Nutrient Dynamics and Their Interaction with Phytoplankton Growth (PP) in the Aquatic Areas of Coastal Wetland in Liaohe Delta, China

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Outline

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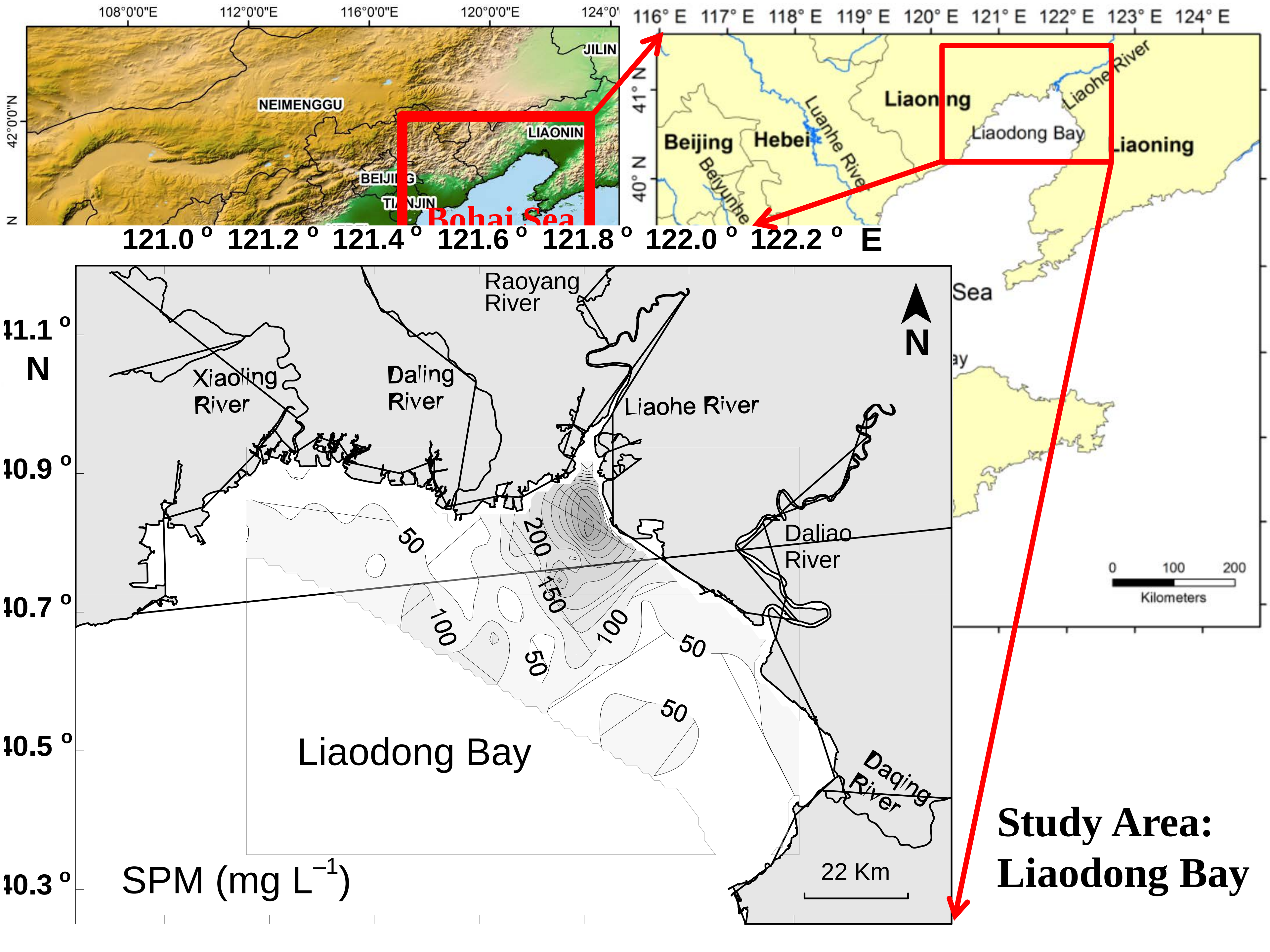
1. Study Area & Problems
2. Questions to study
3. How we do?
4. Results
5. What are the controlling factors?
6. Preliminary conclusions


NEIMENGGU
JILIN
LIAONIN
BEIJING
TIANJIN
Bohai Sea
Liaoning
Beijing
Hebei
Liaodong Bay
Liaohe River
Luanhe River
Beiyunhe
Sea
Kilometers
Raoyang River
Xiaoling River
Daling River
Liaohe River
Daliao River
Daqing River
Liaodong Bay
N
22 Km
SPM (mg L^{-1})
Study Area:
Liaodong Bay

Eutrophication in Liaodong Bay

- Coastal ecosystems are under **multiple-stressors** from both climate change and human activities

- Eutrophication: **nutrients** from industrial wastewater, sewage and agricultural fertilizer caused eutrophication in some coastal zones (incl. Liaodong bay)

- Seasonal hypoxia, HABs, species shift, Fish Kills, etc.

- Addressing the eutrophication problems requires **an informed assessment of the factors** that control algal production

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Questions to study

$$\Sigma PP = C_{surf} \times Z_{eu} \times P^{b}_{opt} \times DL \times F$$

(Behrenfeld & Falkowski, 1997, *L&O*)

Assimilation number (AN) = Ability of fixing carbon

Range: 2–14 gC gChl^{-1} h^{-1}, Max: 25

Photosynthetic rates derived from satellite-based chlorophyll concentration

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Oceanographic and Atmospheric Sciences Division, Brookhaven National Laboratory,
Upton, New York 11973-5000

AN frequently dominates the accuracy of PP estimation

Abstract

We assembled a dataset of ^{14}C-based productivity measurements to understand the critical variables required for accurate assessment of daily depth-integrated phytoplankton carbon fixation (PP_{eu}) from measurements of sea surface pigment concentrations (C_{sat}). From this dataset, we developed a light-dependent, depth-resolved model for carbon fixation (VGPM) that partitions environmental factors affecting primary production into those that influence the relative vertical distribution of primary production (P_z) and those that control the optimal assimilation efficiency of the productivity profile (P^B_{opt}). The VGPM accounted for 79% of the observed variability in P_z and 86% of the variability in PP_{eu} by using measured values of P^B_{opt}. Our results indicate that the accuracy of productivity algorithms in estimating PP_{eu} is dependent primarily upon the ability to accurately represent variability in P^B_{opt}. We developed

Questions to study

1. What is the exact AN of Phytoplankton? And PP?

1.3 叶绿素和初级生产力的计算

叶绿素 a 按照公式: $C_{Chl\text{-}a}=\frac{F_d(R_b-R_a)v}{V}$ 进行计算, 式中, $C_{Chl\text{-}a}$为叶绿素 a 的浓度(mg/m^3), F_d 为量程档的系数(mg/m^3), R_b 和 R_a 分别为酸化前后的荧光值, v 为提取液的体积(ml), V 为过滤海水的体积(ml)。

初级生产力采用叶绿素法, 按照Cadée 和 Hegeman (1974) 提出的简化公式: $P=\frac{P_sED}{2}$ 计算, 式中, P 为每日现场的初级生产力(mgC/m^2·d), P_s 为表层水中浮游植物的潜在生产力(mgC/m^2·h), E 为真光层的深度(m), D 为白昼时间的长短(h)。其中, 表层水(1 m 以内)中浮游植物的潜在生产力(P_s)根据表层水中叶绿素 a 的含量计算: $P_s=C_aQ$, 式中, C_a 为表层叶绿素 a 的含量(mg/m^3), Q 为同化系数(mgC/mg Chl-a · h)。真光层(E)的深度取透明度的 3 倍(Yukuya 1980)。同化系数(Q)采用 3.7(Ryther 1969)。

2. Ambiguity: what are the controlling factors for AN and PP?

Nutrients, Temperature, Light?

