Welcome and thank you for joining today's workshop

Thank you Stephanie for organizing and supporting the effort here at NOAA

Date: December 16, 2013

Organizers:

Dr Christopher Krembs, Ecology,

Dr Stephanie Moore, NOAA

Participants:

Dr Linda Rhodes, NOAA

Kim Stark, King County

Dr Evelyn Lessard, UW

Dr Andrew Juhl (LDEO, Columbia UW)

Dr Correigh Greene, NOAA

Dr Casimir Rice, NOAA

Dr Joaquim Goes (LDEO, Columbia UW)

Dr Suzanne Strom, Western Washington University

Dr Tessa Francis, Puget Sound Institute/UW Tacoma

Dr Jan Newton, UW/NANOOS

Dr Simone Alin, NOAA

Potential goals of this workshop

1. **Inform and involve you in lower trophic food web observations in PS.**

2. **Discuss observations in context of existing data, efforts and future needs.**

3. **Tackle the scale and complexity of lower food web processes in PS.**

4. **Funding strategies; e.g., PS as model system for…….(expertise, contextual information, and sensor platforms).**

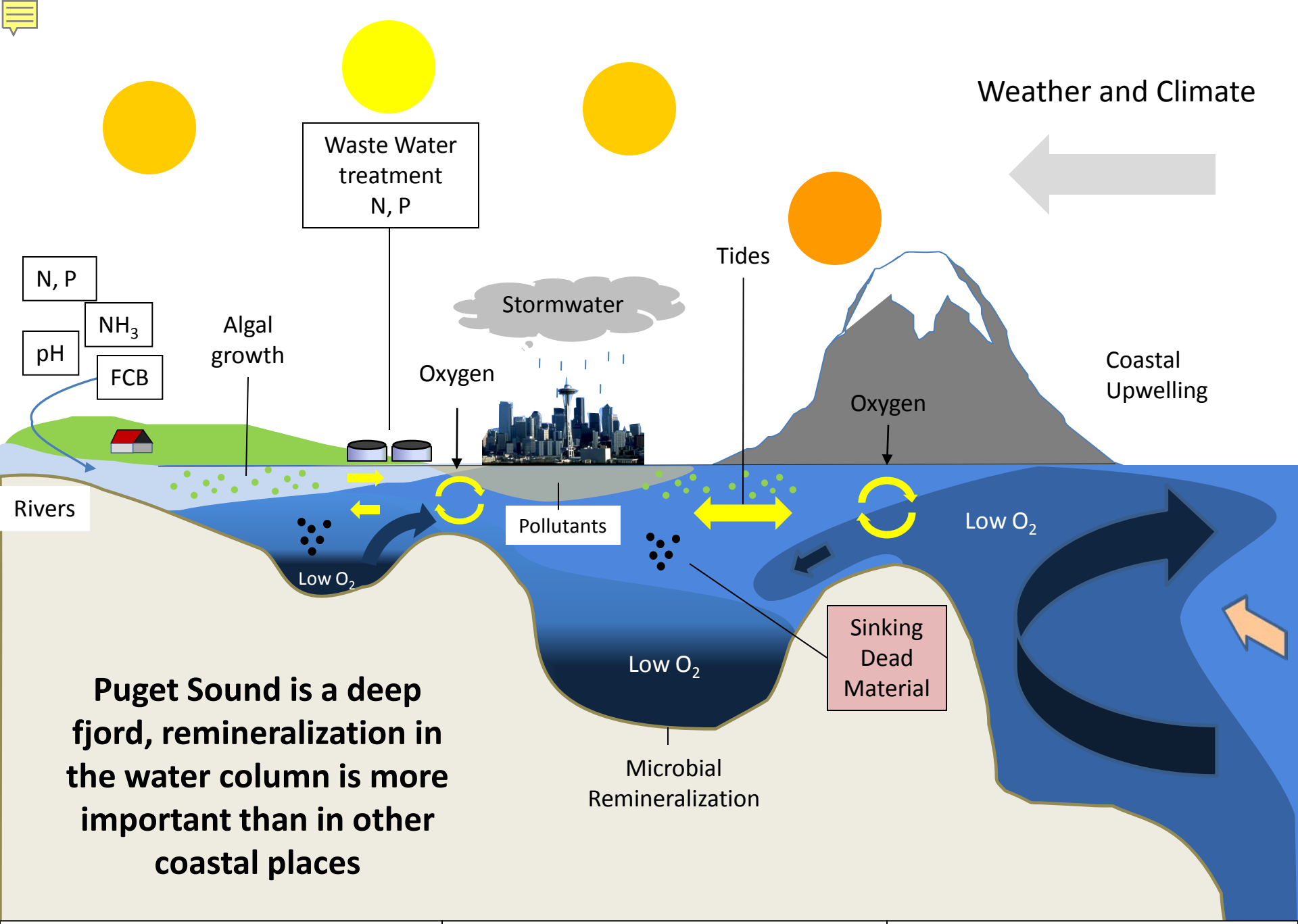
5. **Encourage experts to develop proposals for focused studies.**

What PS marine monitoring data could be telling us? Stimulating a discussion

Dr. Christopher Krembs, Marine Monitoring Unit, Ecology

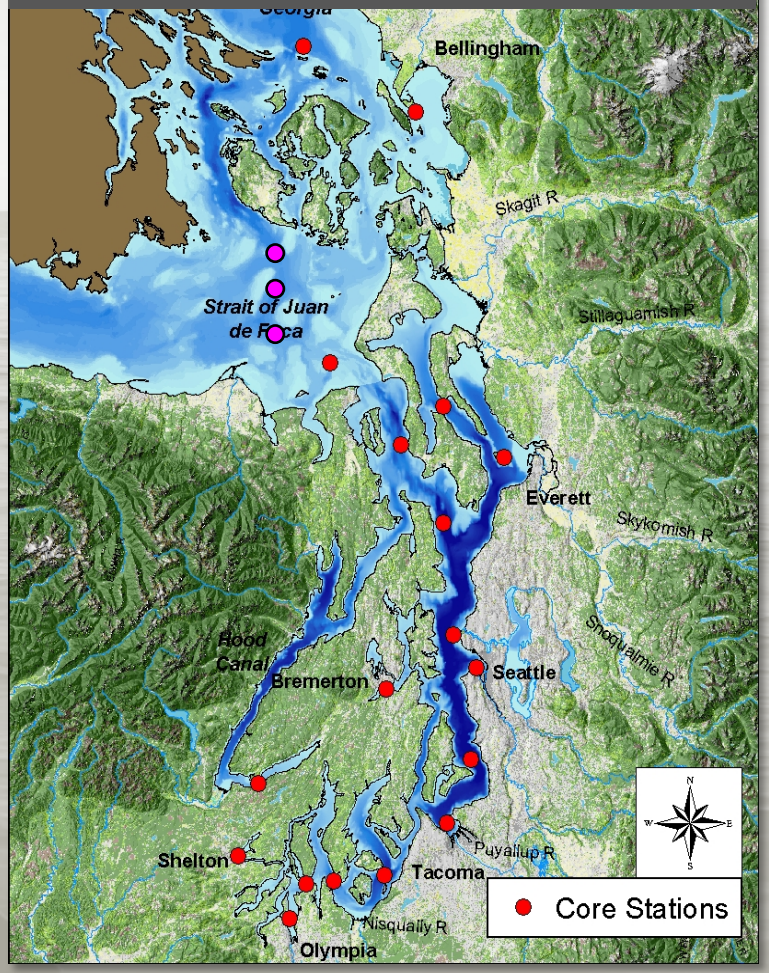
1. The ocean's influence is big, yet something else is going on in PS!
2. Microbial food webs, energy transfer and biogeochemical cycling. A large information gap in PS?
3. Drawing a bigger picture using a unified hypothesis.

NOAA, Seattle, Dec. 16, 2013

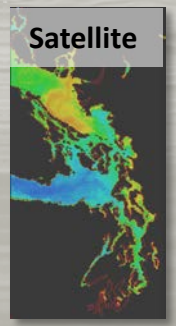

Weather and Climate
Waste Water treatment N, P
N, P
NH_3
pH
FCB
Algal growth
Stormwater
Oxygen
Tides
Oxygen
Coastal Upwelling
Rivers
Pollutants
Low O_2
Low O_2
Low O_2
Sinking Dead Material
Microbial Remineralization
Puget Sound is a deep fjord, remineralization in the water column is more important than in other coastal places
Estuaries and Bays
Basins
Ocean

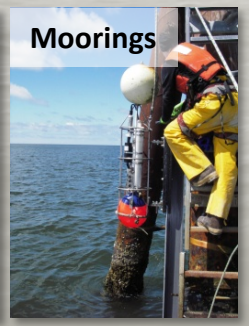
Measuring long-term trends in Eutrophication, dissolved oxygen and physical variables

Greater Puget Sound region



Water Quality variables measured monthly at 27 stations





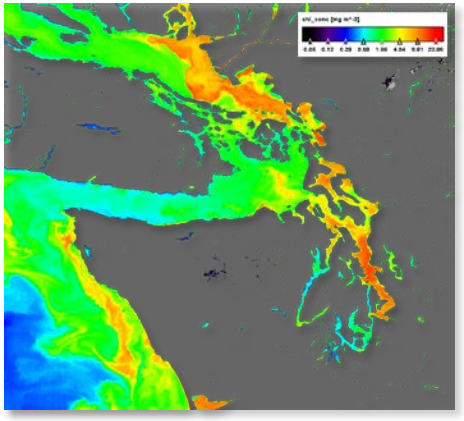
Physical variables
- Temperature
- Salinity
- Density

Chemical variables
- Oxygen
- Nitrate
- Silicate
- Phosphate
- Ammonium
- Nutrient ratios
- pH

Bio-optical variables
- Water clarity
- Chlorophyll a
- Euphotic depth

Monthly Baselines 1999-2008

Oceanic Boundary Conditions (3 year running avg.)



Satellite data for Chl a (MERIS)

Sea Surface Temperature

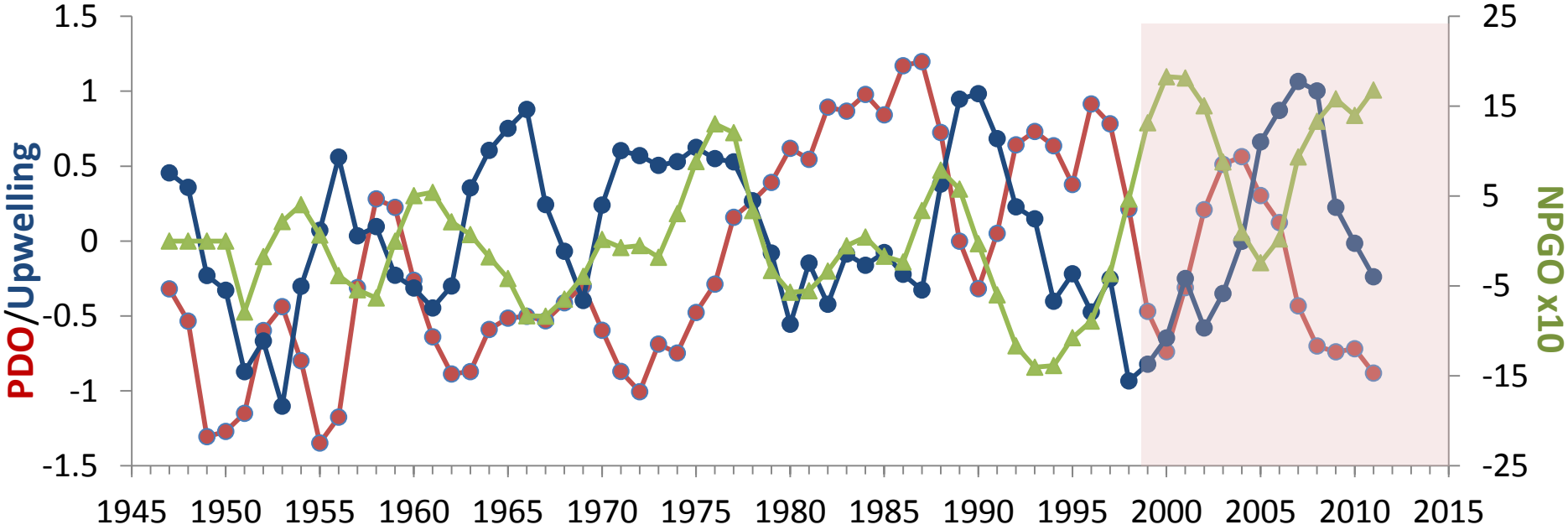
Pacific Decadal Oscillation Index (**PDO**)

Currents

North Pacific Gyre Oscillations Index (**NPGO**)

Upwelling

Upwelling Index (anomalies) (**PFEL, NOAA**)

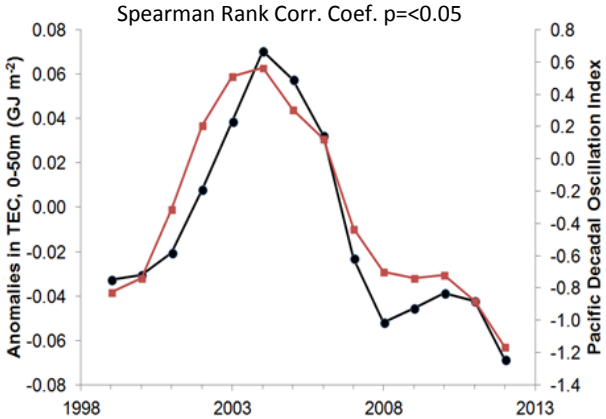


Ocean Boundary Conditions Impact PS Water Quality

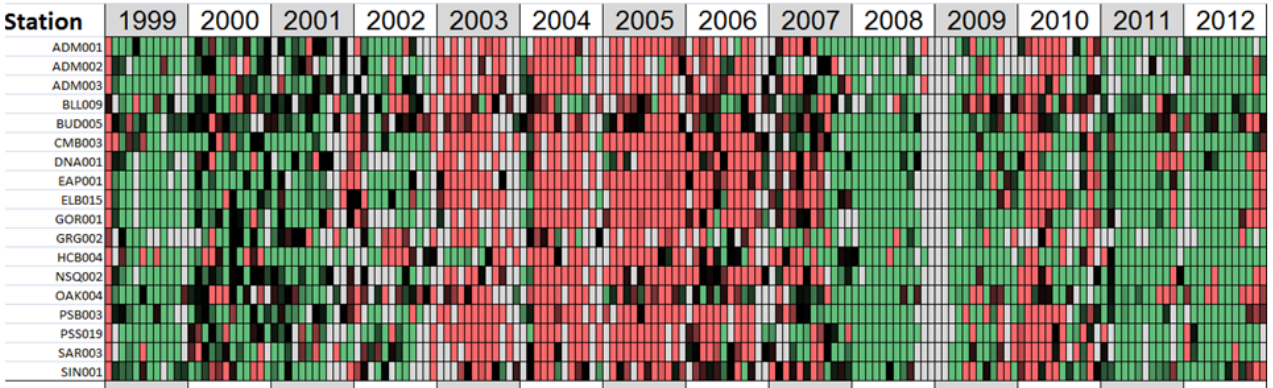
A-B **Sea Surface Temperature -** Pacific Decadal Oscillations Index

