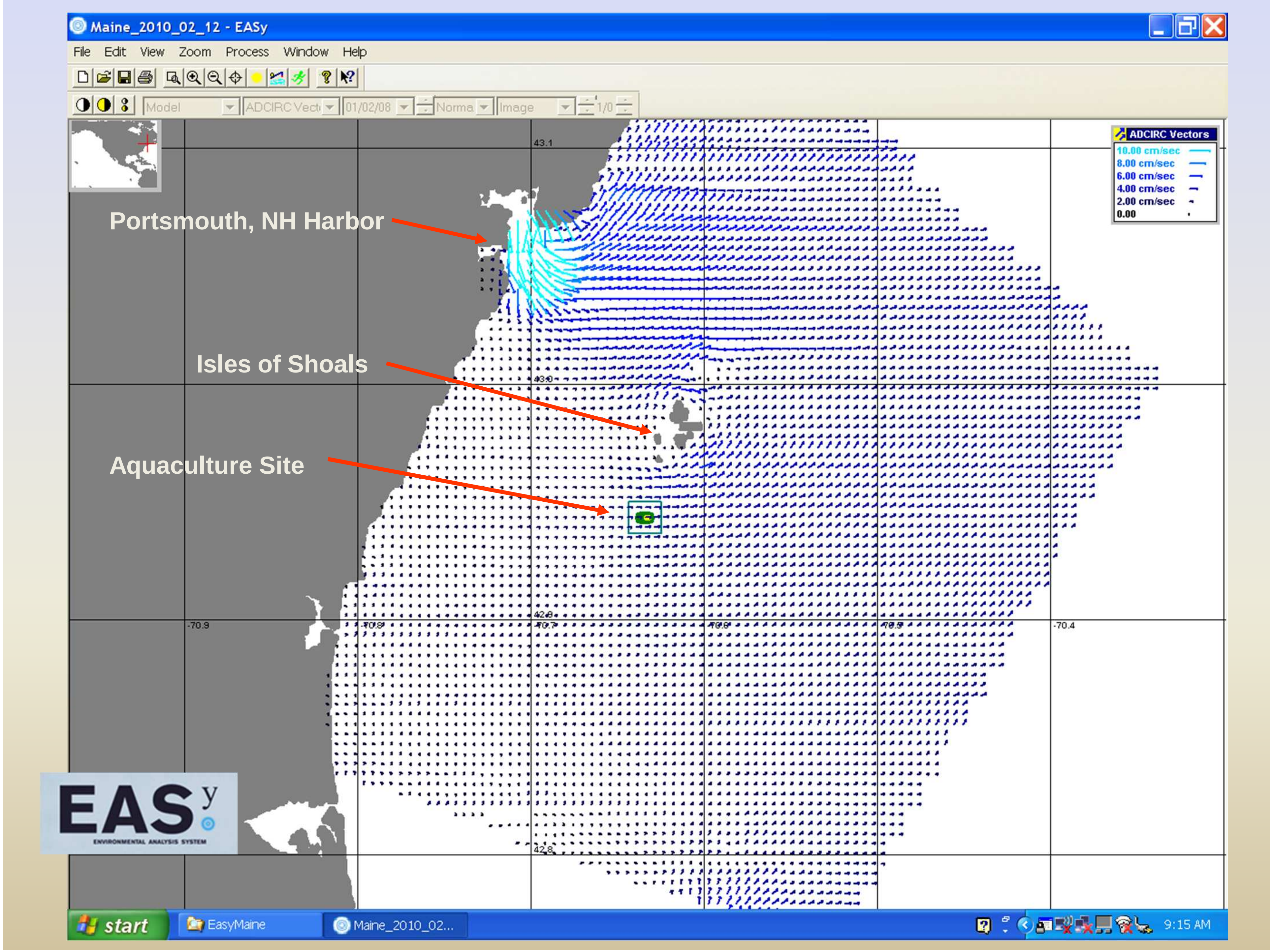
Circulation Tidal Model: AquaModel Far Field

1. ADCIRC Model
2. Unstructured Mesh (triangular elements)
3. Interpolated Bathymetry
4. High Resolution at aquaculture site (~50 m)