Especially, whether nutrients are over-enriched or limited for phytoplankton growth in this area

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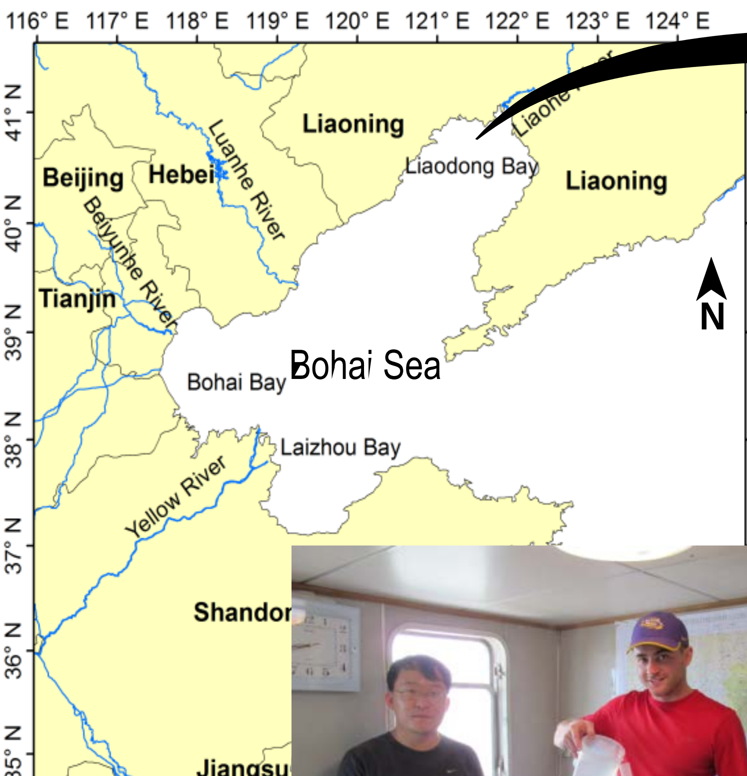
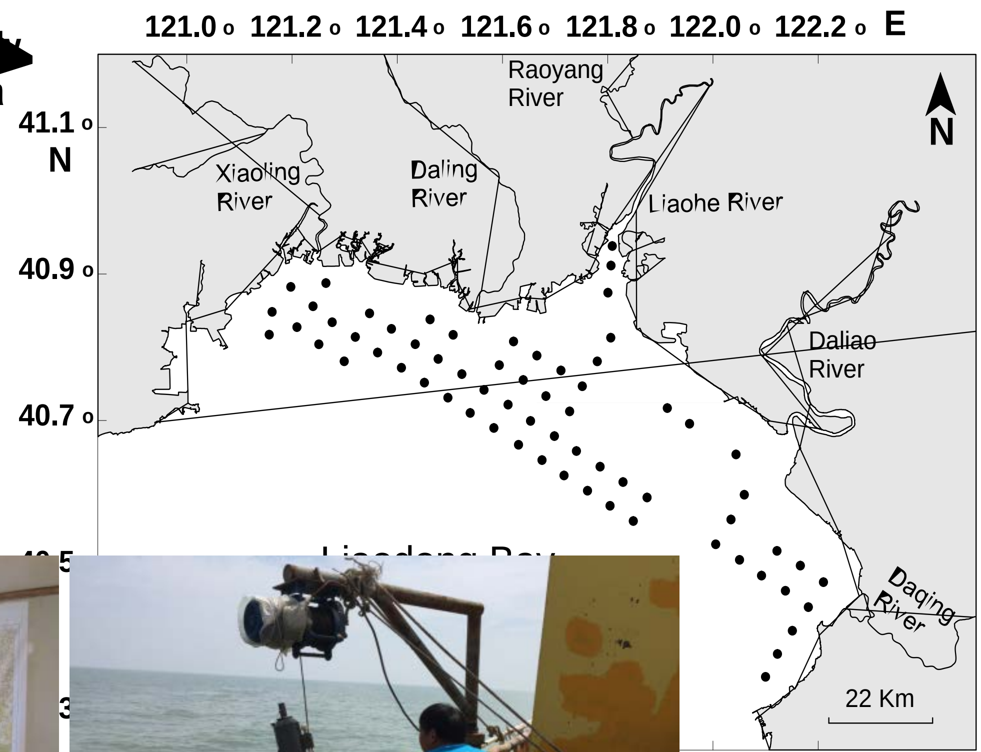
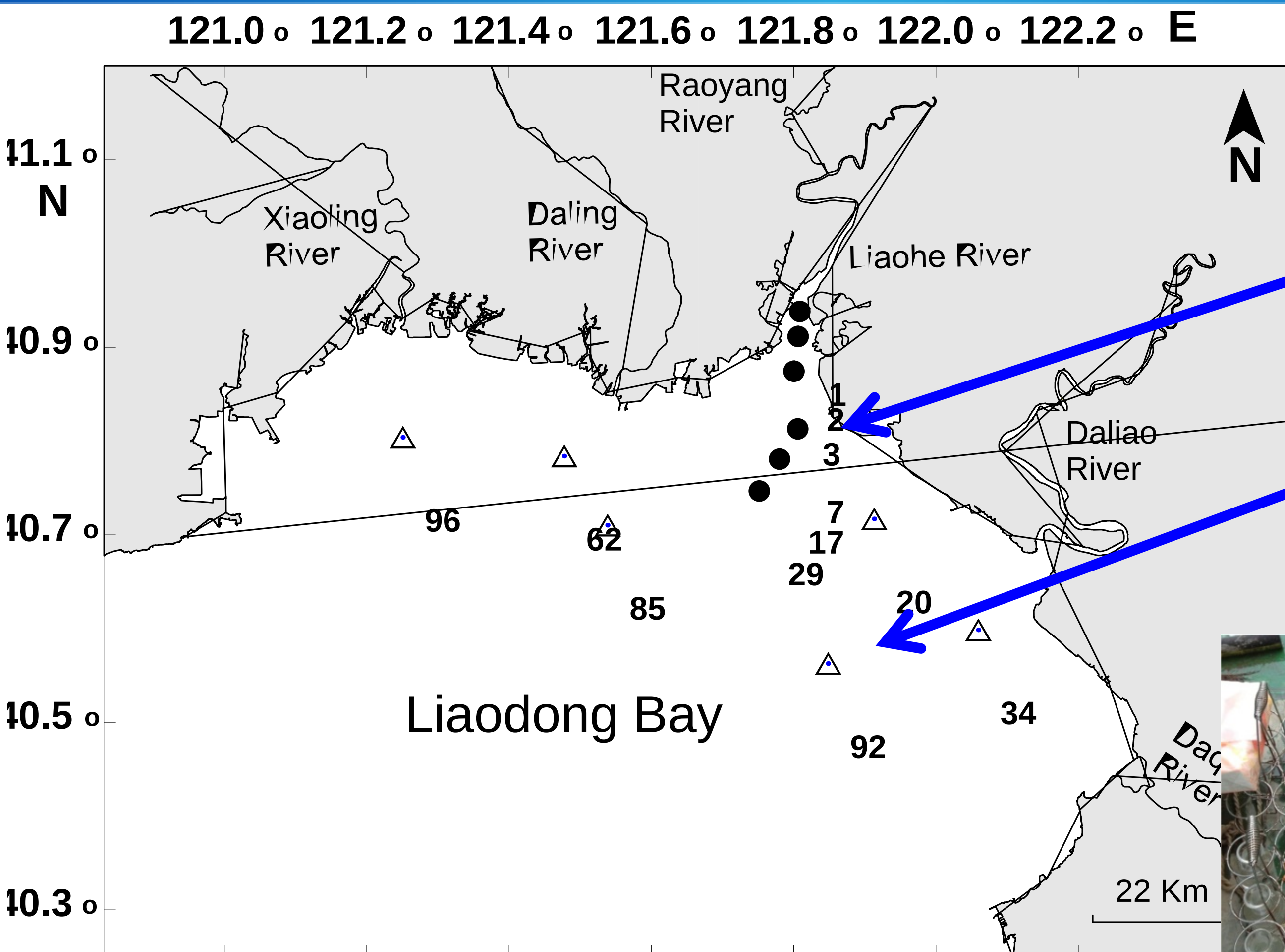
Field Investigation