C-D **Upwelling -** Upwelling Index (anomalies)

A. Pacific Decadal Oscillation Index

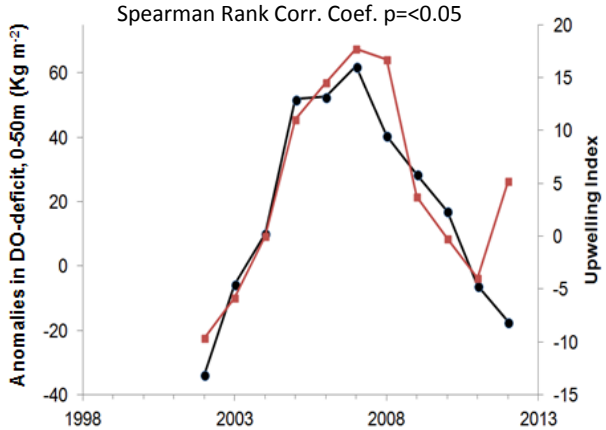


B. *Anomalies in Thermal Energy Content (TEC) (GJ m^{-2}), 0-50 m in Puget Sound*

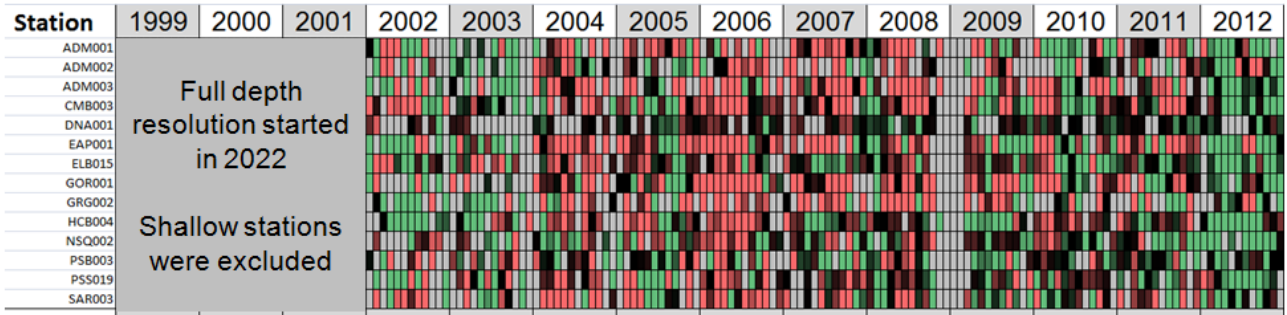


Avg.	-0.050	-0.016	-0.026	-0.020	0.070	0.066	0.075	0.031	-0.009	-0.091	-0.056	0.011	-0.071	-0.066

C. Upwelling Index (NOAA)



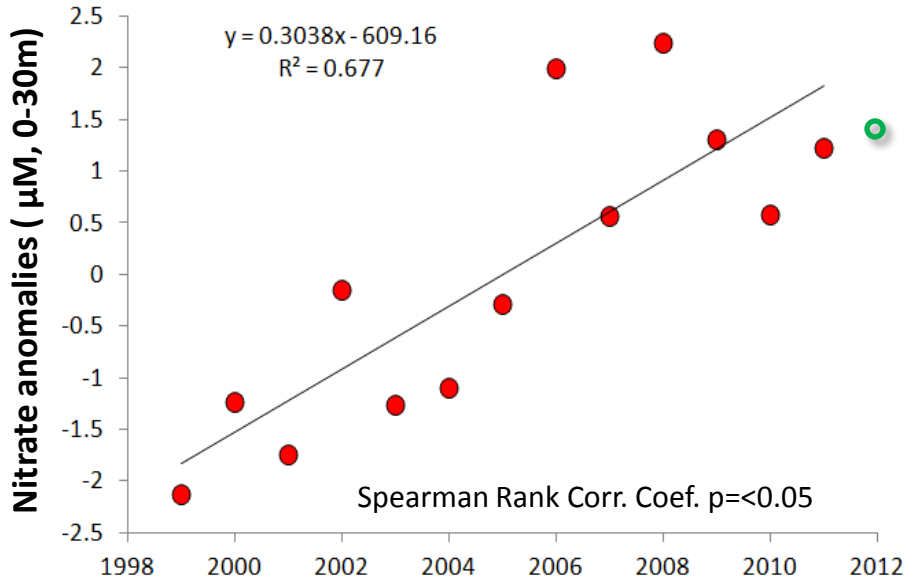
D. *Anomalies in Dissolved Oxygen deficit (Kg DO m^{-2}), > 20m in Puget Sound*



Avg.	n.a.	n.a.	n.a.	-25.24	-42.27	50.38	22.07	83.33	52.58	50.20	18.86	16.38	15.76	-50.55

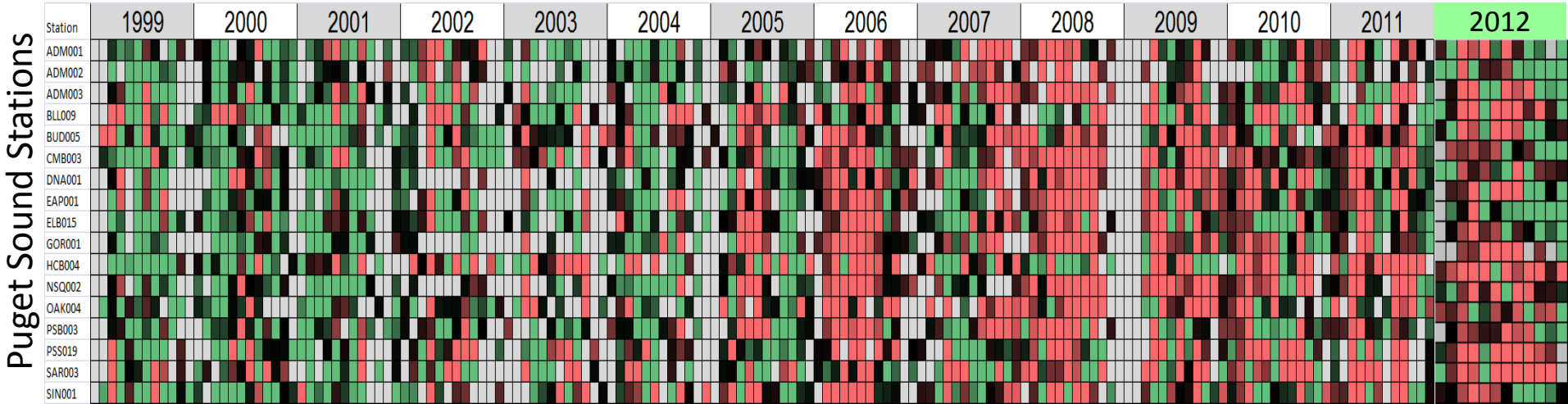
Increasing nitrogen concentrations

Depth: 0-30m



10-year nitrate increase in Puget Sound equals about 3 µM 10 yr^{-1}

Anomalies in nitrate



Common assumptions for Puget Sound

1. **Eutrophication at the surface and oxygen drawdown at depth are coupled.**
2. Puget sound is predominantly a diatom-based food web.
3. Export of org. carbon to depth is predictable by phytoplankton biomass.
4. Nutrient additions promote the accumulation of excessive algal biomass.
5. The microbial food web and micro-zooplankton grazing (<200µm) are of lower importance.
6. A decline in benthic species is a reflection of toxins.

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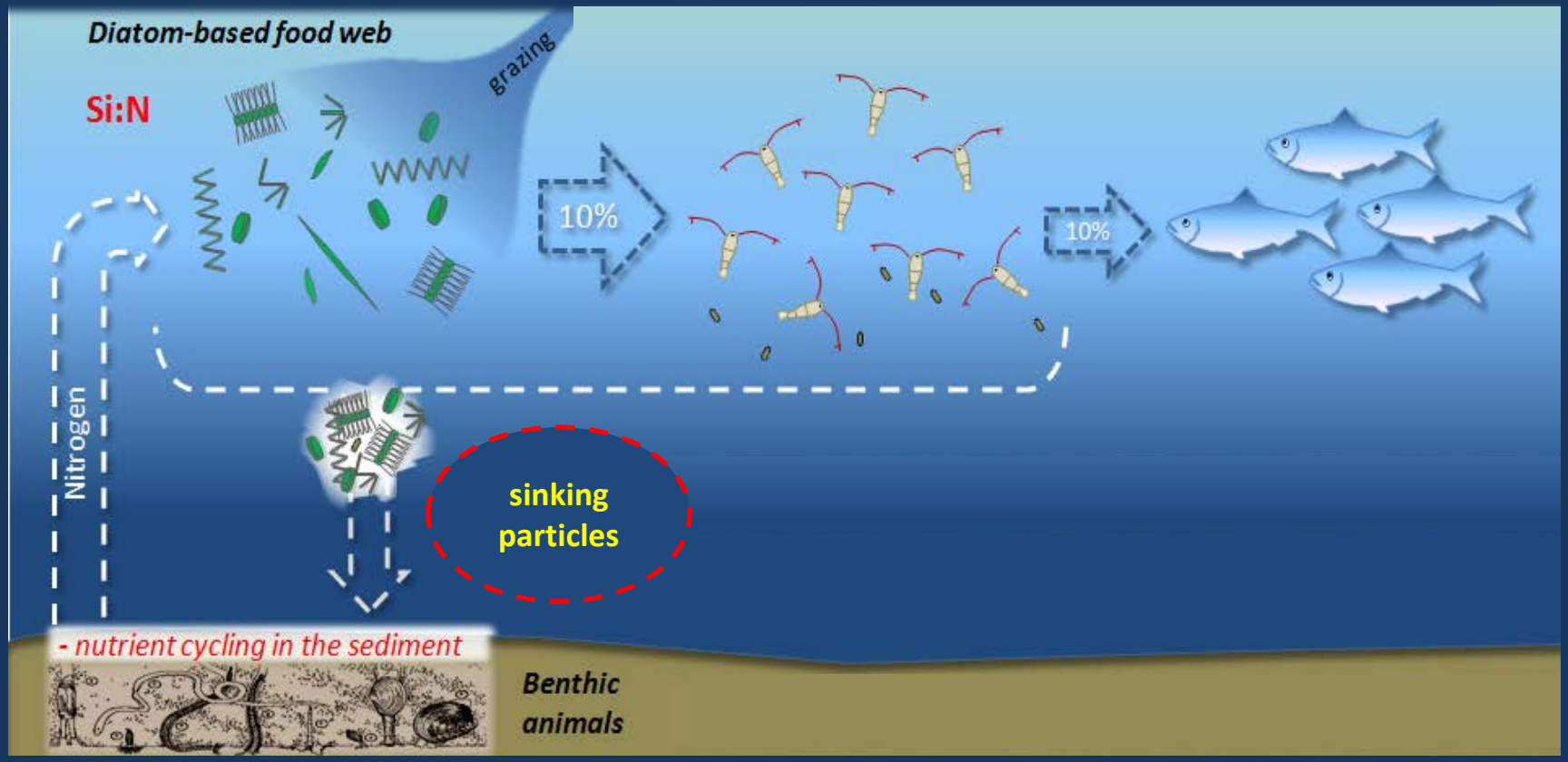
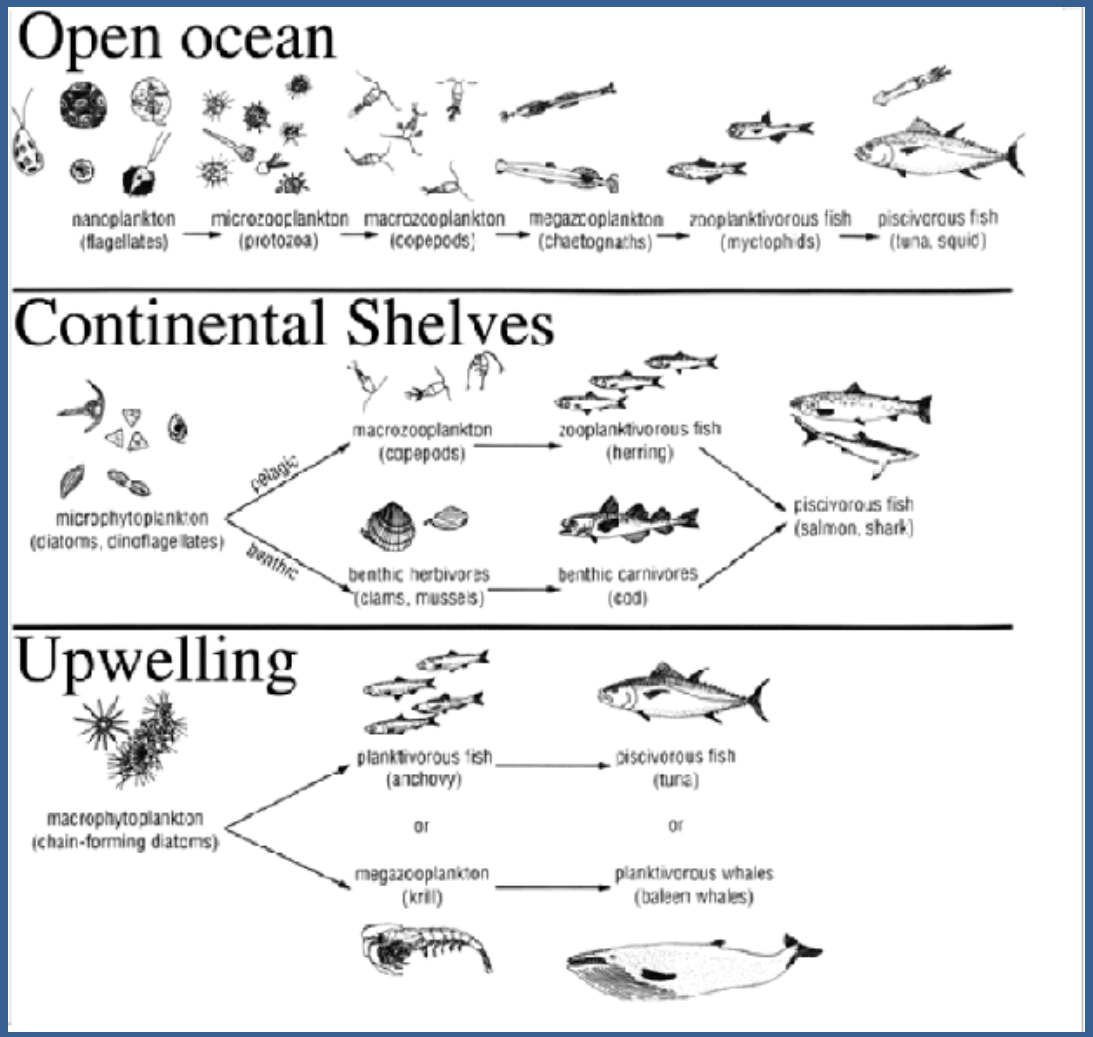
Diatom-based food web and silica