EAS y
ENVIRONMENTAL ANALYSIS SYSTEM



Apply tide elevations (5 components) and phases at open boundaries

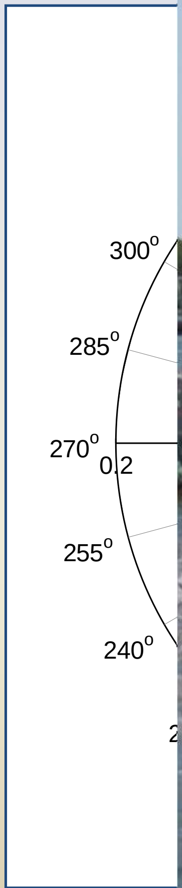


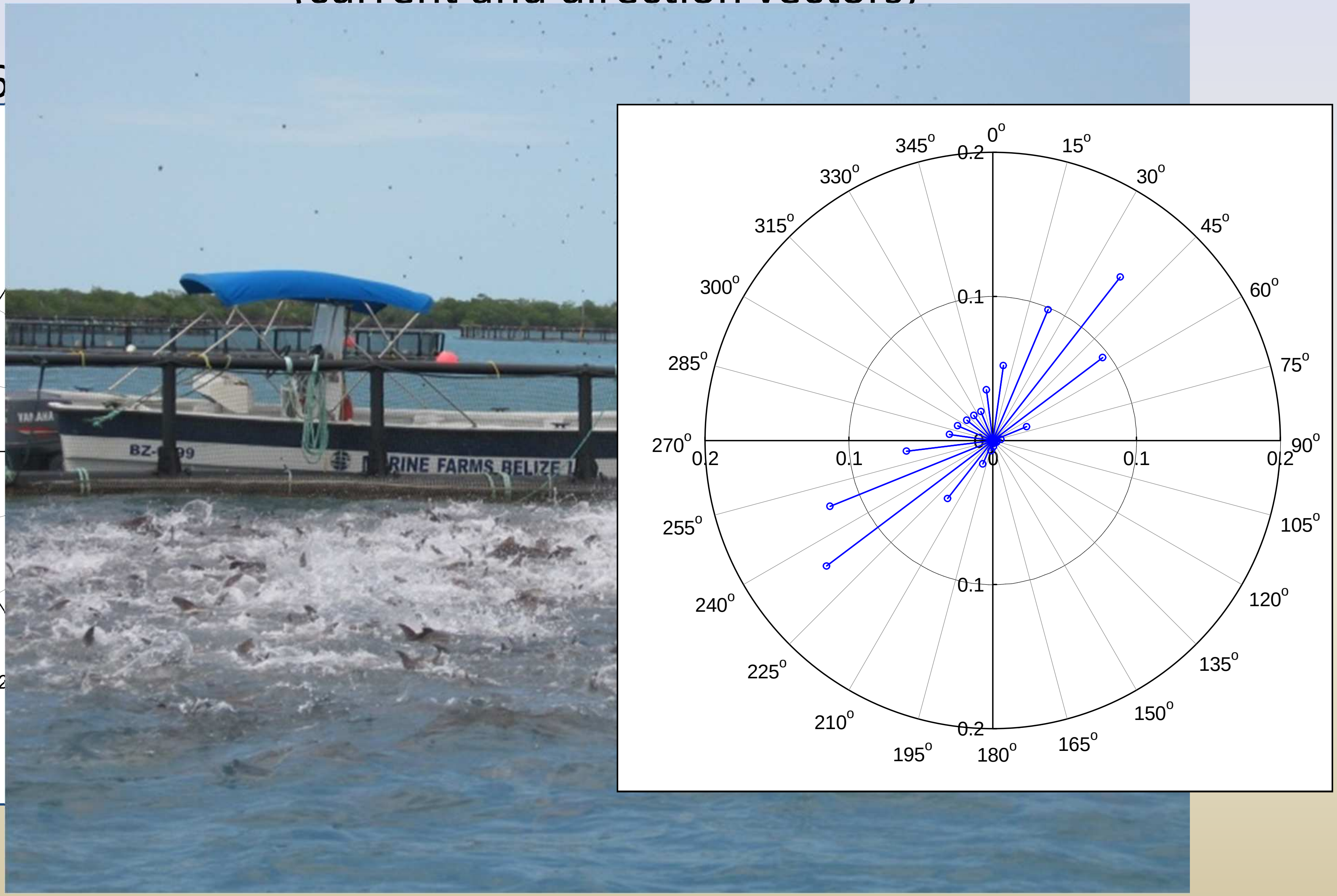
Maine_2010_02_12 - EASy
File Edit View Zoom Process Window Help
Model
ADCIRC Vect
01/02/08
Norma
Image
1/0
ADCIRC Vectors
10.00 cm/sec
8.00 cm/sec
6.00 cm/sec
4.00 cm/sec
2.00 cm/sec
0.00
Portsmouth, NH Harbor
Isles of Shoals
Aquaculture Site
43.1
43.0
42.9
42.8
-70.9
-70.8
-70.7
-70.6
-70.5
-70.4
EASy
ENVIRONMENTAL ANALYSIS SYSTEM
start
EasyMaine
Maine_2010_02...
9:15 AM

Example Offshore Current Rose

(current and direction vectors)