- **66 sampling stations:** physical and chemical parameters: NO_3-N, NO_2-N, NH_4-N, PO_4-P, SiO_3-Si, S, T, Chl *a*, SPM, Secchi depths, DIC, etc.





In-situ ^{14}C incubations for AN and PP



Six Estuarine Sta.

Six Coastal Sta.

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Primary Productivity Calculation at 12 Stations

$$P_z = \frac{(A_{\mathrm{POC}} + A_{\mathrm{DOC}})_{light} - (A_{\mathrm{POC}} + A_{\mathrm{DOC}})_{dark}}{A_{\mathrm{TC}} \times T_{inc}} \times DIC \times 1.05$$

Peterson (1980), Vernet & Smith (2007)

- P_Z (g C m^{-3} h^{-1}) = photosynthetic rate at depth Z;
- A_{POC}, A_{DOC}, and A_{TC} (dpm) = radioactivities of POC, DOC, and TC, respectively;
- DIC = the concentration of DIC (g m^{-3}),
- T_{inc} = the duration of the incubation (h), and
- 1.05 corrects for isotope discrimination in favor of ^{12}C versus ^{14}C.
- $(A_{\mathrm{POC}}+A_{\mathrm{DOC}})_{light}$ and $(A_{\mathrm{POC}}+A_{\mathrm{DOC}})_{dark}$ = radioactivities of total organic carbon in the light bottle and dark bottle, respectively.

- Assume that the rate of photosynthesis is a hyperbolic function of irradiance:

$$P = \frac{P_M I}{K_I + I}$$

(Falkowski & Raven, 2007; Lalli & Parsons, 1997)

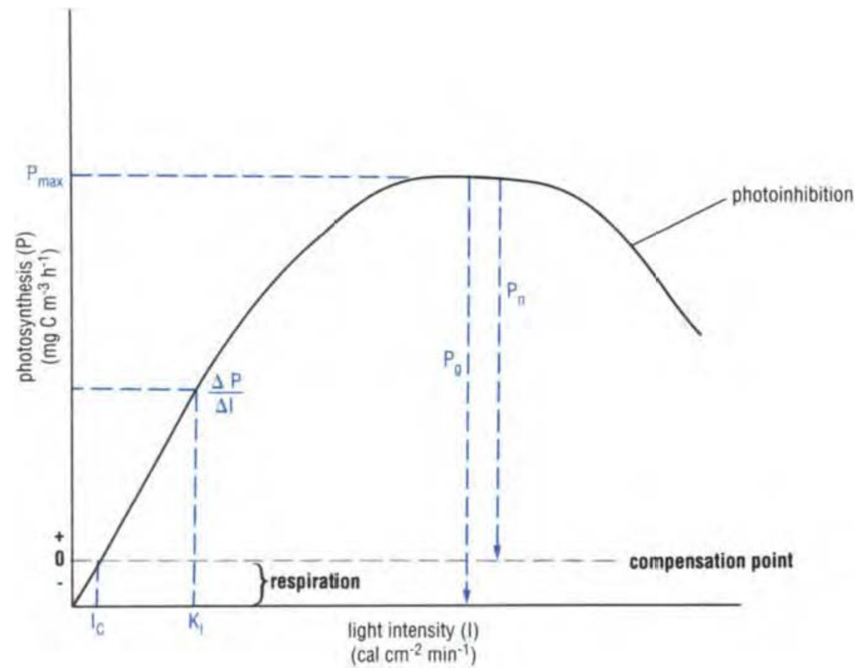
P (gC m^{-3} h^{-1}) = photosynthesis rate;

$\boldsymbol{P_M}$ (gC m^{-3} h^{-1}) = light-saturated P;

$\boldsymbol{P_M/Chl}$ (gC g^{-1} Chl h^{-1}) = **assimilation number (P^b_{opt})**;

I (mol quanta m^{-2} d^{-1}) = irradiance at a specific water depth;

$\boldsymbol{K_I}$ (mol quanta m^{-2} d^{-1}) = half-saturation constant;



- Assume that I decays exponentially in the water column with depth Z (m):

$$I = I_0 e^{-(K + K_{Chl} Chl)Z}$$

I_0 (mol quanta m^{-2} d^{-1}) = Photosynthetically Active Radiation (PAR) in surface water,

K (m^{-1}) = **extinction coefficient** due to everything other than chlorophyll, and

K_{Chl} (m^2 g^{-1} Chl *a*) = the **chlorophyll-specific extinction coefficient**.

- Assume that virtually all the light is absorbed in the water column, so that for practical purposes the depth of integration for calculating the areal photosynthetic rate can be assumed to be infinity. Then the **areal photosynthetic rate (*P_D***, in gC m^{-2} h^{-1}) is:

$$P_D = \int_0^{\infty} \frac{P_M I}{K_I + I} dz = \frac{P_M}{K + K_{Chl} Chl} \ln(1 + I_0 / K_I)$$

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Results of AN (P^b_{opt}) & P_D

Area	I_0	P^b_{opt} gC gChl^{-1} h^{-1}	P_D mg C m^{-2} d^{-1}	Surface Chl *a* mg m^{-3}	Areal Chl *a* mg m^{-2}
Bay: (Coastal)	29.15	**9.13±2.17**	**475.99**	6.35±3.36	14.45±14.87
Bay: (Estuarine)	29.15	**3.14±0.81**	**19.47**	4.80±3.56	0.96±0.71
Louisiana Coast	26.47	6.6±0.3	1050	3.0±1.4	47.6±4.5
BATS	29.52	5.16	462.04	0.11±0.09	21±10
HOT (Sta. ALOHA)	34.49	6.88	530	0.088±0.013	23.0±2.2
Peru Coast	33.32	3.9−4.7	3580	2.55	111

- Significant difference in P^b_{opt} and P_D between coastal and estuarine stations;
- P^b_{opt} and P_D in coastal zone is much higher than estuary;
- **What are the controlling factors for the differences in P^b_{opt}, P_D & biomass?**