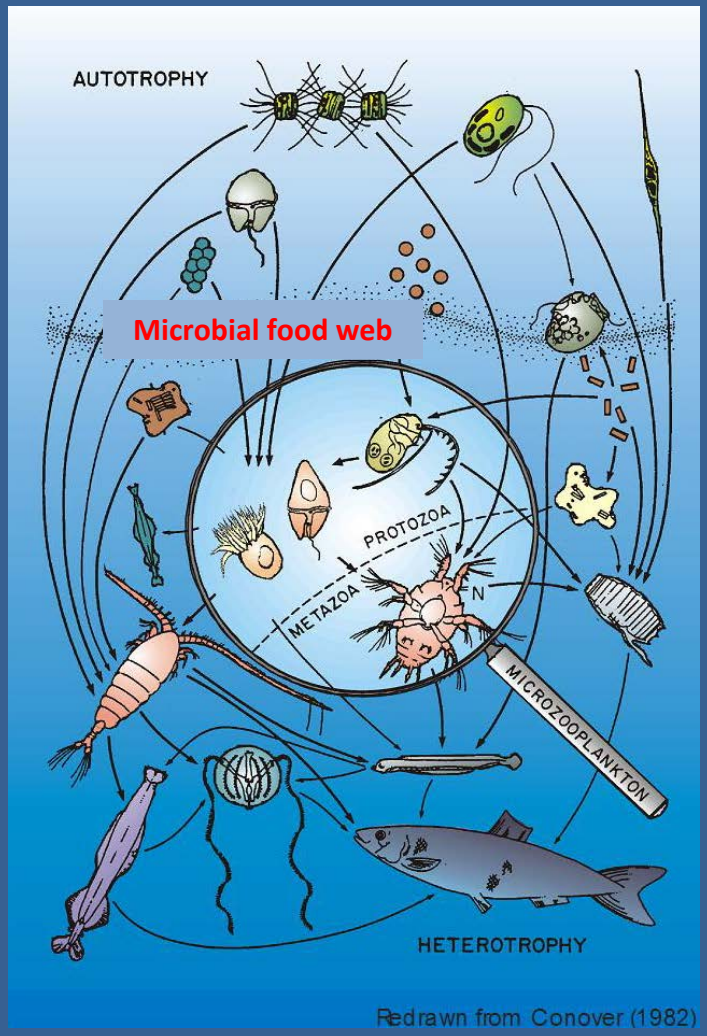
Diatoms are main players in the **biogeochemical cycle and dominate export production.** (Buesseler, 1998).



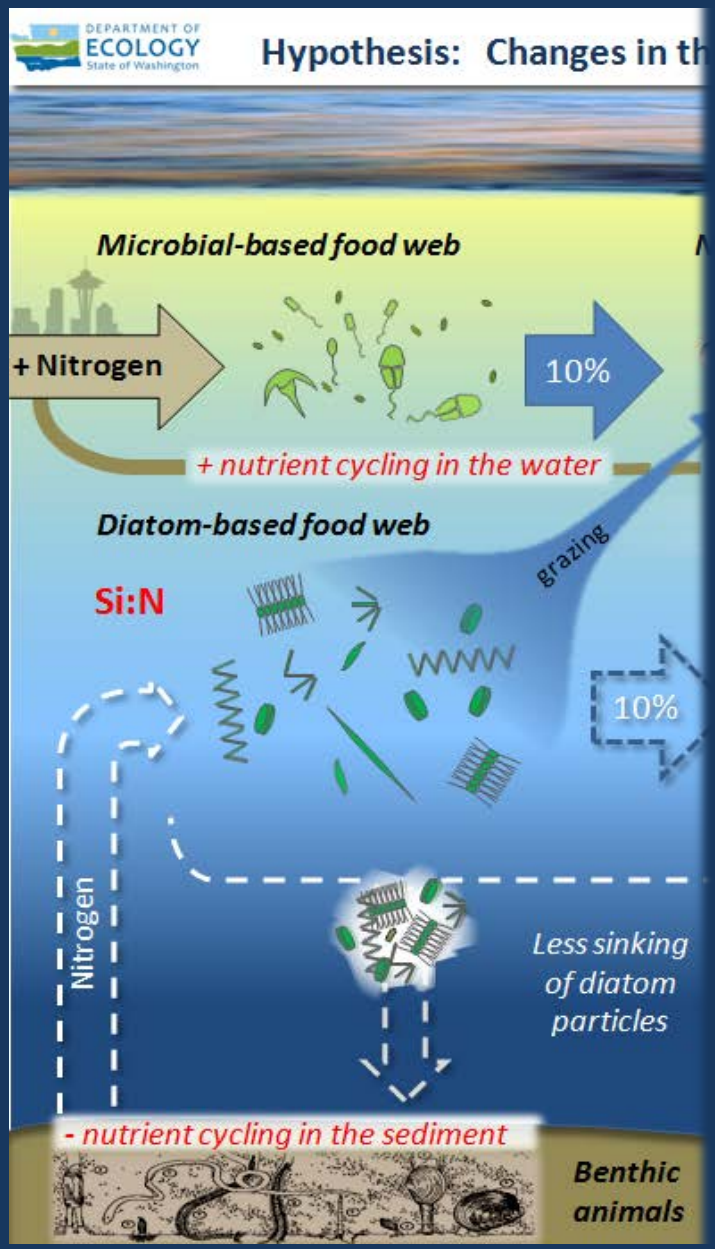
Drawn by Christopher Krembs

Trophic energy transfer efficiency, 10%





Redrawn from Conover (1982)



Diatom dominated: *Food for zooplankton and fish.*

1. Diatoms use silicate with a ratio of Si:N of 1:1. (Redfield et al., 1963)
2. Silicate stems from land weathering.
3. Grazed diatoms quickly release N and P but not silicate (frustules slow remineralization).

Flagellate dominated: *Poor food for grazers*.

1. Motility allows positioning in the water.
2. Need only nitrogen and phosphorus.
3. Sewage effluents high N & P have lower level of silicate.

Temporal shift:

Late spring-early summer diatom dominated blooms -

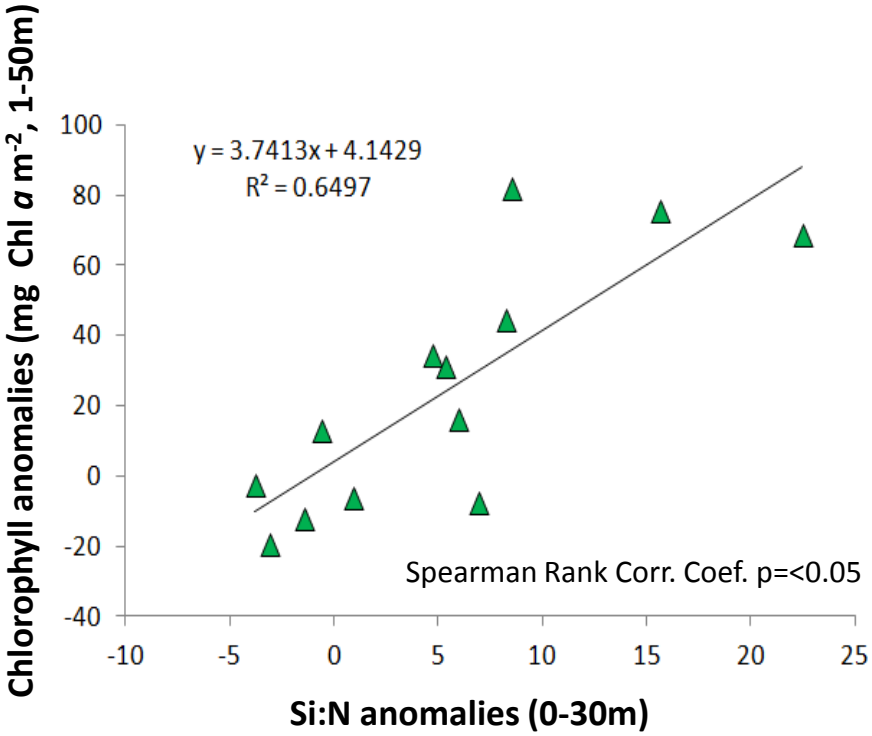
Late summer flagellate dominated blooms. (Margalef, 1958)

Spatial shift:

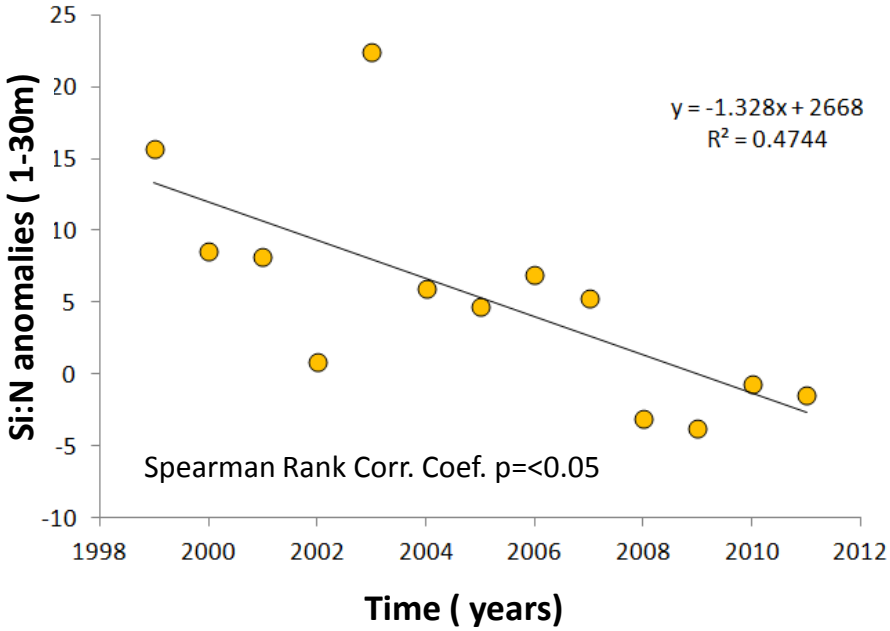
Sewage effluent input leads to plankton blooms and promotes a flagellate dominated population. (Officer and Ryther 1980)

Is the diatom-based food web losing significance because of a nutrient imbalance (Si:N)?

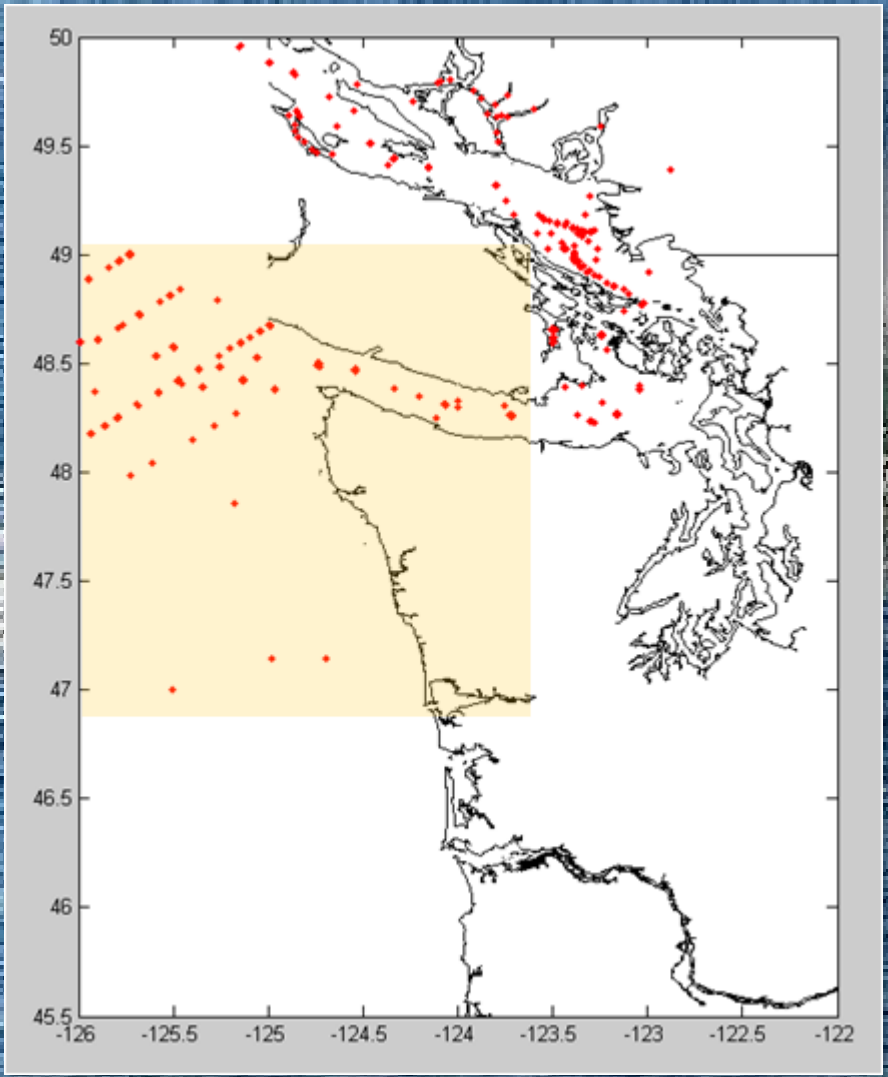
In the water column phytoplankton biomass and Si:N correlate