First 6





AquaModel 3-D Far Field Multiple Farm Simulation

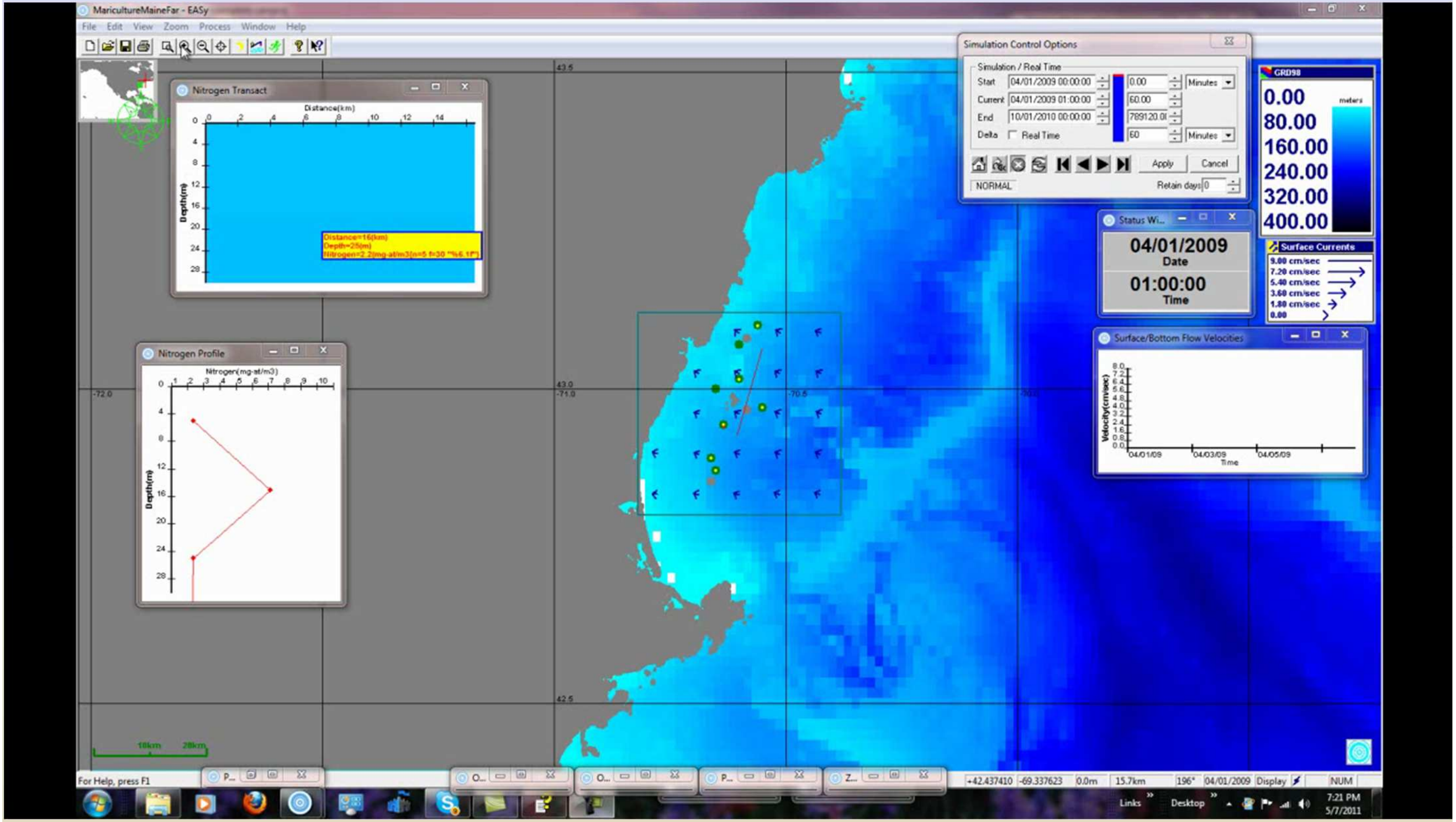
Gulf of Maine: University of New Hampshire OOA Site