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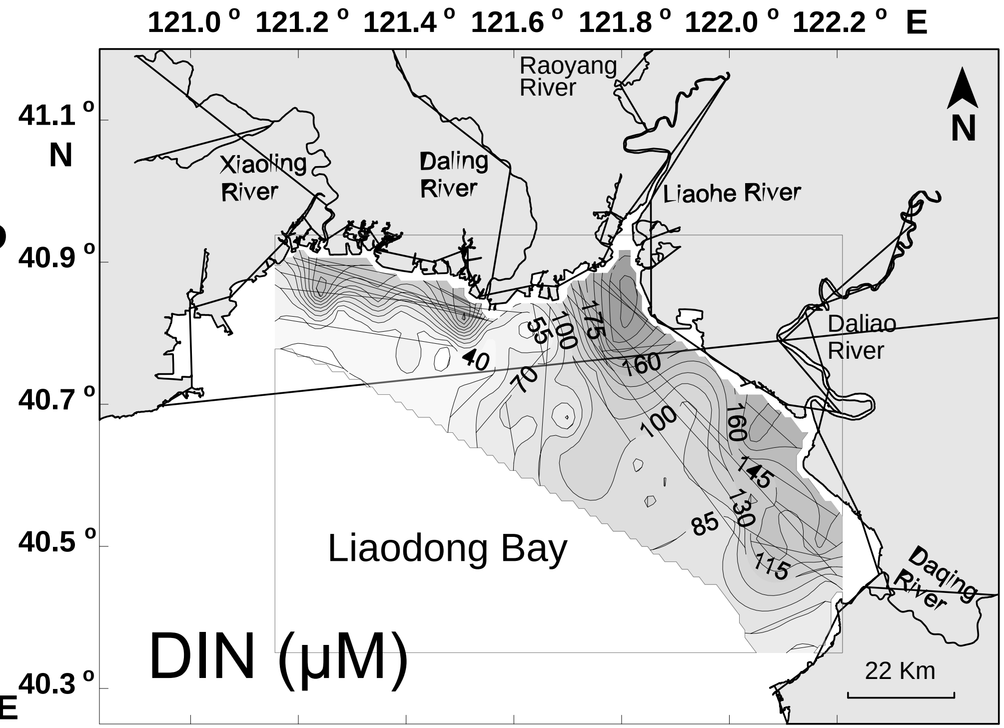
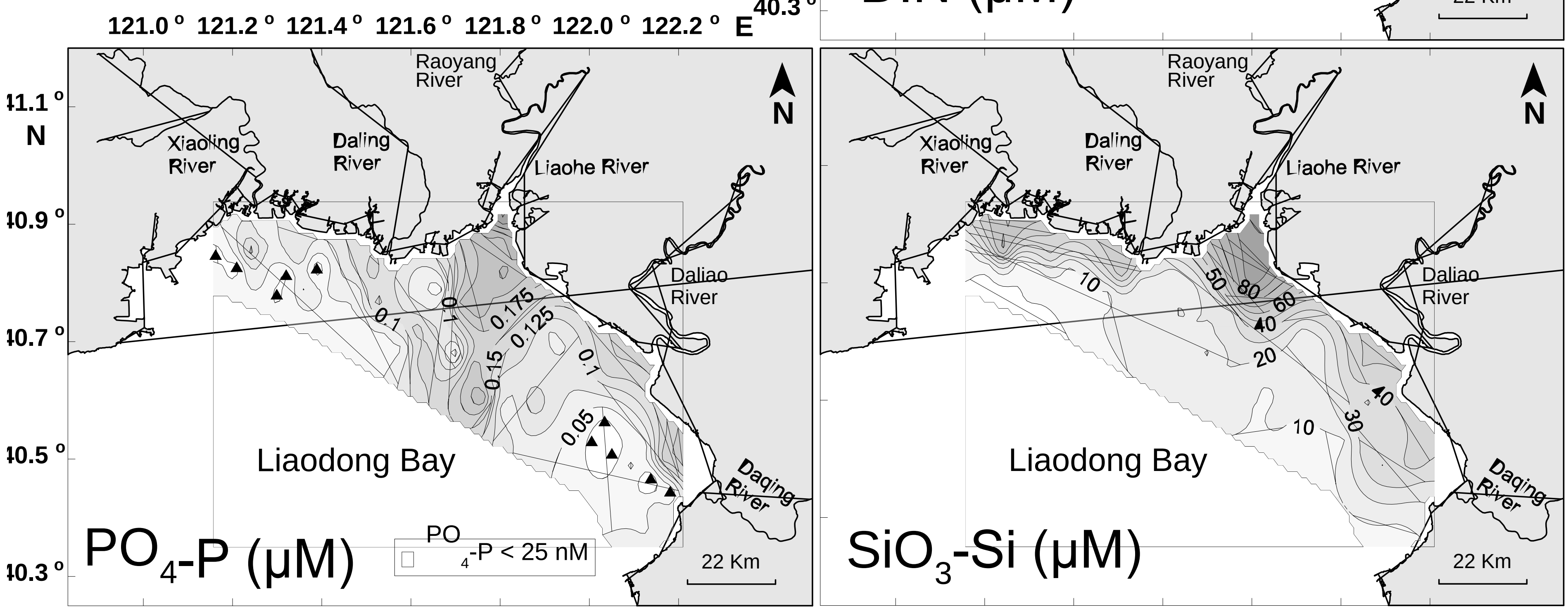
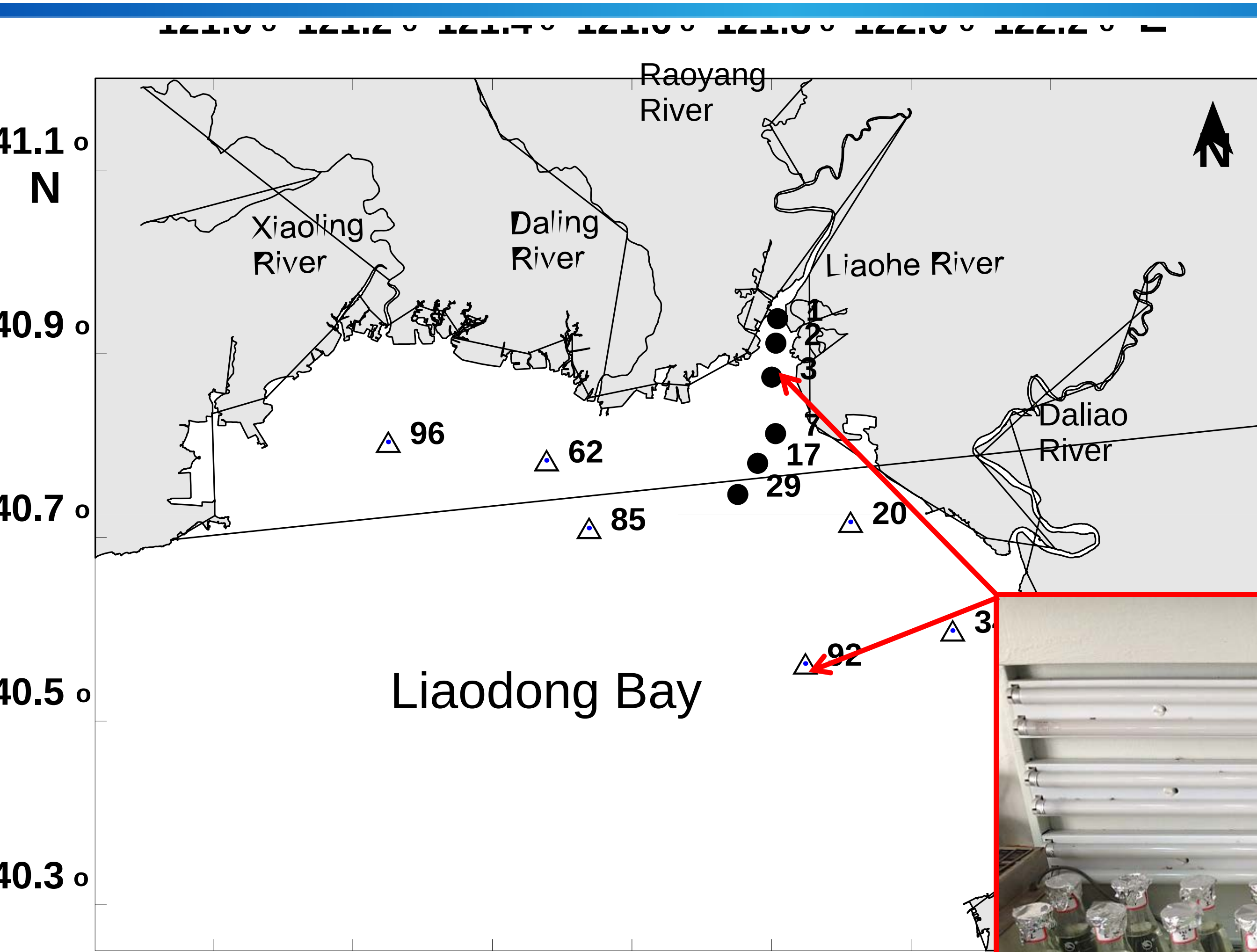
Whether nutrients are over-enriched or limited for phytoplankton growth?