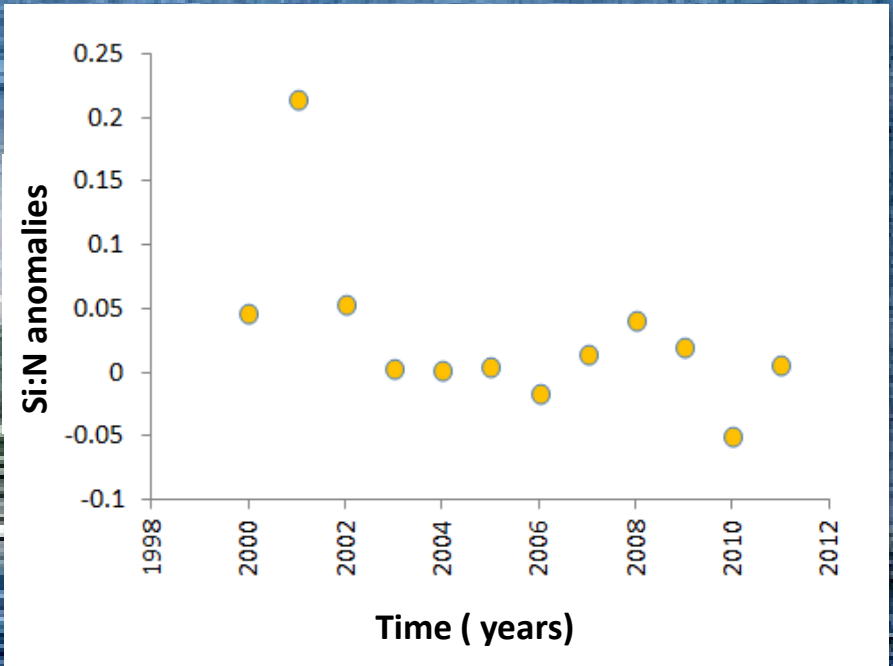


A shifting Si:N ratio favors non-silicified phytoplankton taxa



Variability of boundary conditions for Si:N is one order of magnitude lower (WOCE)



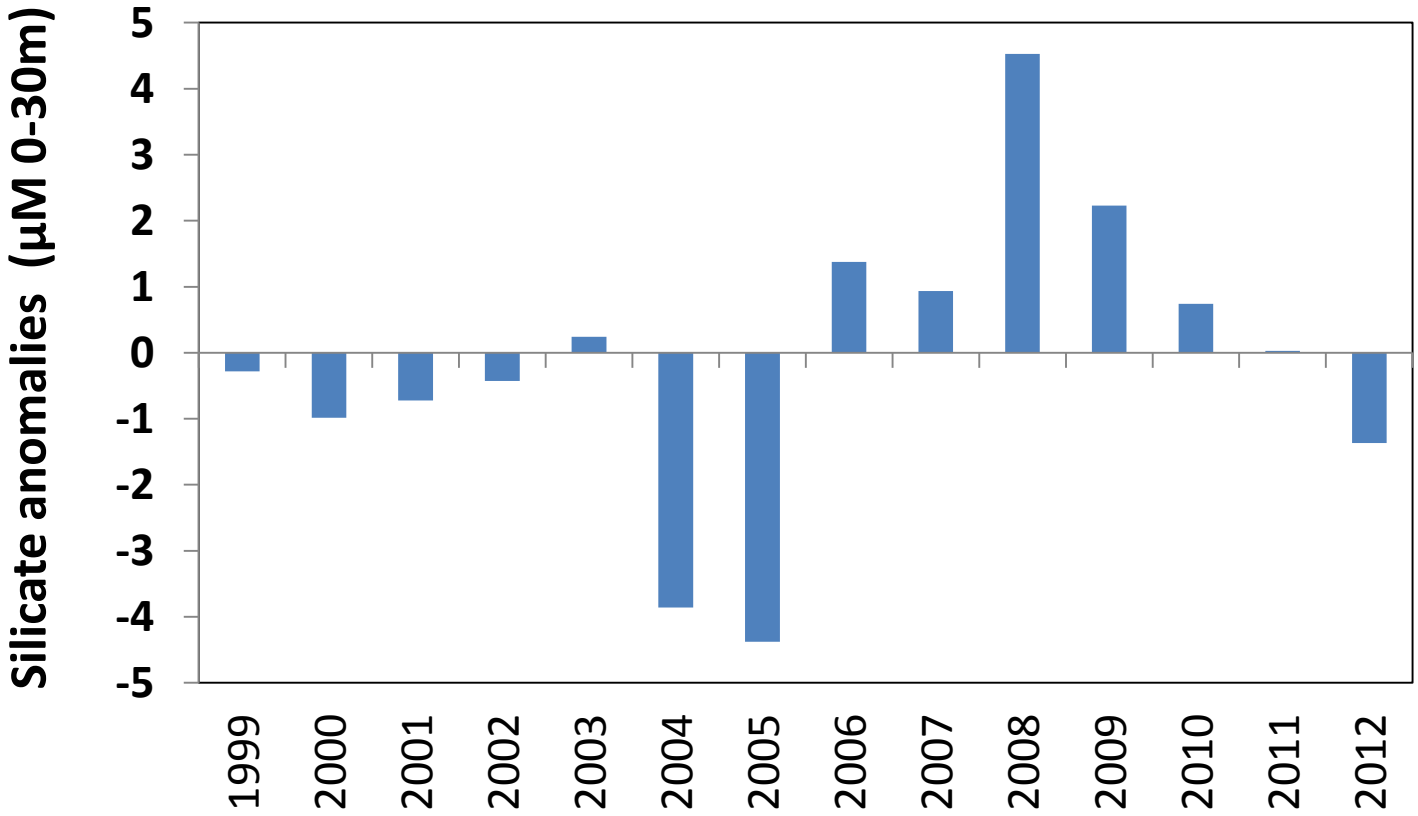


<u>Ocean not a driver</u>:

1. No ocean signal in Si:N
2. Variability two orders of magnitude lower

Silicate anomalies in Puget Sound

Silicate variability <u>does not</u> correlate with any ocean index.



Important Topic

Dongyan Liu et al. 2013

Altered **nutrient supply ratios** from increased nitrogen inputs play an important role in the **shifts in diatom and dinoflagellate** assemblages.

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doi: 10.3354/meps10234

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FEATURE ARTICLE

Palaeoecological analysis of phytoplankton regime shifts in response to coastal eutrophication

Dongyan Liu[1,*], Xuhong Shen[1,2], Baoping Di[1], Yajun Shi[1], John K. Keesing[1,3], Yujue Wang[1], Yueqi Wang[1,2]

[1]Key Laboratory of Coastal Zone Environmental Processes, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences; Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, 264003, Yantai, Shandong, PR China

[2]Graduate University of the Chinese Academy of Sciences, 100049, Beijing, PR China

[3]CSIRO Wealth from Oceans National Research Flagship, Marine and Atmospheric Research, Private Bag 5, Wembley, Western Australia 6913, Australia

ABSTRACT: We used a multiple-proxy palaeoecological method to reconstruct a 100 yr time series showing coastal eutrophic processes and phytoplankton responses. Total organic carbon, total nitrogen, diatom frustules, dinoflagellate cysts, brassicasterol and dinosterol were extracted from chronologic sediment cores in Sishili Bay, a polluted area in China. The cores showed that eutrophication occurred during about 1975 to 1985, which corresponds to increased human activity associated with China's economic development since 1978. During eutrophication, the biomass of diatoms and dinoflagellates increased, and dominant species shifted abruptly. The small, heavily silicified diatoms *Cyclotella stylorum* and *Paralia sulcata* gradually took the place of the large dominant diatom *Coscinodiscus radiatus*, while dinoflagellates displayed a progressive increase since 1975. Compared to changes in temperature and rainfall during 1950 to 2010, increased fertilizer use, marine aquaculture and sewage discharge showed a better match to the increasing trend in biomass, species shift and nutrient concentration. Altered nutrient supply ratios caused by increased nitrogen inputs play an important role in the shifts in diatom and dinoflagellate assemblages.

KEY WORDS: Palaeoecology · Eutrophication · Diatom · Dinoflagellate · Biomarkers

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*Email: dyliu@yic.ac.cn

Paleoecological methods make it possible to reconstruct anthropogenic effects such as coastal eutrophication over periods of a century.

Photos: Dongyan Liu & Zhijun Dong

INTRODUCTION

Over recent decades, coastal waters have undergone significant deterioration, much of it due to anthropogenic eutrophication (de Jonge et al. 2002) and climate change (Harley et al. 2006). Setting a target for nutrient reduction requires not only information on nutrient sources, distribution and recycling, but also requires knowledge of the trends and baselines of nutrient concentrations in coastal waters

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Si:N ratio and species composition

A shift in the Si:N atomic ratio <1:1 increases the proportion of flagellate algae. (Officer and Ryther, 1980)

Independent of the ocean, the Si:N ratios continue to fall!

Projected 1:1 ratio is reached in few years!

Month	Delta 14-y	Years
ADM002	-0.2	56
ADM001	-0.2	83
PSB003	-0.6	24
GRG002	-1.0	12
EAP001	-0.4	39
GOR001	-0.4	43
ADM003	-3.0	5
ELB015	-0.4	43
CMB003	-0.7	25
NSQ002	-0.5	37
DNA001	-0.8	24
SIN001	-8.4	2
PSS019	-7.2	2
SAR003	-3.3	6
BLL009	-7.3	2
OAK004	-120.6	0
HCB004	-43.4	1
BUD005	-37.9	1

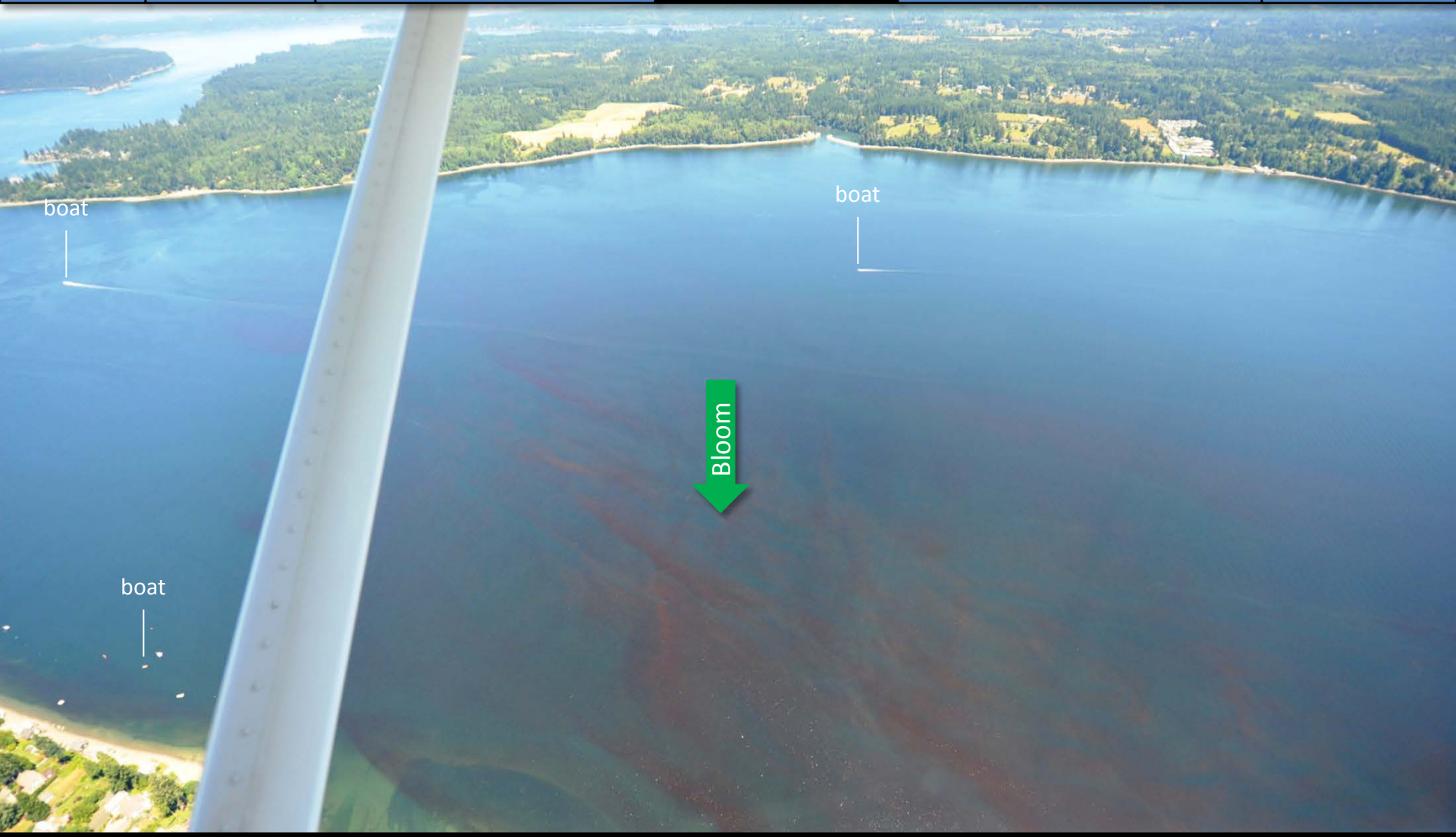
Aerial photography, Eyes Over Puget Sound

Red-brown bloom. Location: Quartermaster Harbor (Vashon Island), 4:32 PM

Aerial photography, Eyes Over Puget Sound

Extensive red-brown bloom. Location: Case Inlet (South Sound), 4:33 PM

Aerial photography 7-15-2013



Red-brown algae bloom near the surface.