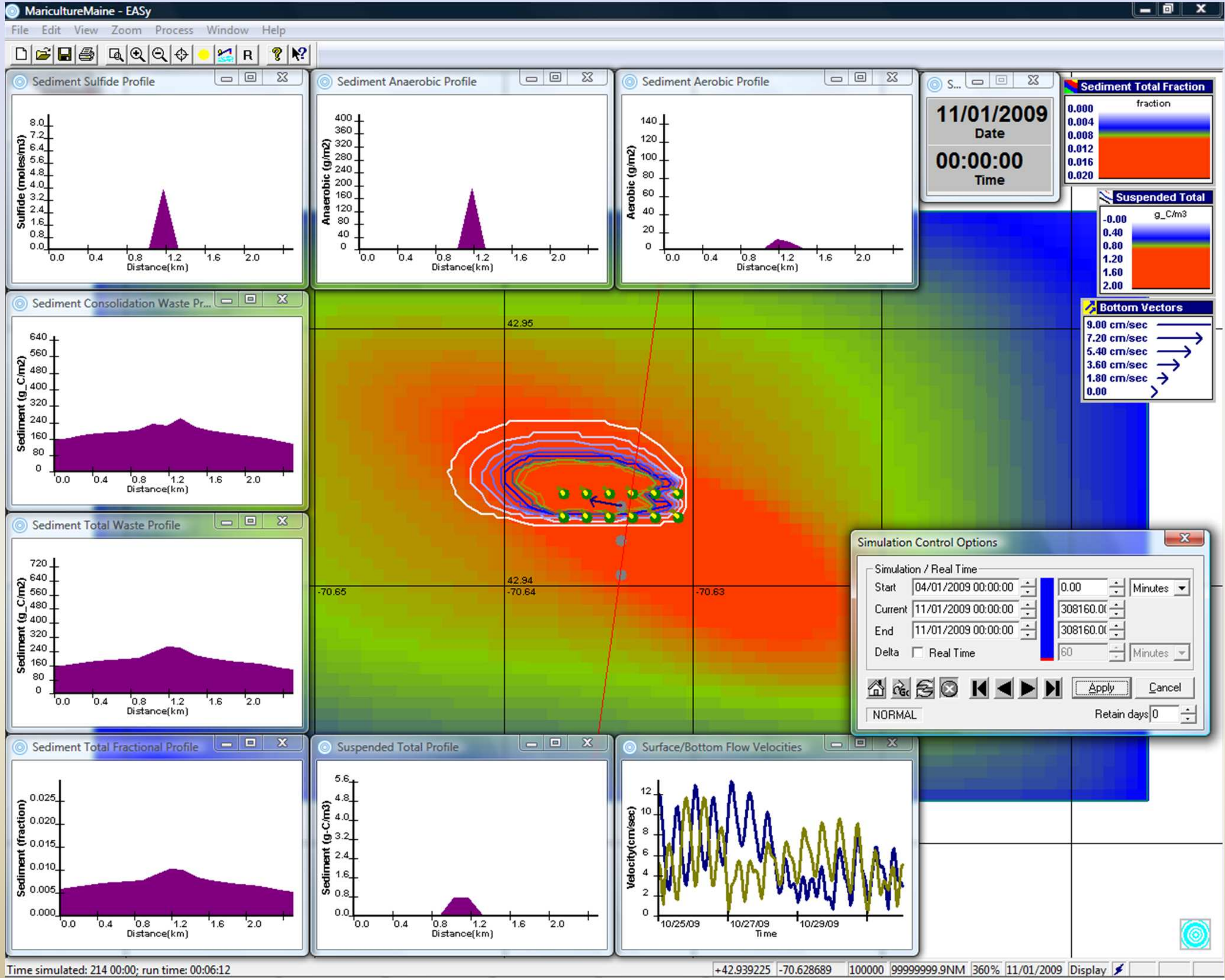
Eight Farms of 12 Large (75m Dia) Cages Each