- **DIN > 15 μM**
- **Si > 2 μM**
- **P: Only 11 sites were < 30 nM, and 3 sites were < 11 nM**





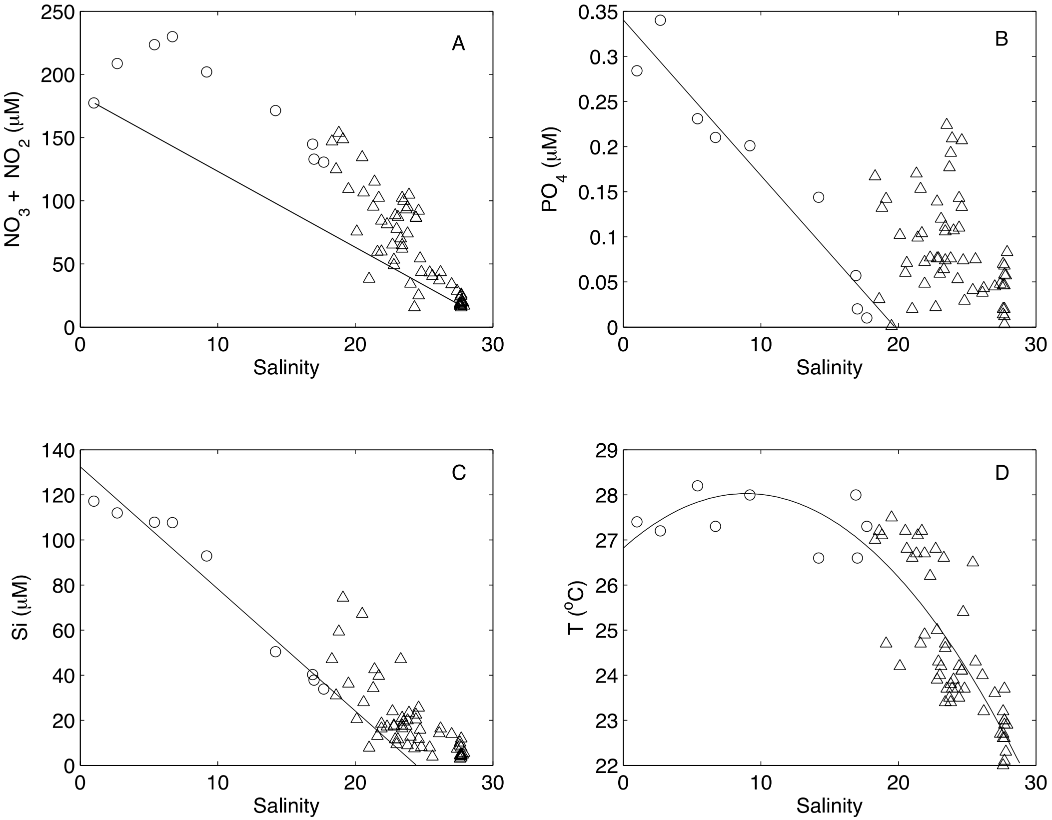
Nutrient Enrichment Experiments



- N, P, Si
- Low N:P
- High N:P

No significant difference between nutrient-enriched cultures and control cultures was found.

Whether nutrients are limiting factor?



Relationships between S and concentrations of $NO_2 + NO_3$, P, and Si, and between S and T at the 66 stations in Liaodong Bay

Preliminary conclusions:

Nutrients are replete, probably not the key limiting factor for algal growth

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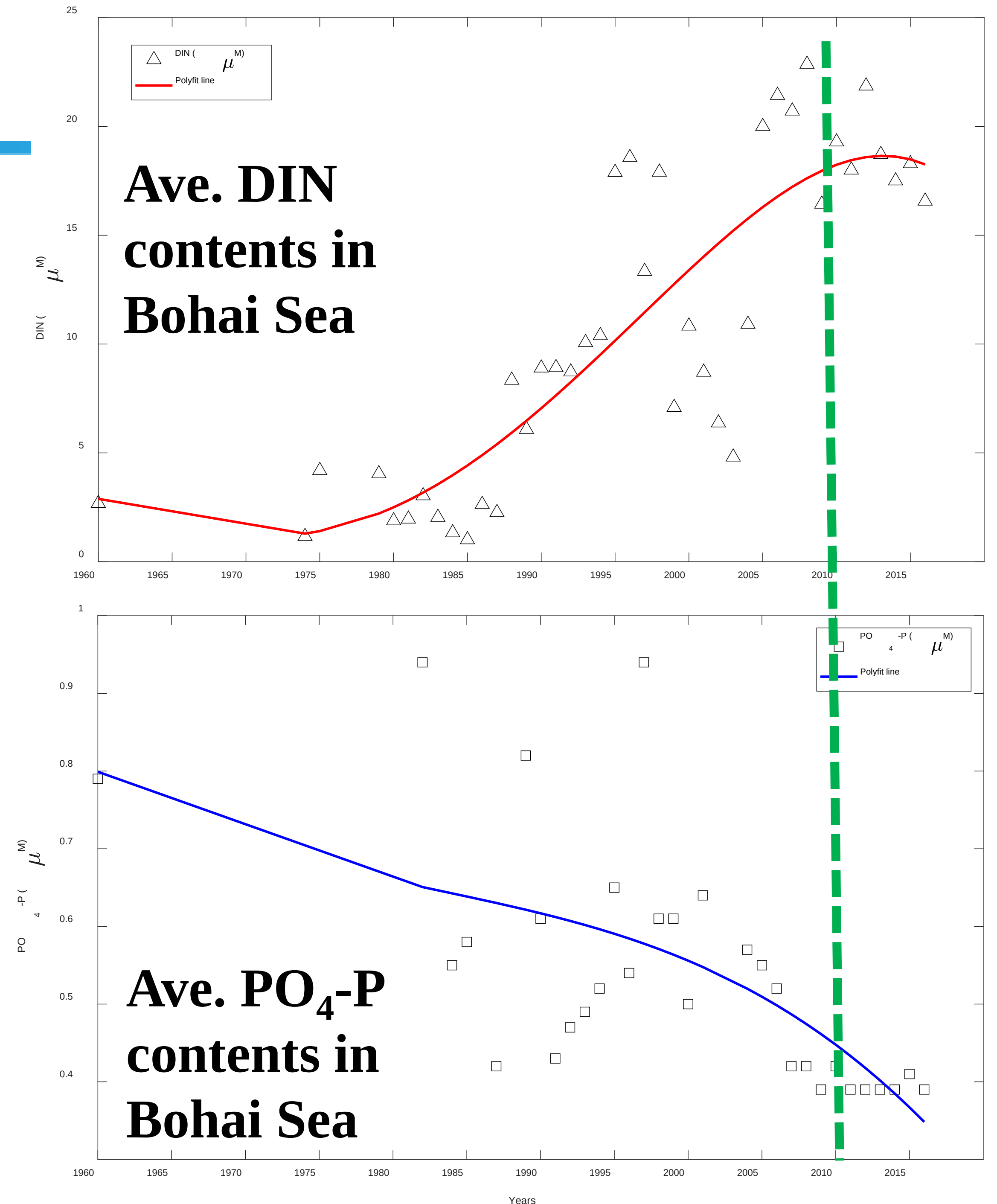
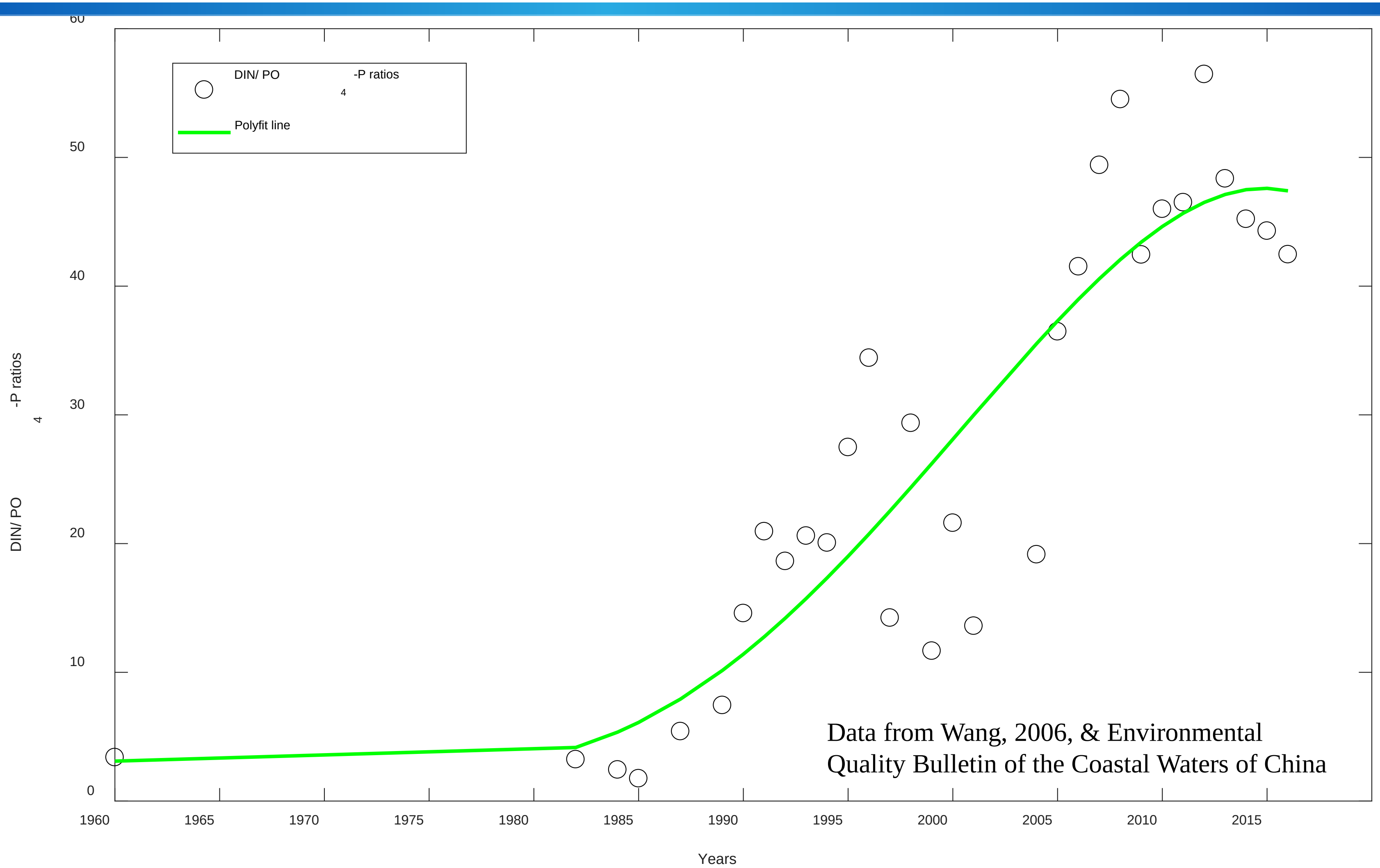
Nutrient Pollutions

- Reason: Liaodong Bay receives **excessive nutrients** discharged from several large rivers surrounding it;



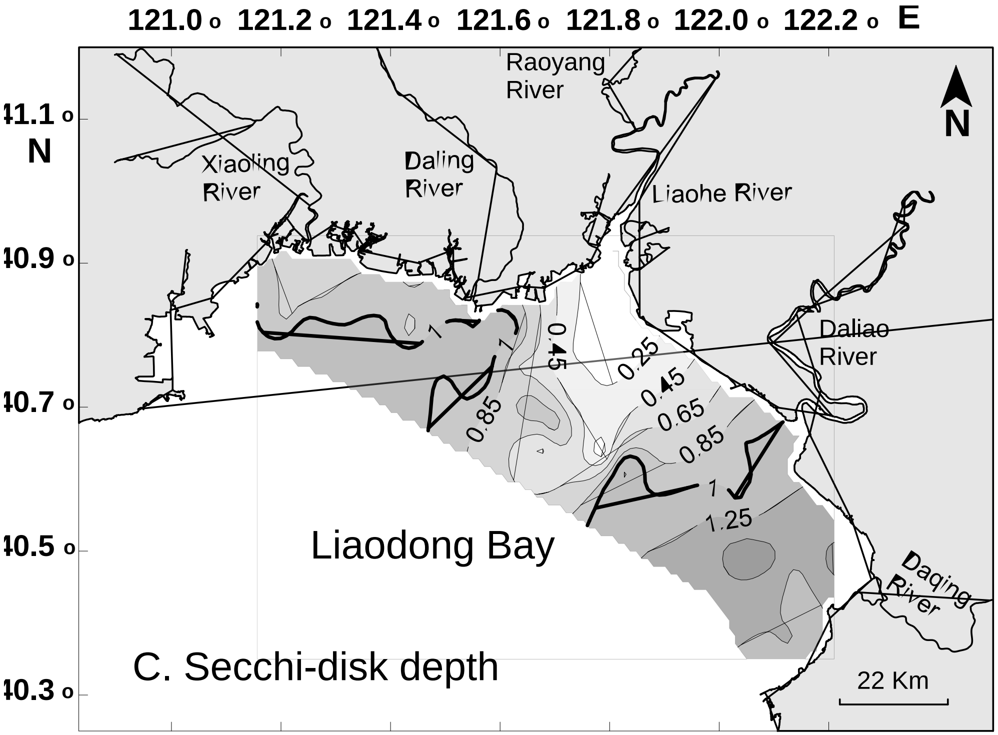
Data from Wang, 2006, & Environmental Quality Bulletin of the Coastal Waters of China