Location: Budd Inlet (South Sound), 1:45 PM.

Aerial photography 3-25-2013

Large and intense red-orange-brown plankton bloom.

Location: Hood Canal, 3:35 PM

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4. Nutrient additions promote the accumulation of excessive algal biomass.
5. The microbial food web and micro-zooplankton grazing (<200µm) are of lower importance.
6. A decline in benthic species is a reflection of toxins.

Important Topic

Durkin et al. 2013

Elevated Columbia River silicate concentrations increase coastal diatom silicate content and **sinking rates by two fold**.

Increased silicate does not change diatom growth rates or species composition.

Silicate concentrations strongly modulate vertical export of diatoms in coastal waters **(ballasting)**

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© 2013, by the Association for the Sciences of Limnology and Oceanography, Inc.
doi:10.4319/lo.2013.58.5.1707

Silicic acid supplied to coastal diatom communities influences cellular silicification and the potential export of carbon

Colleen A. Durkin,[a] Sara J. Bender, Kit Yu Karen Chan,[a] Kelsey Gaessner, Daniel Grünbaum, and E. Virginia Armbrust *

School of Oceanography, University of Washington, Seattle, Washington

Abstract

Microcosm experiments were conducted along the Washington and Oregon coasts in May 2009, May 2010, and July 2010 to determine whether variation in the supply of silicic acid from the Columbia River could influence the silicification and sinking potential of coastal diatom blooms. The chlorophyll *a* concentration increased similarly in communities incubated with added nitrate or both nitrate and silicic acid, indicating that growth was limited by nitrate availability. Communities that grew in the treatment with added silicic acid and nitrate were more silicified than communities in the treatment with only nitrate added. No difference in community composition was detected between these treatments in three out of four experiments. Isolates of *Minutocellus*, *Cylindrotheca*, *Thalassiosira*, and *Odontella* were obtained from the microcosm experiment conducted in May 2010 and were maintained in the laboratory in 20 μmol L^{-1} silicic acid. All four diatom isolates contained ~ 2.5 times more silica per cell when silicic acid concentration in the media was increased to 80 μmol L^{-1}. The intensity of a fluorescent cellular stain of newly precipitated silica (2-(4-pyridyl)-5{[4-dimethylaminoethyl-aminocarbamoyl)-methoxy]phenyl}oxazole) strongly correlated with silica content among species, but was a less sensitive indicator of changing silicification within a single species. Changes in silicification were not correlated with changes in the transcript abundance of silicic acid transporters. Sinking rates increased roughly 2-fold for cells that contained ~ 2.5 times more silica. Variation in silicic acid supply alters the silicification of nitrate-fueled coastal diatom blooms and the potential sink of carbon from coastal zones.

Primary production in coastal regions is dominated by diatoms (Nelson et al. 1995), which require silicon (Si) to form their cell walls (frustules). As a result of their high productivity and silicon requirement, diatoms link the marine carbon cycle to the fate of silicon. Silicon enters the marine system at the continental margins, where an estimated 5 Tmol of silicic acid drain from rivers into the coastal oceans every year and are eventually transformed into the silica frustules of blooming diatoms (Treguer et al. 1995). The heavy silica frustules act as a ballast that enhances the sinking rate of diatom-fixed carbon (Buesseler 1998). This tendency for diatoms to sink is a mechanism for long-term net carbon removal from the atmosphere and influences global climate. Changes in supply and utilization of silicic acid in coastal regions could influence the carbon cycle, and perhaps the role of coastal regions in global carbon budgets. Characterizing the response of diatoms to variations in the concentration of silicic acid will help constrain how biological variability influences the coastal carbon cycle.

Diatoms transport silicic acid into their cells with silicic acid transporter (SIT) proteins embedded in the outer membrane of the cell. Diatom cells typically reach a maximum uptake rate when silicic acid concentrations are above 0.2–8 μmol L^{-1}, depending on the diatom species (Martin-Jezequel et al. 2000). Above these concentrations, SITs are saturated and cells maintain a constant, maximum SIT-mediated uptake rate. At concentrations below these levels, the uptake rate is reduced because the transporters are limited by their encounter rate with silicic acid; this condition is called uptake limitation. When cells are uptake limited, the rate of incorporation of silicic acid into the frustule cannot keep up with the rate of cell division. To maintain their growth rate, cells precipitate less silicified frustules (Paasche 1973; Harrison et al. 1977). This plasticity enables diatom cells to avoid growth limitation in low concentrations of silicic acid. Therefore, the concentration of silicic acid can limit uptake without limiting growth.

Diatoms appear to actively respond to nutrient conditions that affect silicic acid uptake by changing the transcript abundance of their SIT genes and, presumably, the abundance of the transporters in their outer membrane. All diatoms studied to date possess multiple SIT genes, and often these gene copies have diverged into separate clades of the gene family (Thamatrakoln et al. 2006; Durkin et al. 2012). The diverged SIT genes are transcribed differently from one another across the cell cycle (Thamatrakoln and Hildebrand 2007) and when cells are silicon starved, iron starved, or iron limited (Allen et al. 2008; Mock et al. 2008; Durkin et al. 2012). These transcriptional patterns suggest that SIT genes have evolved to function in specific environmental and growth conditions. The transcriptional regulation of SIT genes does not directly correlate to changes in silicic acid uptake or the timing of protein production (Thamatrakoln and Hildebrand 2007), indicating that part of the regulatory process occurs posttranscriptionally. Although additional regulatory steps are involved in the silicic acid uptake pathway, when changes

*Corresponding author: armbrust@uw.edu

[a]Present address: Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Si:N ratio and sinking rates (export)

10-year median for each month

Ecology long-term stations

Month	1	2	3	4	5	6	7	8	9	10	11	12
ADM002	1.9	1.9	1.9	1.9	1.9	1.8	1.9	1.8	1.9	1.9	2.0	1.9
ADM001	2.3	2.1	2.1	2.2	2.3	2.0	2.0	2.0	2.0	2.0	2.2	2.0
PSB003	2.2	2.2	2.2	2.3	2.5	2.3	2.7	2.4	2.1	2.0	2.1	2.0
GRG002	2.1	2.1	2.0	1.9	2.6	2.4	3.3	2.9	2.2	2.1	1.9	2.0
EAP001	2.1	2.2	2.2	2.4	3.0	2.2	2.6	2.6	3.0	2.1	2.2	2.2
GOR001	2.3	2.4	2.4	2.4	2.2	2.2	2.8	3.1	2.9	2.5	2.4	2.3
ADM003	2.2	2.2	2.4	2.4	3.5	2.3	3.2	2.5	2.8	2.3	2.2	2.1
ELB015	2.5	2.4	2.4	2.6	3.1	2.9	3.3	2.5	2.4	2.2	2.4	2.6
CMB003	2.6	2.7	2.7	2.6	2.8	3.4	2.4	2.7	2.7	2.2	2.4	2.2
NSQ002	2.4	2.5	2.4	2.5	2.7	2.8	3.7	3.8	3.9	2.8	2.5	2.3
DNA001	2.4	2.5	2.5	2.5	3.4	2.3	3.3	3.8	4.9	3.2	2.6	2.4
SIN001	2.3	2.2	2.2	2.9	3.9	2.6	6.9	7.4	5.4	2.9	2.4	2.2
PSS019	2.4	2.5	2.5	2.8	10.7	5.1	5.4	8.4	7.8	2.4	2.4	2.2
SAR003	2.4	2.8	2.7	3.2	13.2	12.5	6.1	9.2	6.8	5.7	2.6	2.4
BLL009	2.1	2.1	2.4	2.9	3.6	30.1	9.1	5.5	4.9	3.1	2.2	2.0
OAK004	3.4	3.5	4.1	5.7	31.5	13.1	124.9	112.4	17.4	4.3	3.2	2.5
HCB004	3.9	10.8	33.8	45.9	23.6	12.1	33.7	86.6	46.0	30.4	2.9	3.7
BUD005	2.7	2.9	2.7	3.8	17.0	4.8	152.5	208.7	70.8	4.6	2.9	2.7

1. **Large seasonal and geographical ranges in Si:N ratios in PS.**
2. **Puget Sound Si:N dropped on average by 10 units (over 10 years)!!!**
3. **Sinking rates decreased 2-fold by changing ratios from 4:1 to 1:1 (Columbia River estuary**, Durkin et al. 2013).

Percentile s:
<10 (red), 50 (yellow), >90 (green)

II. Falling Si:N ratios affect the ballasting of particles and sinking rates

Common assumptions for Puget Sound

1. Eutrophication at the surface and oxygen drawdown at depth are coupled.
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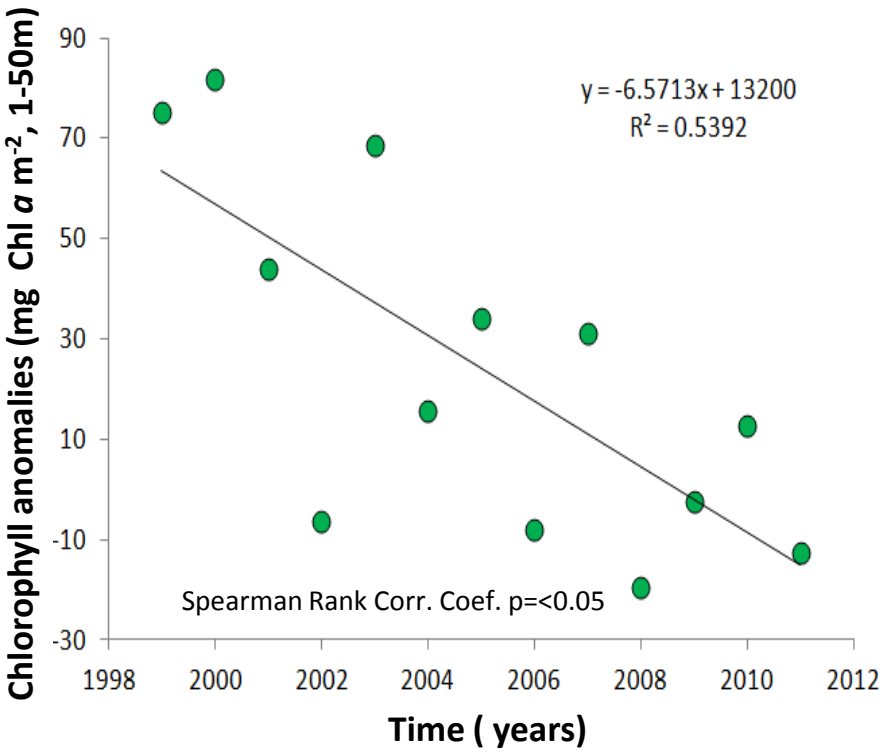
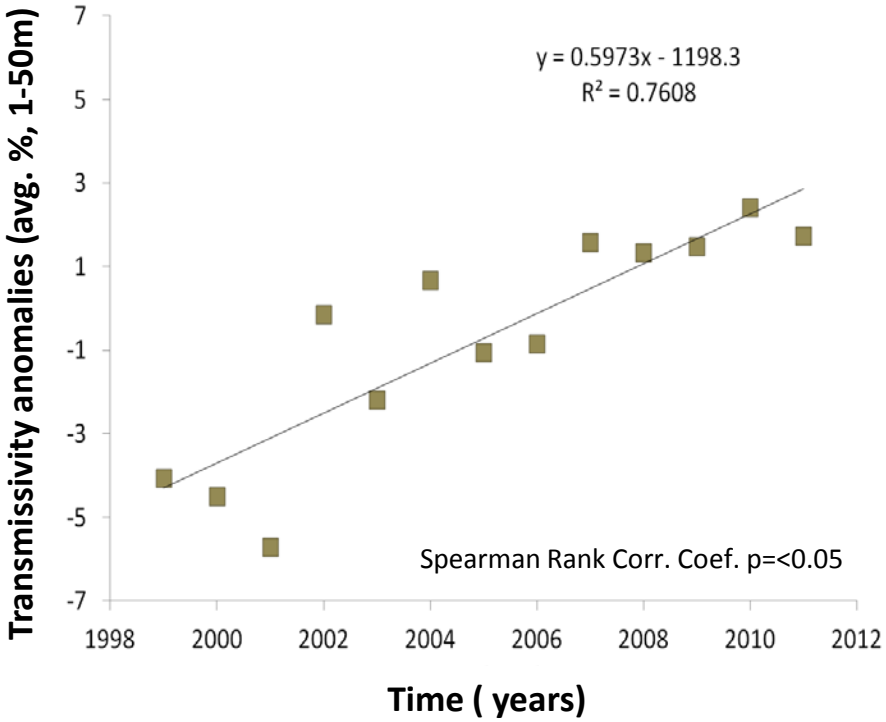
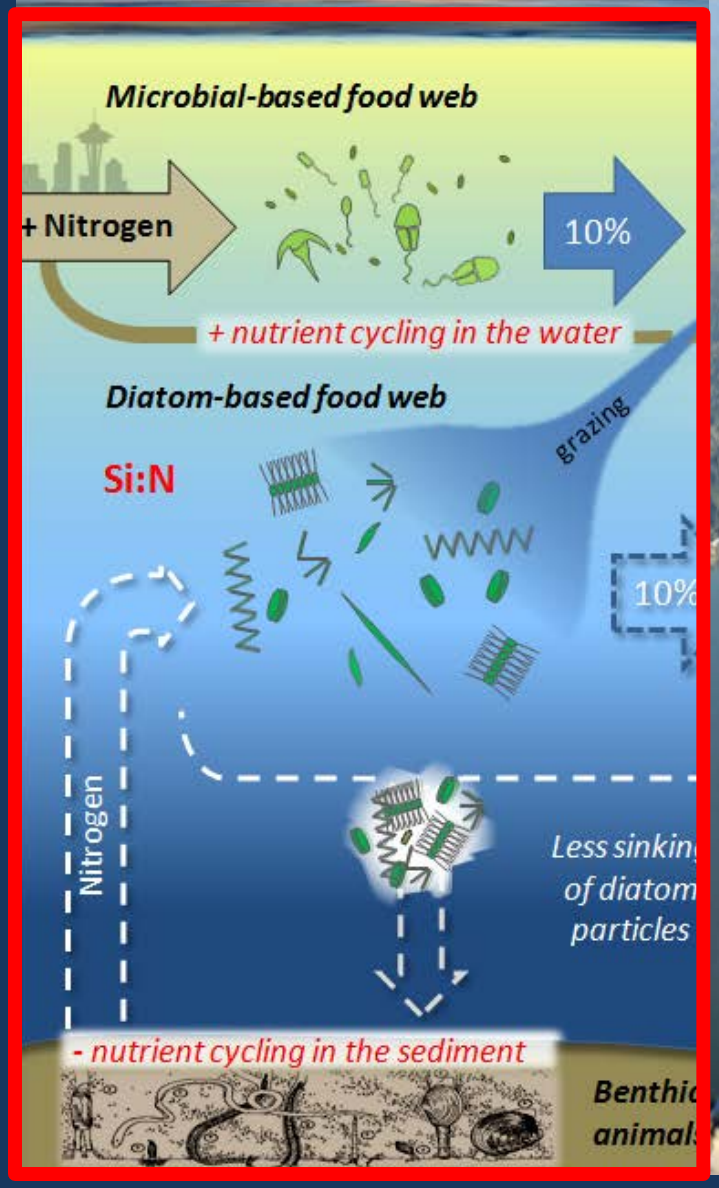
4. **Nutrient additions promote the accumulation of excessive algal biomass.**
5. The microbial food web and micro-zooplankton grazing (<200µm) are of lower importance.
6. A decline in benthic species is a reflection of toxins.