Total 18 Month Production 95,000 MT

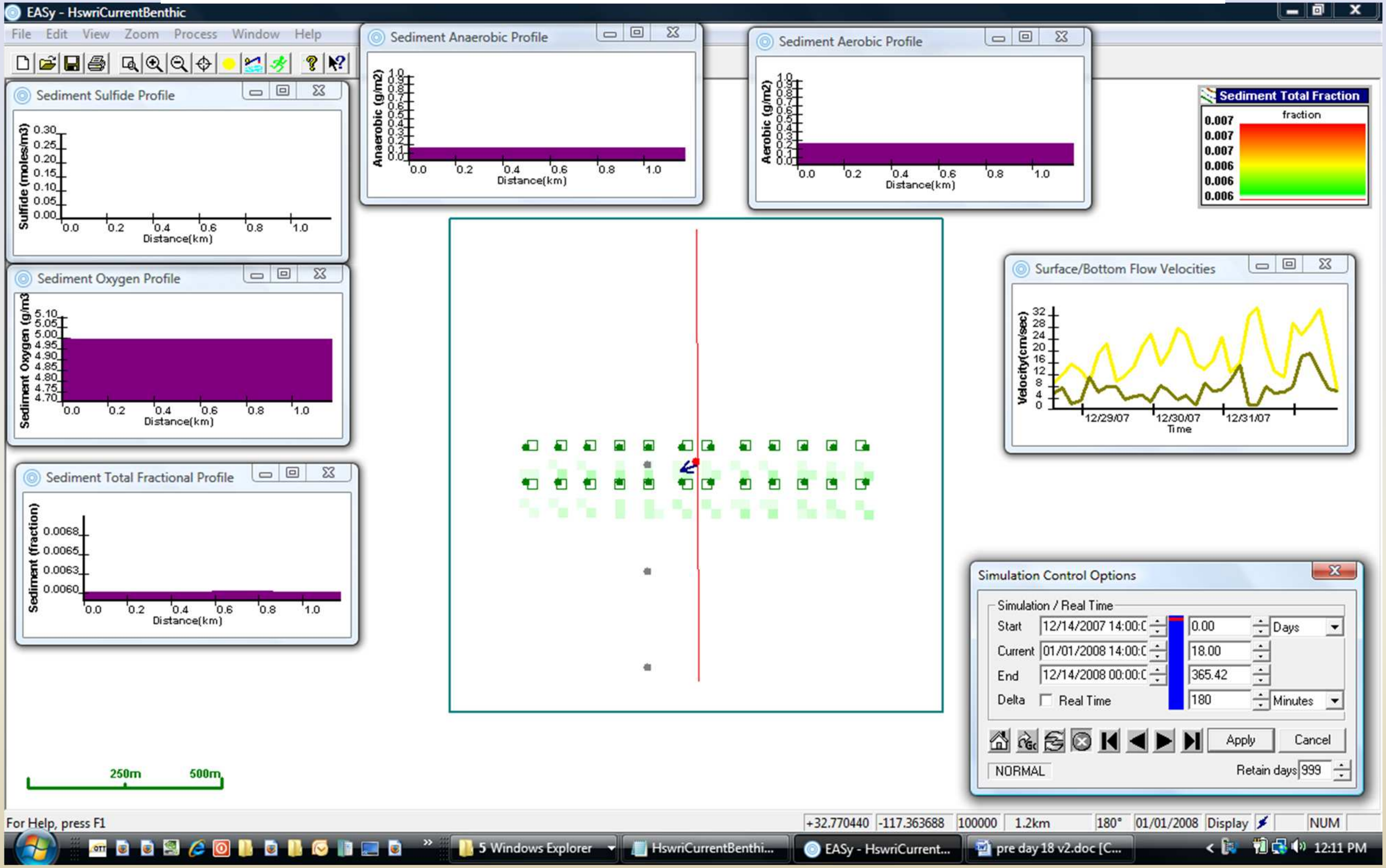
Way Over the Top Large to Evaluate

Massive Offshore Development Effects

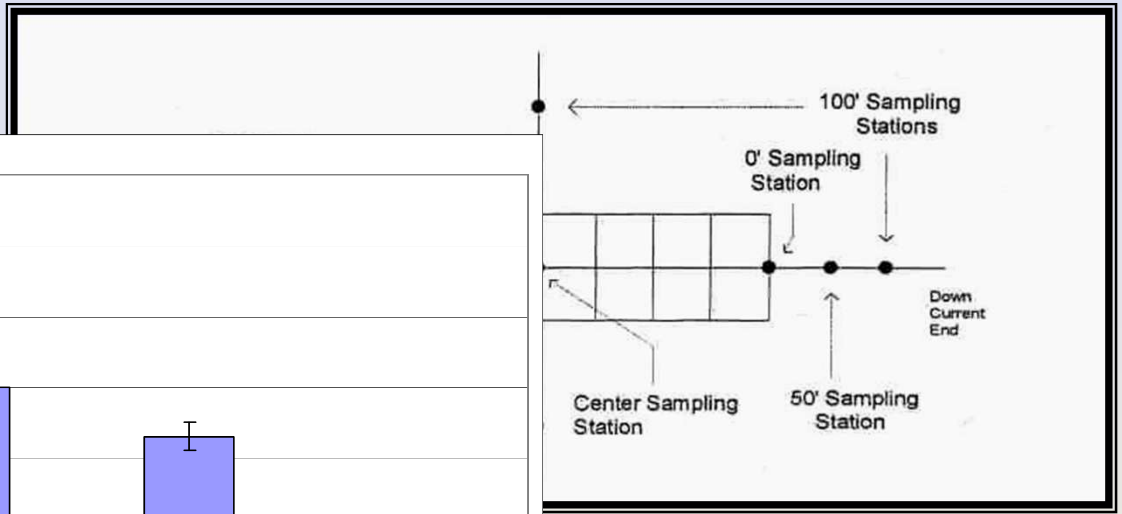

MaricultureMaineFar - EASy
File Edit View Zoom Process Window Help
Nitrogen Transact
Distance(km)
Depth(m)
Nitrogen Profile
Nitrogen(mg-at/m3)
Simulation Control Options
Simulation / Real Time
Start
Current
End
Delta
Real Time
Minutes
Apply
Cancel
NORMAL
Retain days
Status Wi...
04/01/2009
Date
01:00:00
Time
Surface/Bottom Flow Velocities
Velocity(cm/sec)
Time
Surface Currents
9.00 cm/sec
7.20 cm/sec
5.40 cm/sec
3.60 cm/sec
1.80 cm/sec
0.00
GRD98
0.00
80.00
160.00
240.00
320.00
400.00
meters
For Help, press F1
7:21 PM
5/7/2011