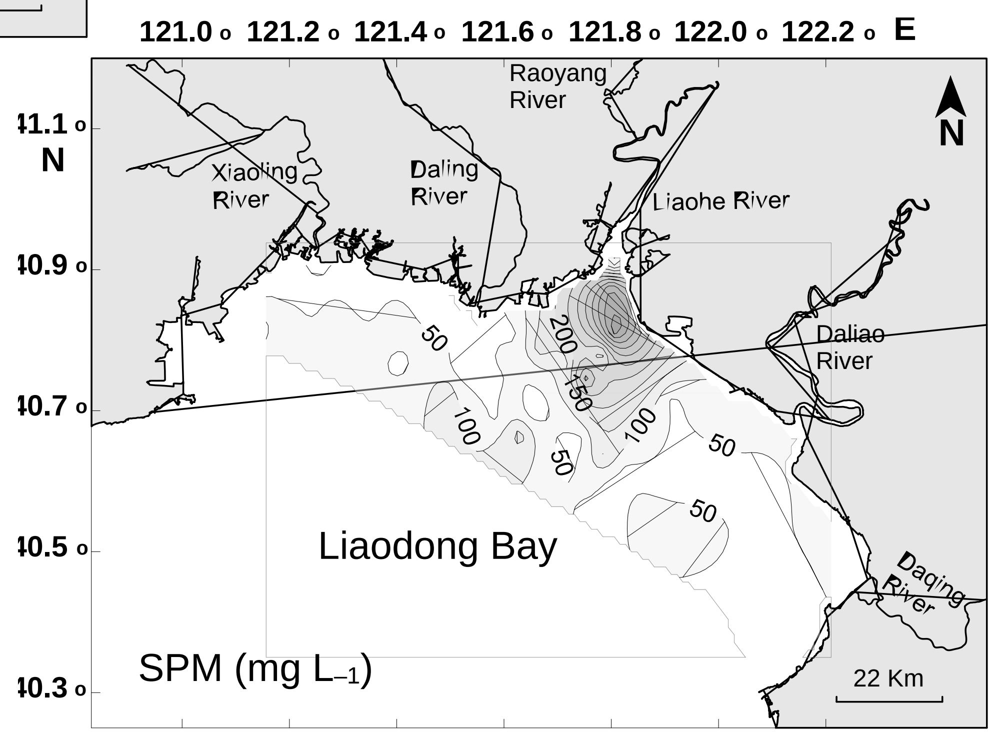
Nutrient Pollutions in Liaodong Bay



More studies are required about its effects in the future … …

Light condition & SPM





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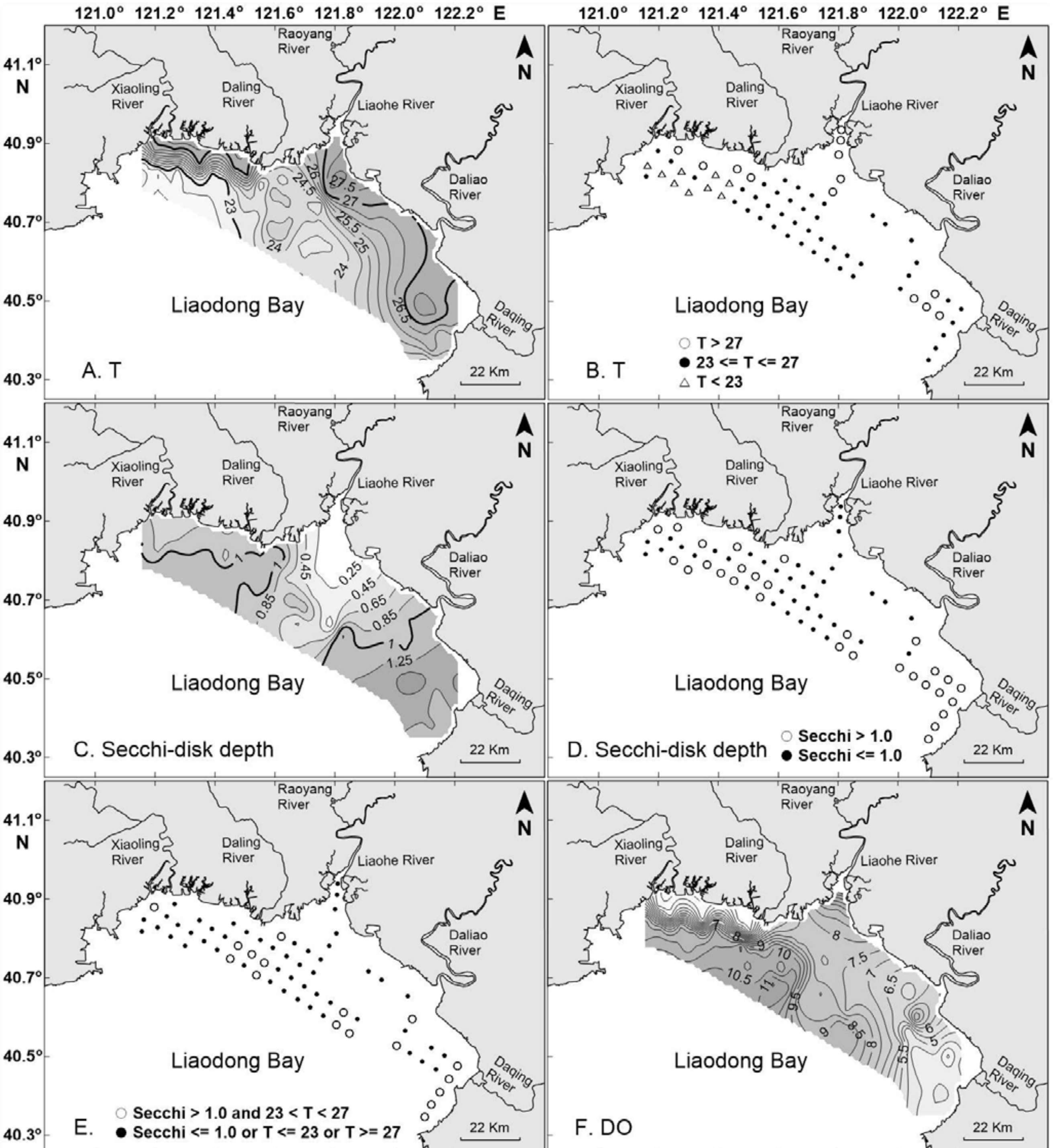