Depth integrated chlorophyll, a proxy for sub-surface phytoplankton biomass has been declining.





Hypothesis: Changes in the Marine Food Web and Energy Transfer in Puget Sound



Drawn by Christopher Krembs

Common assumptions for Puget Sound

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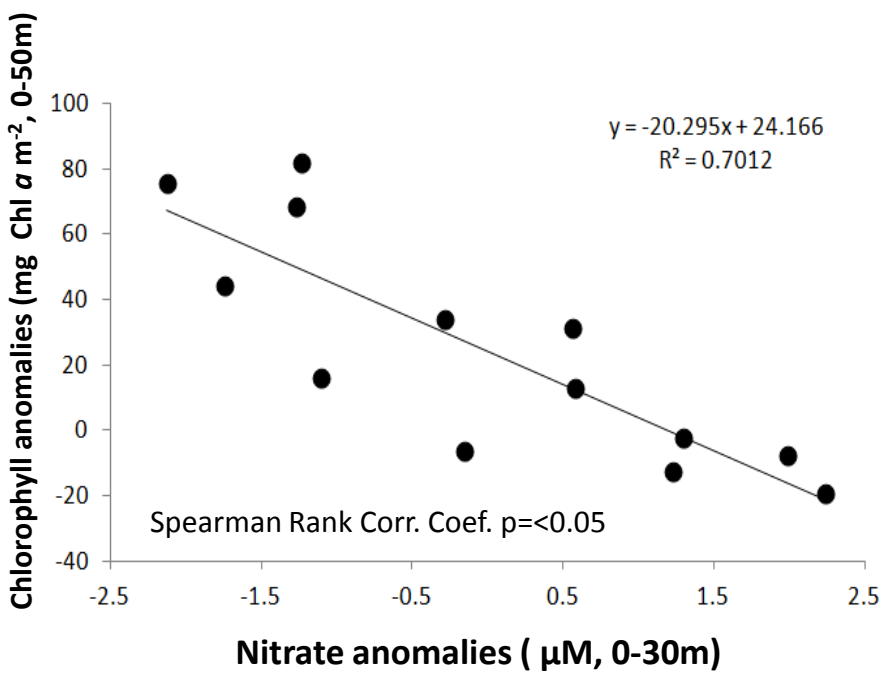
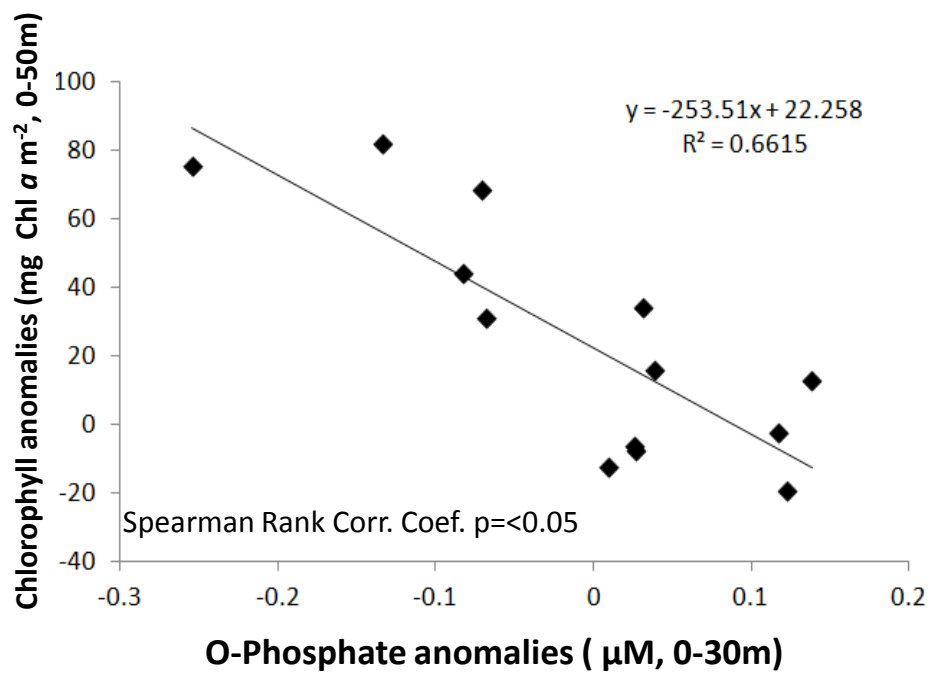
Do we potentially have a top-down grazer control on phytoplankton biomass?

Nitrate and Chl *a*



Phosphate and Chl *a*



Microzooplankton (<200µm) grazing is very important in marine waters

- **In coastal environments 45–110% of the standing stock of diatoms can be removed each day by microzooplankton grazing.**

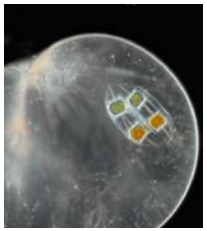
  (Verity et al., 1996a; Nejstgaard et al., 1997; Landry et al., 2000a; Calbet, 2001; Strom et al., 2001; Olson and Strom, 2002; Suzuki et al., 2002).

- **Balance between microzooplankton grazing and phytoplankton growth in Dabob Bay…**

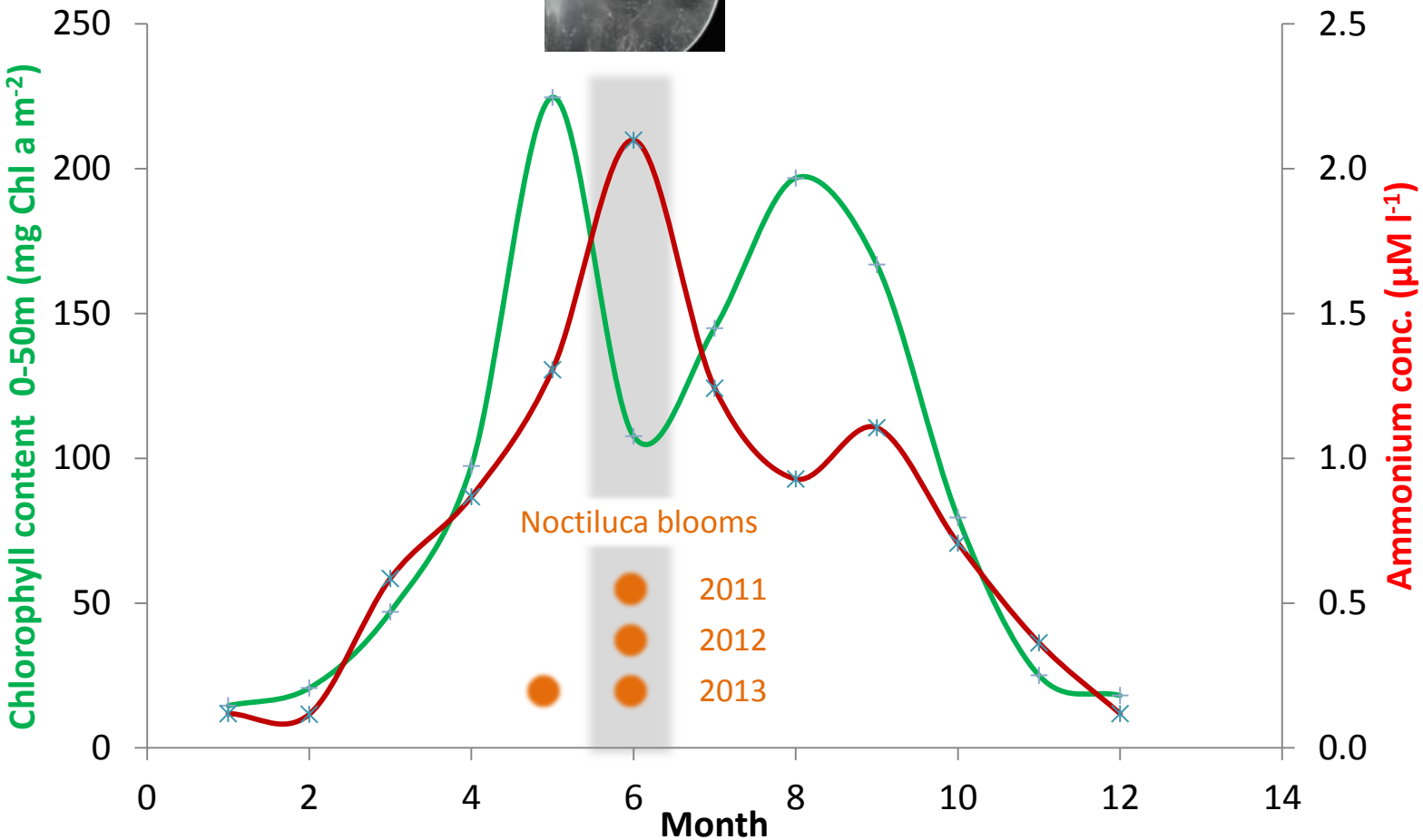
  Leising A.W., Horner R., Pierson J., Postel J., C. Halsband-Lenk 2005. The balance between microzooplankton grazing and phytoplankton growth in a highly productive estuarine fjord. Progress in Oceanography 67, 366–383.

Grazing is reflected in the seasonality of Chl a and NH_4 in Puget Sound.

10-year median, Puget Sound



Diatoms inside Noctiluca



Eyes Over Puget Sound

Surface Conditions Report

June, 20th 2011

Up-to-date observations of visible water quality conditions in Puget Sound and the Straits

Eyes Over Puget Sound

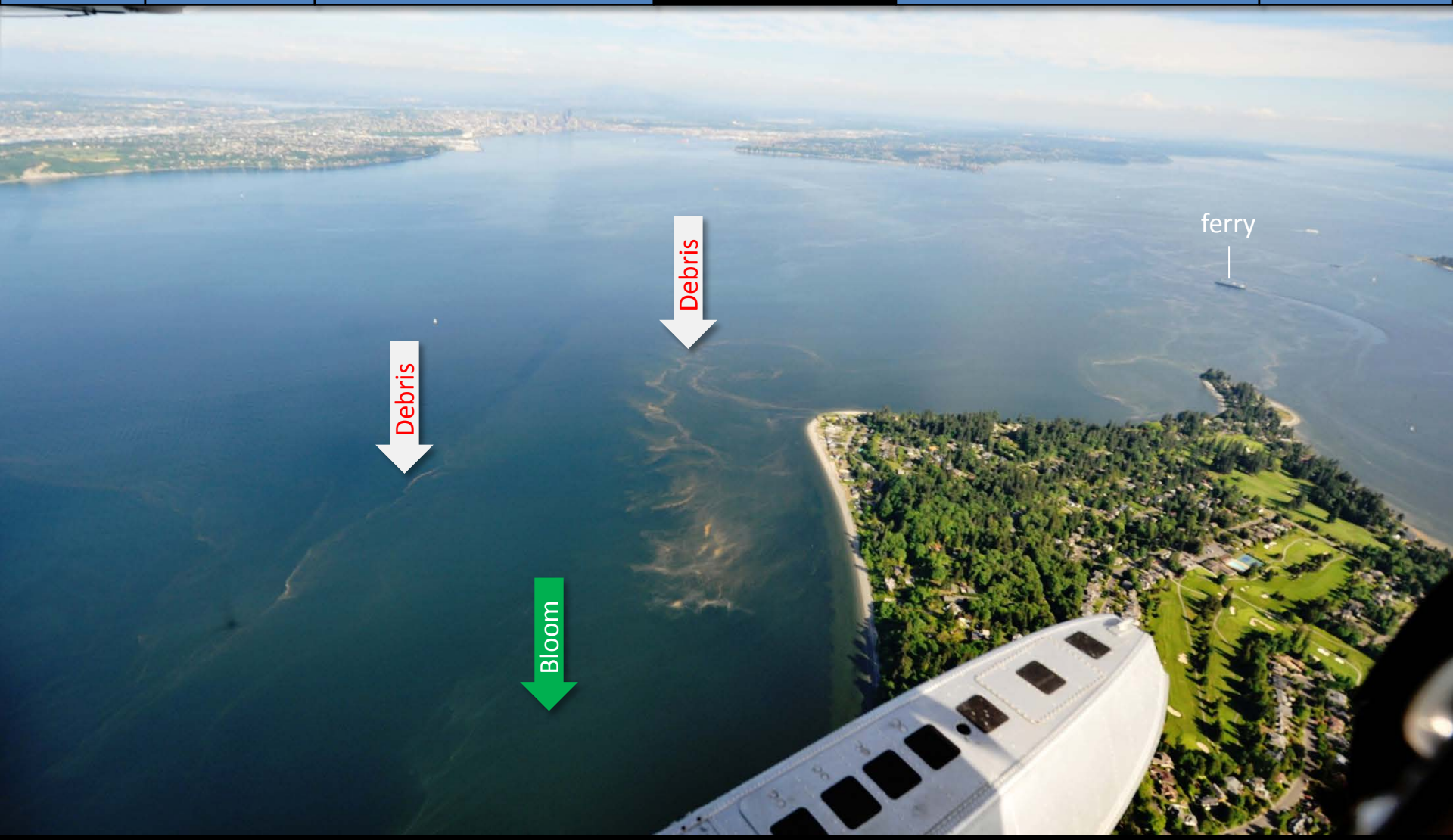
Surface Conditions Report

June 12, 2012

Start here

Up-to-date observations of visible water quality conditions in Puget Sound and the Strait of Juan de Fuca