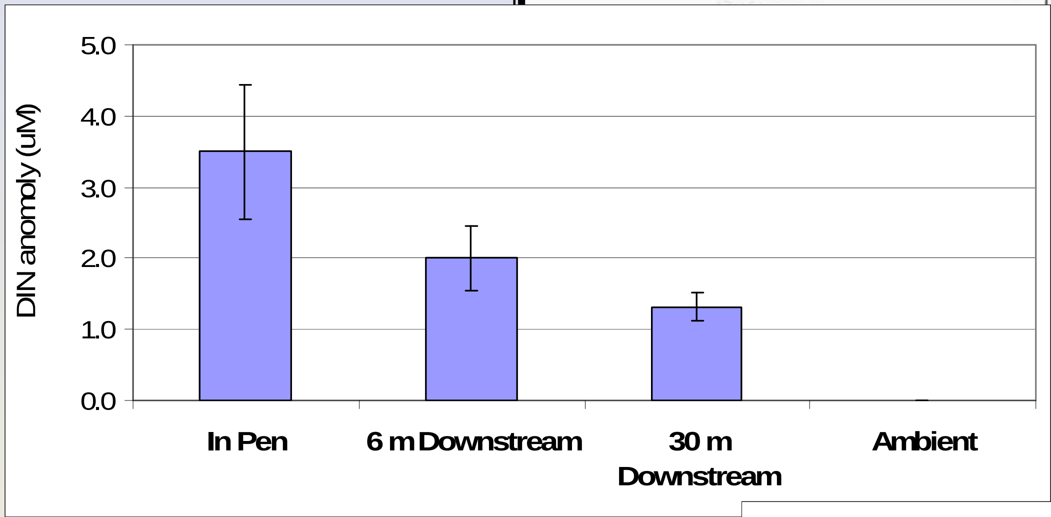

MaricultureMaine - EASy
File Edit View Zoom Process Window Help
Sediment Sulfide Profile
Sulfide (moles/m3)
Distance(km)
Sediment Anaerobic Profile
Anaerobic (g/m2)
Sediment Aerobic Profile
Aerobic (g/m2)
11/01/2009
Date
00:00:00
Time
Sediment Total Fraction
fraction
Suspended Total
g_C/m3
Bottom Vectors
9.00 cm/sec
7.20 cm/sec
5.40 cm/sec
3.60 cm/sec
1.80 cm/sec
0.00
Sediment Consolidation Waste Pr...
Sediment (g_C/m2)
Sediment Total Waste Profile
Sediment Total Fractional Profile
Sediment (fraction)
Suspended Total Profile
Sediment (g-C/m3)
Surface/Bottom Flow Velocities
Velocity(cm/sec)
Time
Simulation Control Options
Simulation / Real Time
Start 04/01/2009 00:00:00
Current 11/01/2009 00:00:00
End 11/01/2009 00:00:00
Delta
Real Time
Minutes
Apply
Cancel
NORMAL
Retain days
Time simulated: 214 00:00; run time: 00:06:12
+42.939225 -70.628689 100000 99999999.9NM 360% 11/01/2009 Display

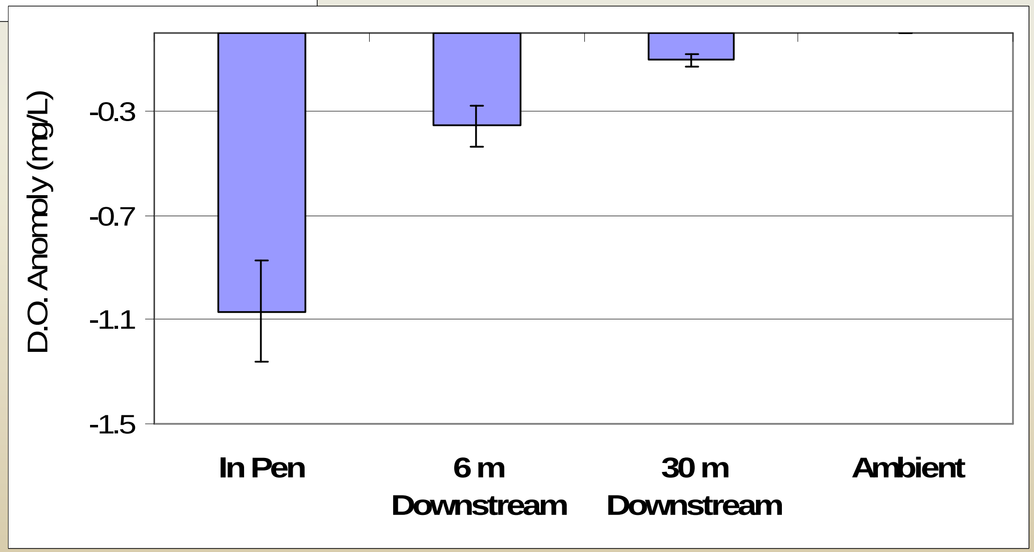
Hubbs SeaWorld Research Institute: Offshore Farm Site 91 m depth 21 cm/s mean velocity 5000MT Striped Bass