Aerial photography 5-20-2013



Noctiluca *bloom with Seattle to Bainbridge ferry in background*.
Location: Near Winslow, Bainbridge Island, 4:51 PM

Eyes Over Puget Sound

Surface Conditions Report
June 17, 2013

Visit our website (http://www.ecy.wa.gov/programs/eap/mar_wat/) Start here

Up-to-date observations of visible water quality conditions in Puget Sound and the Strait of Juan de Fuca

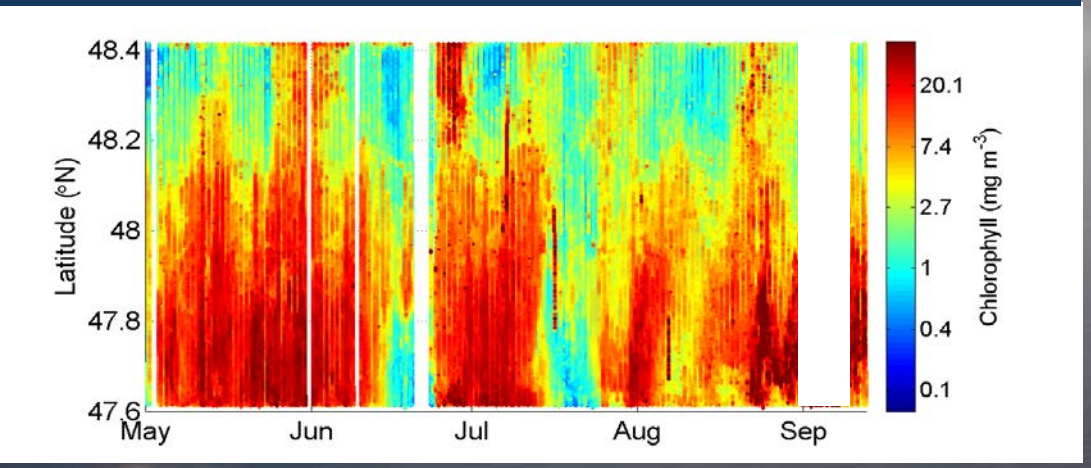
Aerial photography 6-17-2013

Noctiluca bloom at surface in very long bands.

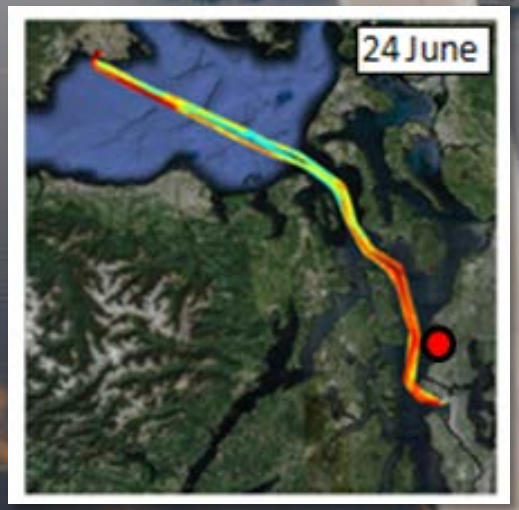
Location: Between Bainbridge Island and Elliott Bay (Central Basin), 5:27 PM.

Eyes Over Puget Sound, June 2011

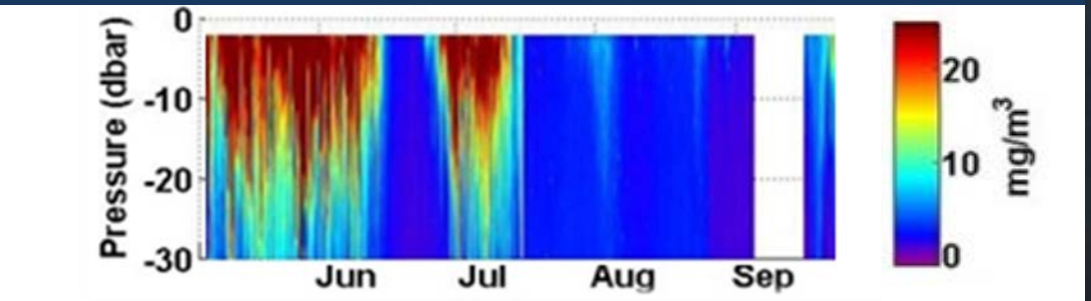
Chlorophyll a (in situ fluorescence)



Noctiluca



Chlorophyll a (in situ fluorescence)



Source: Al Devol, Orca mooring, UW

Noctiluca feeding facts

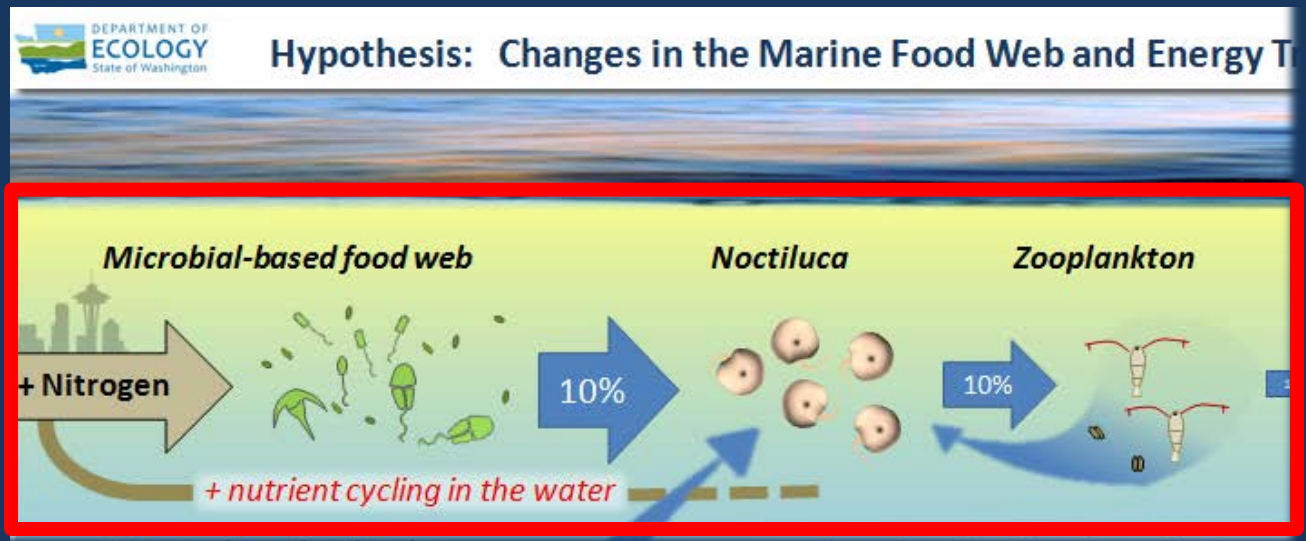
Large cell size (up to millimeters)
Exclusively heterotrophic and no food preference!

Food spectrum:
Diatoms, other dinoflagellates, protozoans, detritus, and fish eggs.

Toxic blooms of *Noctiluca* have been linked to massive fish and marine invertebrate kills.

Species does accumulate toxic levels of ammonia and excretes it into the surrounding waters.

(Okaichi & Nishio 1976; Fukuyo et al. 1990).



Implication of significant Noctiluca grazing

"Noctiluca can contribute significantly to the **recycling of rapidly sinking fecal pellets** in the water column.

Kiørboe, Thomas 2003. High turnover rates of copepod fecal pellets due to Noctiluca scintillans grazing. Journal Marine Ecology - Progress Series. Vol 258, p. 181-188

III. Noctiluca affects the sinking rates and biogeochemical cycling on large scales

Important Topic

Vasas et al. 2007

HAB-forming species and Noctiluca **stimulate the microbial network**, but reduce higher trophic levels (fish).

The loss of planktivorous fishes acts together with nutrient enrichment in promoting **HAB species, Noctiluca and jellyfish.**

Vol. 336: 1–14, 2007 | MARINE ECOLOGY PROGRESS SERIES Mar Ecol Prog Ser | Published April 27

OPEN ACCESS

FEATURE ARTICLE

Eutrophication and overfishing in temperate nearshore pelagic food webs: a network perspective

Vera Vasas[1,4,*], Christiane Lancelot[1], Véronique Rousseau[1], Ferenc Jordán[2,3]

[1]Ecologie des Systèmes Aquatiques, Université Libre de Bruxelles, Campus Plaine CP 221, Boulevard du Triomphe, 1050 Bruxelles, Belgium

[2]Collegium Budapest, Institute for Advanced Study, Szentháromság u. 2, 1014 Budapest, Hungary

[3]Animal Ecology Research Group, Hungarian Academy of Sciences, Hungarian Natural History Museum, Ludovika t. 2, 1083 Budapest, Hungary

[4]*Present address:* Department of Plant Taxonomy and Ecology, Eötvös Loránd University, Pázmány Péter s. 1/C, 1117 Budapest, Hungary

ABSTRACT: We investigated the effects of human activities on the pelagic food web structure of nearshore marine ecosystems. Their generic structure was established on the basis of literature review and analyzed by qualitative structural network analysis. Two main issues were addressed: (1) the role of species capable of forming harmful algal blooms (HABs) and red tides (*Noctiluca* spp.), as well as the role of jellyfish, in eutrophicated systems; (2) the contribution of human influences on food webs, focusing on bottom-up (increased nutrient loading) and top-down (overfishing) effects. Results suggest that HAB-forming species and *Noctiluca* stimulate the microbial network, but reduce higher trophic levels such as commercially important fish species. Jellyfish act as a buffer in eutrophicated and overfished systems, as they retain nutrients from the water column, but their blooms lead to a massive accumulation of large phytoplankton organisms. Anthropogenic nutrient enrichment favors undesirable species because of their specific position in the food web, and this crucial position may explain their far-reaching effects. Finally, while it appears that overfishing of piscivorous fishes inhibited HABs and supported blooms of diatoms and other large algae in the past, the present-day loss of planktivorous fishes acts synergistically with nutrient enrichment in promoting HAB species, *Noctiluca* and jellyfish. These fundamental constraints, which are inherent in the generic structure of pelagic food webs, thus largely determine community dynamics in marine coastal ecosystems.

KEY WORDS: Food web · Eutrophication · Overfishing · Network analysis · Coastal ecosystem · Indirect effects · Harmful algal blooms · Gelatinous plankton

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Eutrophication and overfishing are threatening marine coastal communities worldwide. Visible consequences are harmful algal blooms and jellyfish outbreaks. The analysis of the pelagic food web structure by Vasas et al. (diagrammatically idealized above) helps us to understand the mechanisms by which eutrophication and overfishing can generate ecosystem shifts.

Illustration: Sándor Snepp; background from Google Earth™

INTRODUCTION

Coastal waters receive large amounts of anthropogenic nutrients from domestic and industrial effluents and agricultural runoff. Effects of coastal eutrophication are discernible at all trophic levels (Cloern 2001) and appear as direct and indirect qualitative changes in pelagic food webs, e.g. proliferation of harmful algal blooms (HABs), extinction of species at higher trophic levels, and reduced yields of harvestable fishes and invertebrates. These alterations of the food web struc-

*Email: vvasas@yahoo.com

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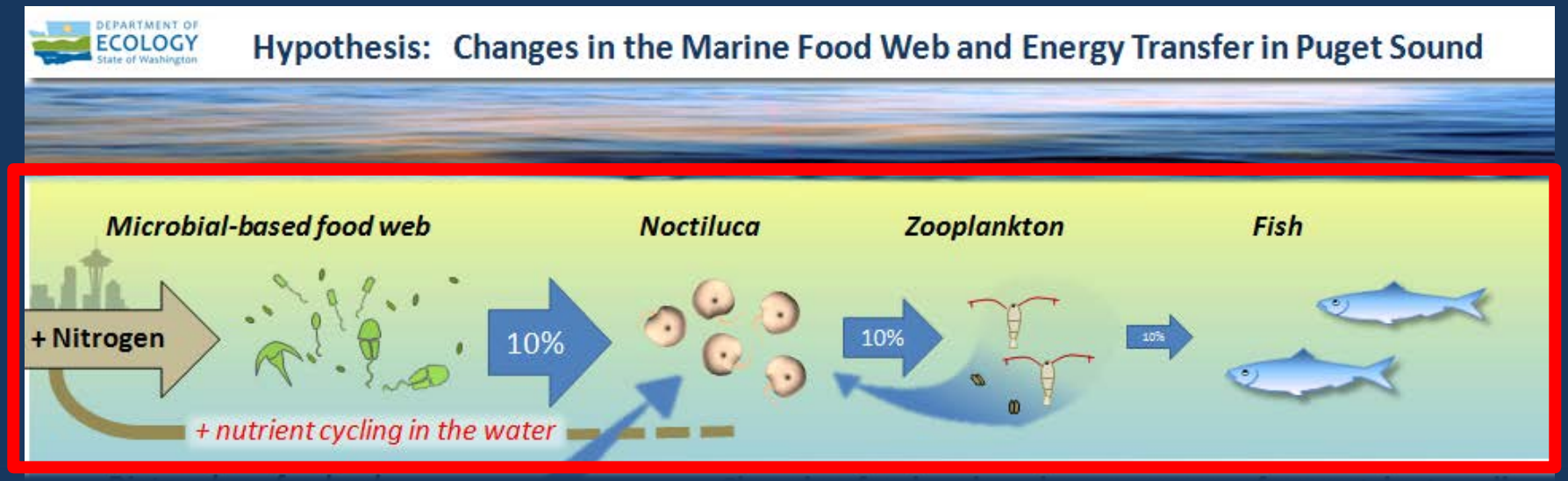
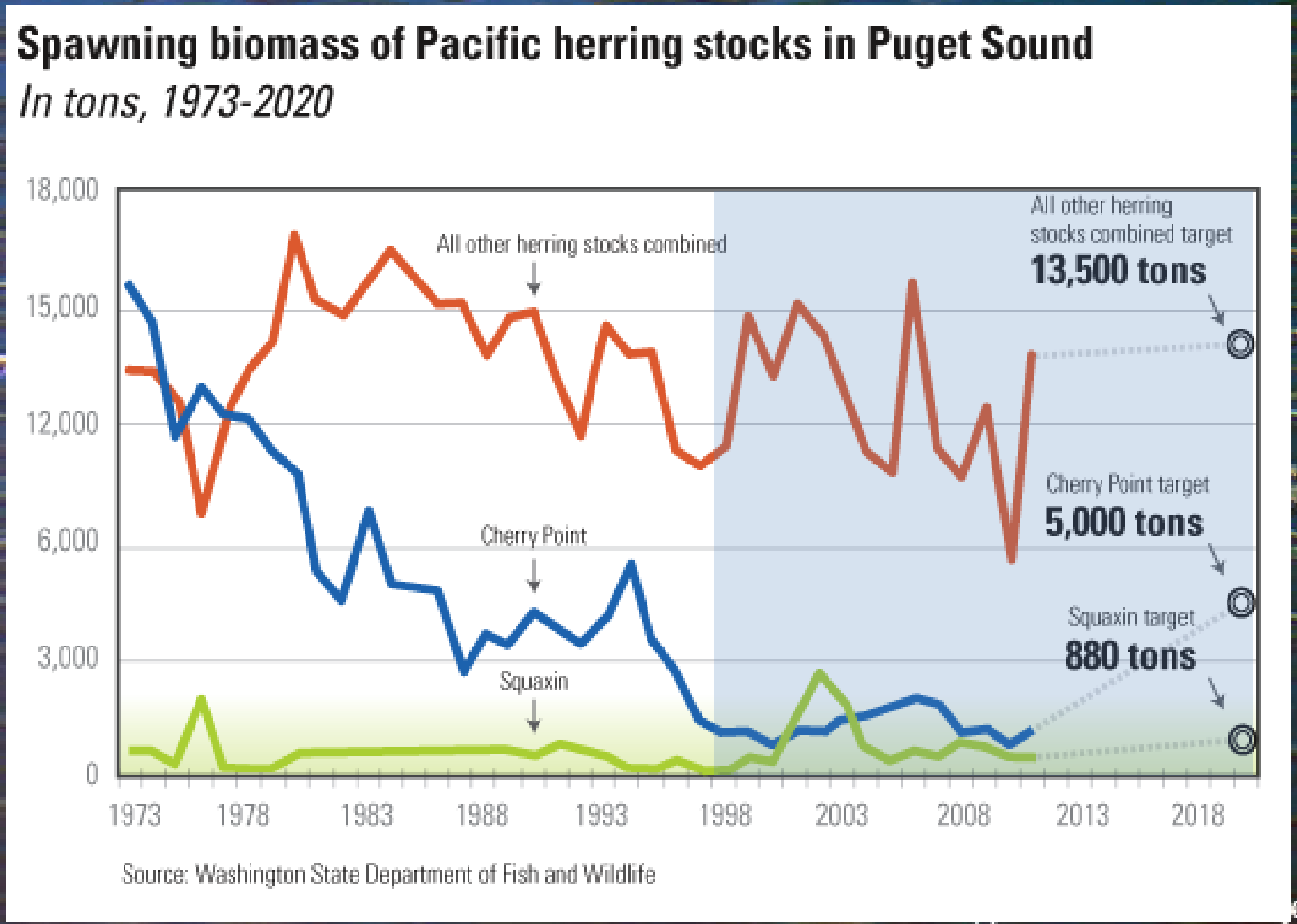


What are the implications of flagellate dominance for higher trophic levels?

- Higher number of trophic links (starving fish?)
- Poor nutritional quality (dinoflagellates *+jellyfish*)
- Available food spectrum for juvenile fish is different
- Toxins for invertebrates and juvenile fish

Declining herring stock in Puget Sound



Common assumptions for Puget Sound

1. Eutrophication at the surface and oxygen drawdown at depth are coupled.
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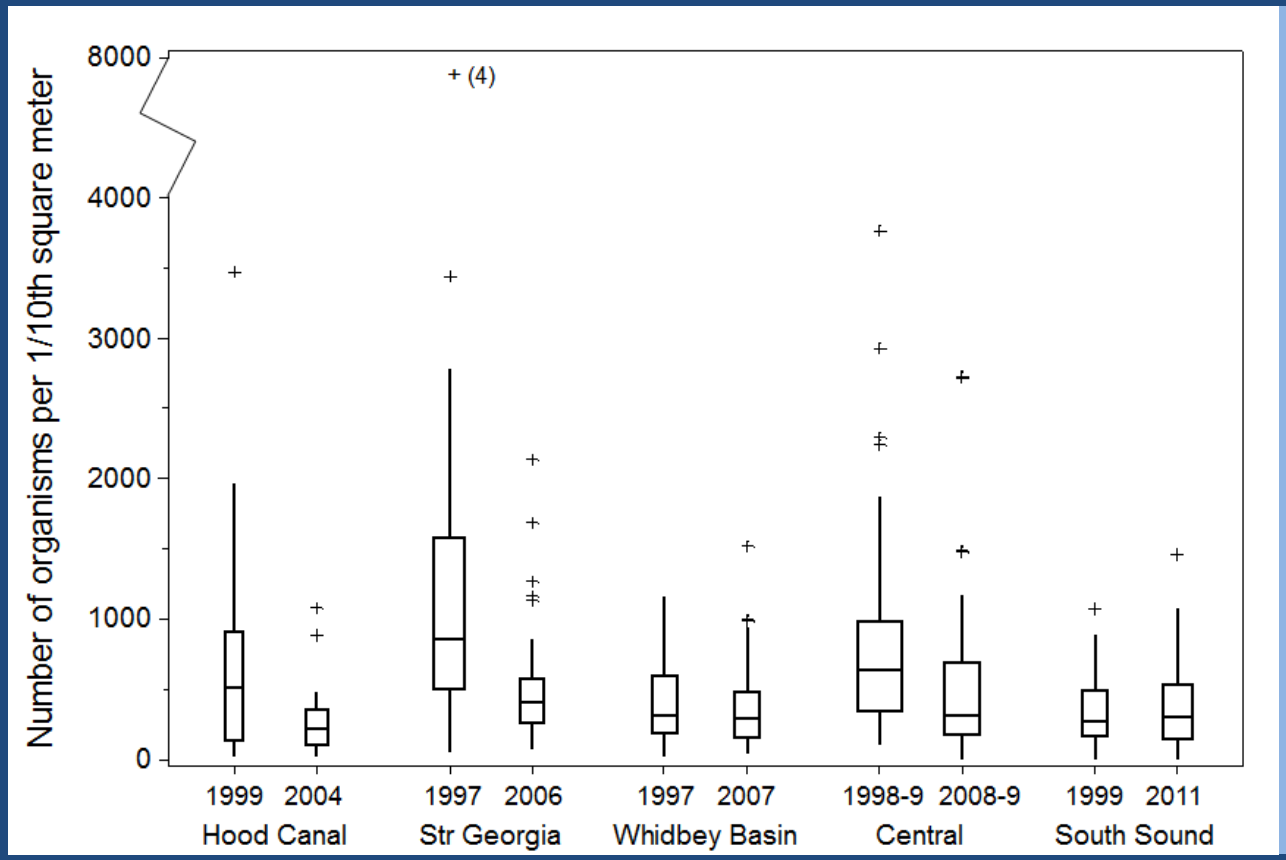
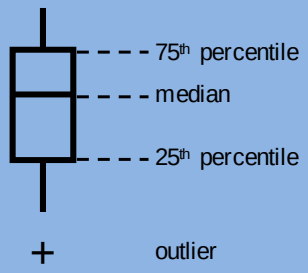
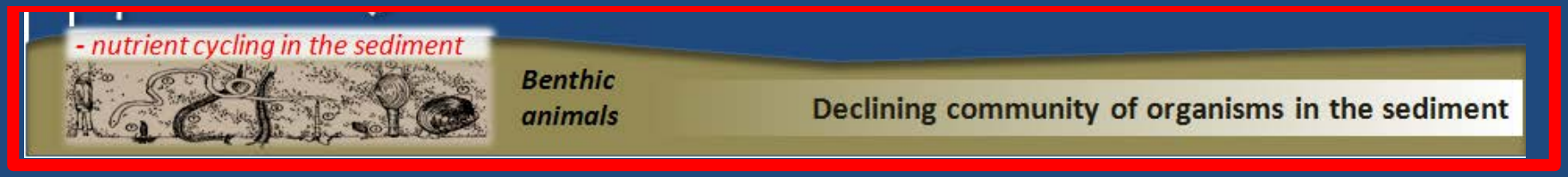
4. Nutrient additions promote the accumulation of excessive algal biomass.
5. The microbial food web and micro-zooplankton grazing (<200µm) are of lower importance.
6. **A decline in benthic species is a reflection of toxins.**

Decline in total benthic abundance by 45%
Decline in benthic taxa richness by 10%





The cause of the decline in benthic organisms **is not explained** by toxic chemicals



Summary

Assumptions

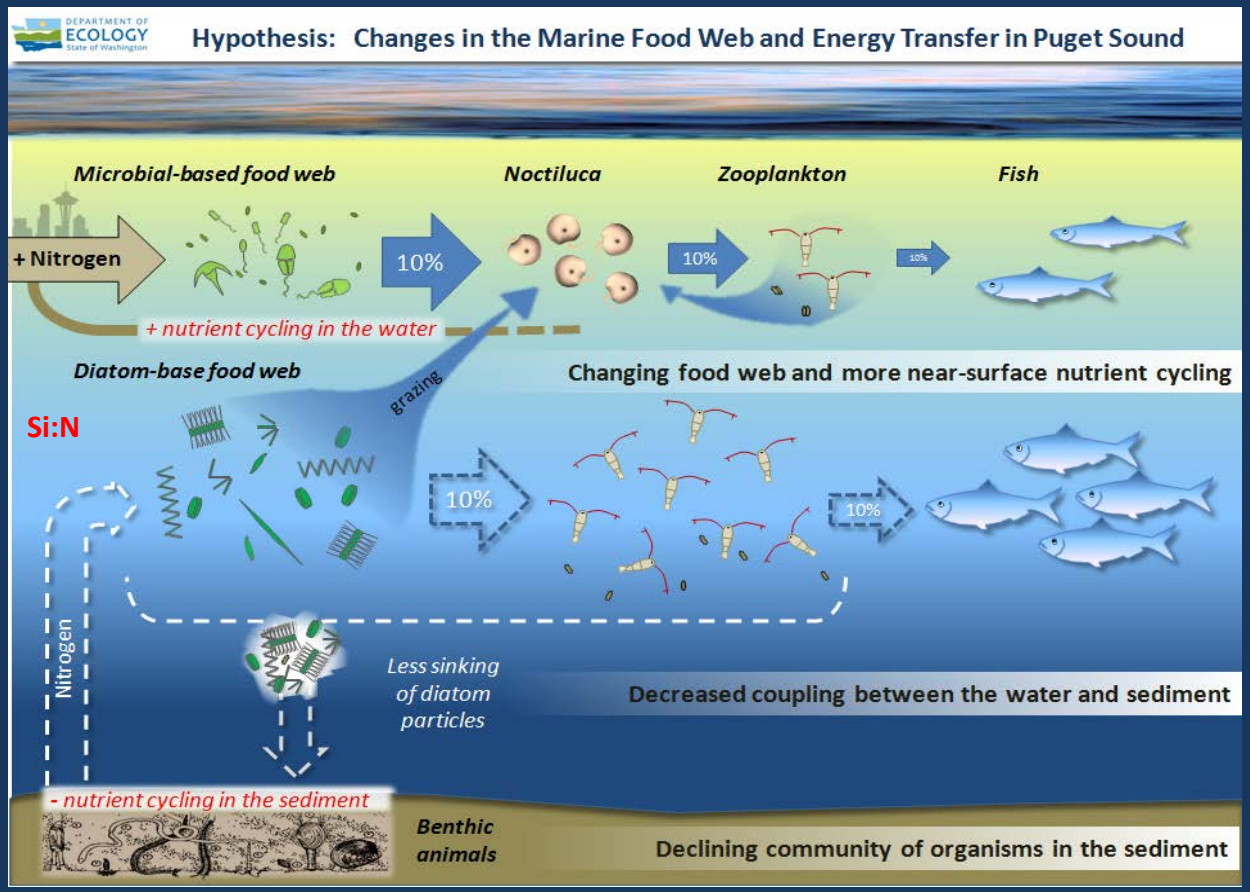
1. Eutrophication at the surface and oxygen drawdown at depth are **coupled.**
2. Puget sound is predominantly a **diatom-based** food web.
3. **Export of org. carbon** to depth is predictable by phytoplankton biomass.
4. Nutrient additions promote the **accumulation of algal biomass**.
5. The microbial food web and micro-zooplankton are **less important**.
6. A decline in benthic species is a reflection of toxins.

Our observations

1. Eutrophication at surface and dissolved oxygen at depth are **not statistically related**.
2. Frequent and **extensive flagellates** blooms at surface.
3. Increasing macro-nutrients, **shifting ratios** Si:N:P, and shifting **species slow the particle export**.
4. **Decline in sub-surface algal** biomass and increasing water clarity.
5. High abundance and **impact of micro-zooplankton** (Noctiluca)
6. Declining benthic invertebrate abundances not clearly linked to toxins.

Is benthic-pelagic coupling weakening?

Hypothesis for combining a series of recent observations



Noctiluca blooms as visible harbinger of the importance of microbial food web dynamics in eutrophied coastal waters.

Hypothesis:

Nitrogen additions to Puget Sound **change nutrient ratios Si:N:P** and encourage larger **energy transfer through the microbial food web**. This has consequences for phytoplankton species composition, food availability for higher tropic level, biogeochemical cycles, benthic-pelagic coupling and oxygen demand at depth.

Should we pay greater attention to
nutrient ratios,
energy transfer,
and material cycling?