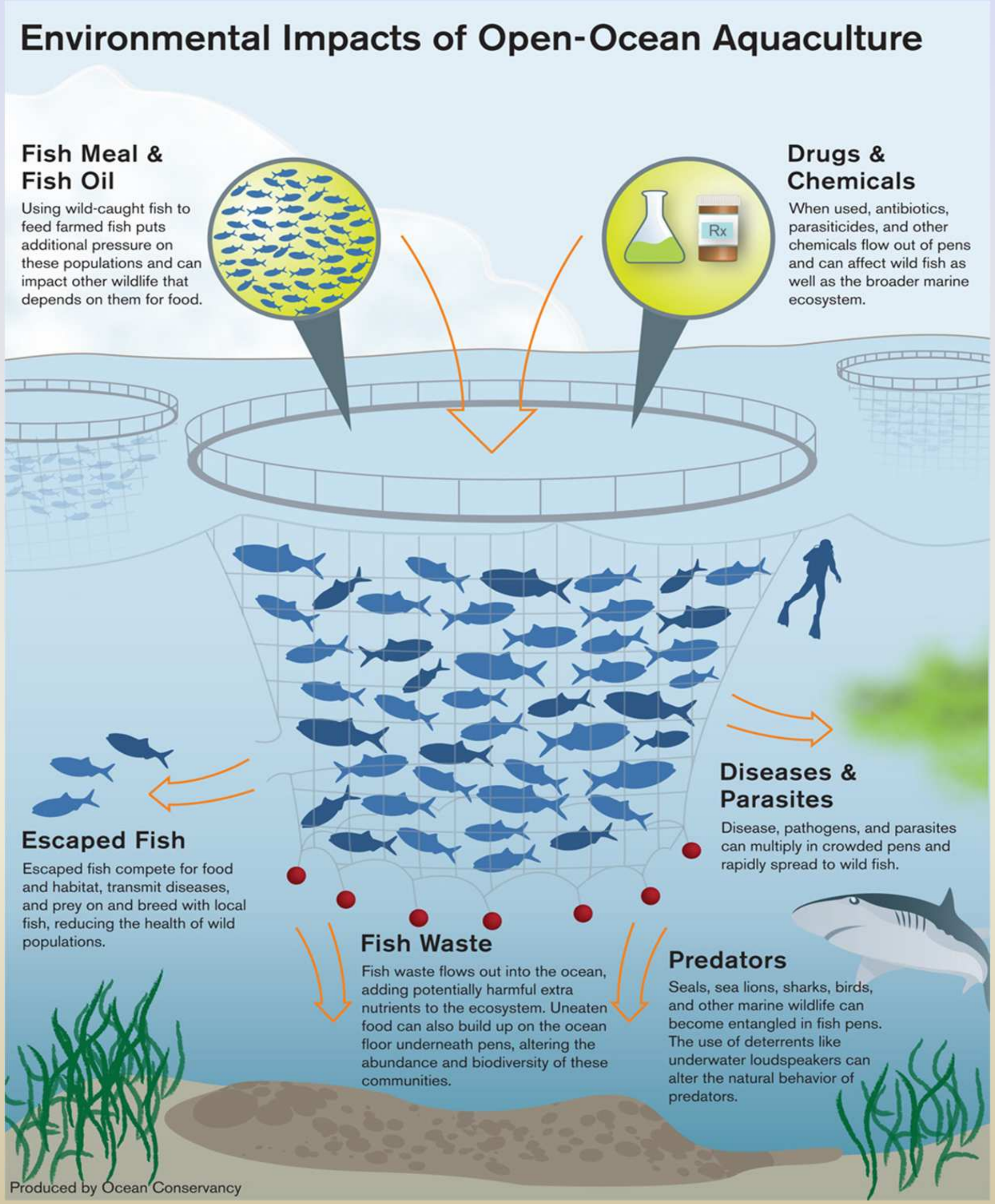


Example of Nitrogen and Oxygen Depletion Plume Validation

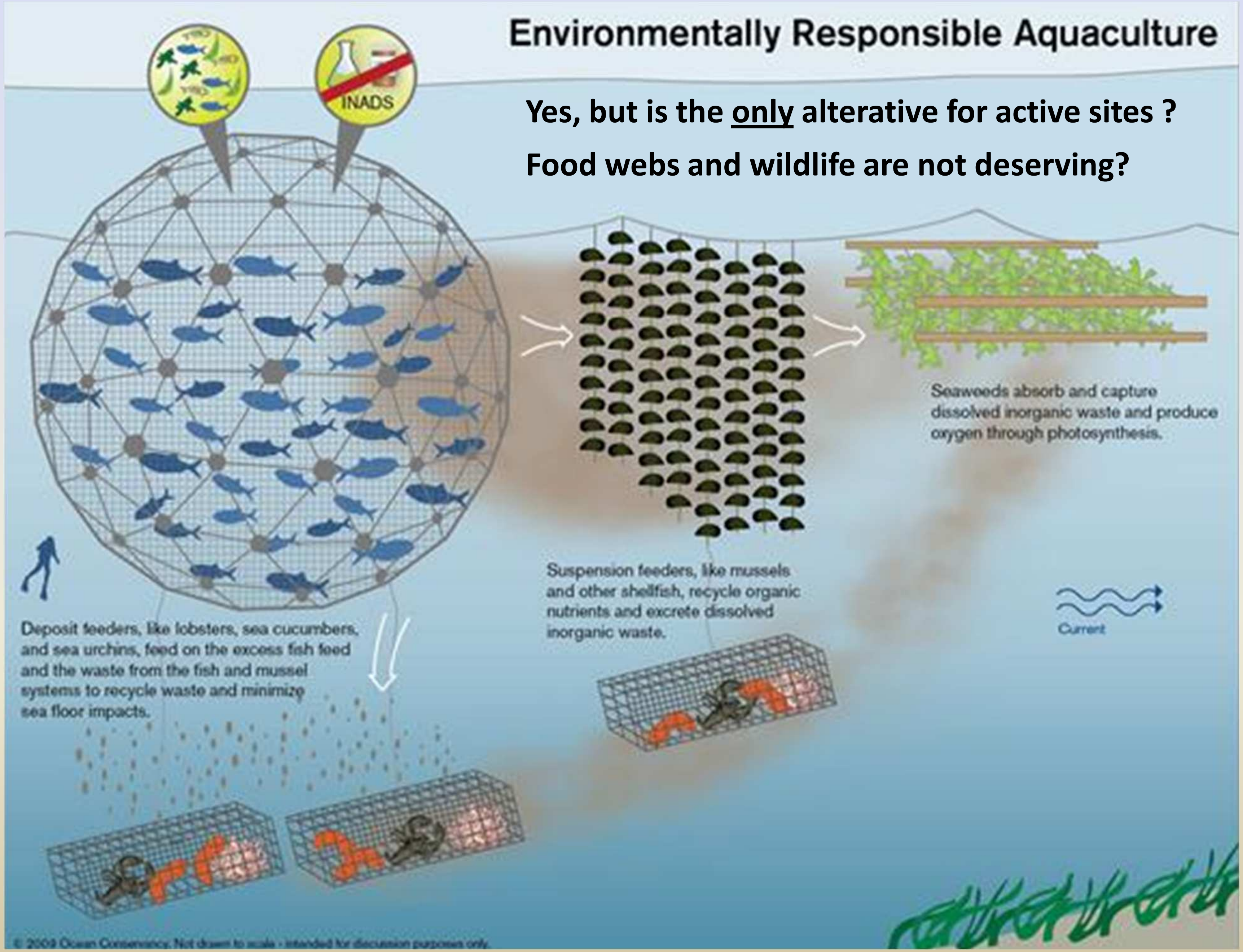








Source: Ocean Conservancy



Yes, but is the <u>only</u> alterative for active sites ?

Food webs and wildlife are not deserving?

Funding

NOAA Office of Oceanic & Atmospheric Research

NOAA SBIR Program

USDA SBIR Program

Hubbs Seaworld Research Institute, San Diego

Hawaii Department of Agriculture

Collaborators

Dale Kiefer, University of Southern California and Science System Applications

David Fredriksson, U.S. Naval Academy, Architecture & Ocean Engineering

Jim Irish, University of New Hampshire, Woods Hole Oceanographic Institution

American Gold Seafoods Inc. (Icicle Seafoods Inc.)

Pacific Aquaculture Inc. (Pacific Seafoods Inc.)

Taylor Shellfish Inc.

Google: AquaModel (www.AquaModel.org)