121.0° 121.2° 121.4° 121.6° 121.8° 122.0° 122.2° E
41.1° N
40.9°
40.7°
40.5°
40.3°
Raoyang River
Xiaoling River
Daling River
Liaohe River
Daliao River
Daqing River
Liaodong Bay
N
22 Km
A. T
B. T
T > 27
23 <= T <= 27
T < 23
C. Secchi-disk depth
D. Secchi-disk depth
Secchi > 1.0
Secchi <= 1.0
E.
Secchi > 1.0 and 23 < T < 27
Secchi <= 1.0 or T <= 23 or T >= 27
F. DO

L (=Light absorption)

- The **rate** of absorption of light by phytoplankton as a function of depth is:

$$K_{Chl}Chl \cdot I = K_{Chl}Chl \cdot I_0 e^{-(K+K_{Chl}Chl)Z}$$

- The **amount** of light absorbed by phytoplankton (*L*, in mol quanta m^{-2} d^{-1}) in the water column is therefore:

$$L = \int_0^{\infty} K_{Chl}Chl \cdot I_0 e^{-(K+K_{Chl}Chl)Z} = \frac{K_{Chl}Chl \cdot I_0}{K + K_{Chl}Chl}$$

F & *R*

- The **fraction** of light absorbed by the phytoplankton in the water column (in %) can be calculated to be:

$$F = \frac{L}{I_0} = \frac{K_{Chl}Chl}{K + K_{Chl}Chl}$$

- The ratio of light absorbed to photosynthesis (***R* = *Photons/C***, in mol quanta mol^{-1} C) can be calculated by dividing L by P_D:

$$R = \frac{L}{P_D} = \frac{K_{Chl}Chl \cdot I_0}{P_M \ln(1 + I_0 / K_I)} = \frac{K_{Chl} \cdot I_0}{P^b_{opt} \ln(1 + I_0 / K_I)}$$

Results of *F* & *R* (=Photons/C)

Area	P^b_{opt} gC gChl^{-1} h^{-1}	P_D mg C m^{-2} d^{-1}	Surface Chl *a* mg m^{-3}	Areal Chl *a* mg m^{-2}	*F*	*R*
Bay: Coastal	**9.13±2.17**	**475.99**	6.35	14.45	**4.4%**	**13.6**
Bay: Estuarine	**3.14±0.81**	**19.47**	4.80	0.96	**0.29%**	**37.3**
Louisiana Coast	6.6±0.3	1050	3.0	47.6	10.8%	**??**
BATS	5.16	462.04	0.11	21	6.4%	**??**
HOT	6.88	530	0.088	23.0	4.3%	**??**
Peru Coast	3.9−4.7	3580	2.55	111	34%	**??**

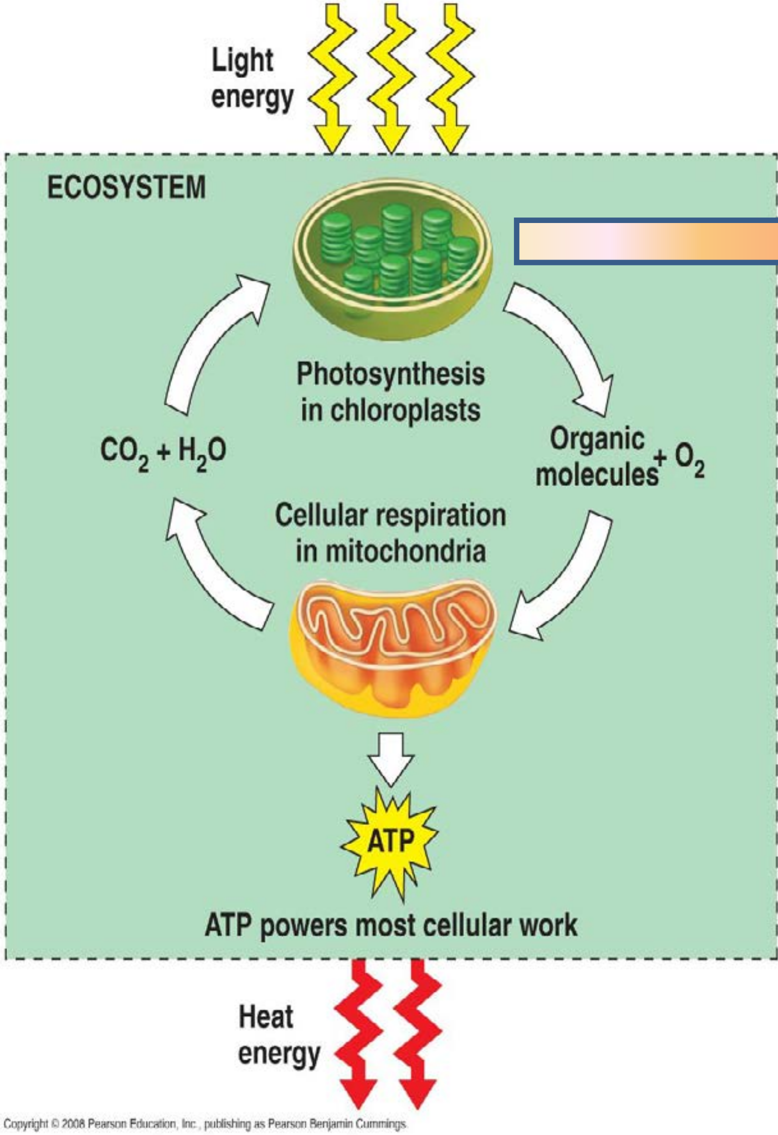
***F*: Phytoplankton at coastal stations absorbed more light energy, because most of light energy at estuarine stations was scattered;**

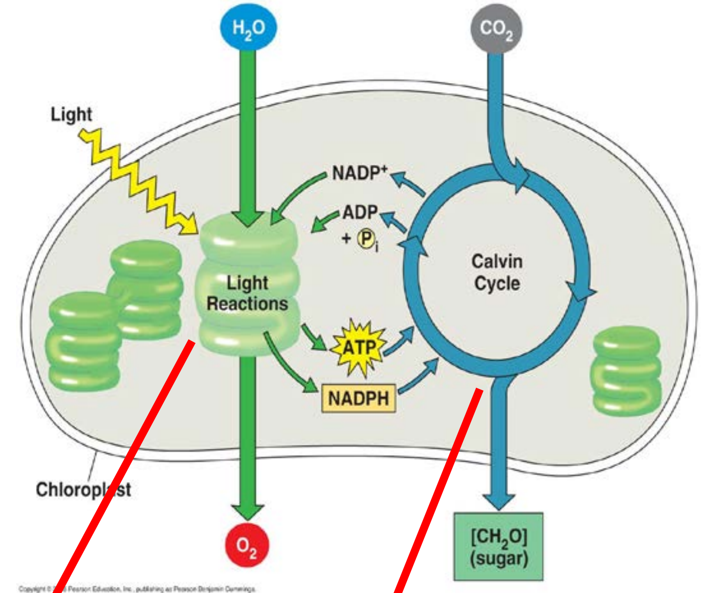
***R*: Why are the *R* ratios at coastal stations lower than estuarine stations?**

① **What is the minimum quantum requirement for fixing one carbon?**

② **What about the *R* ratios compared with Louisiana Coast, open ocean, HOT, BATs? What does that mean?**

Photosynthesis



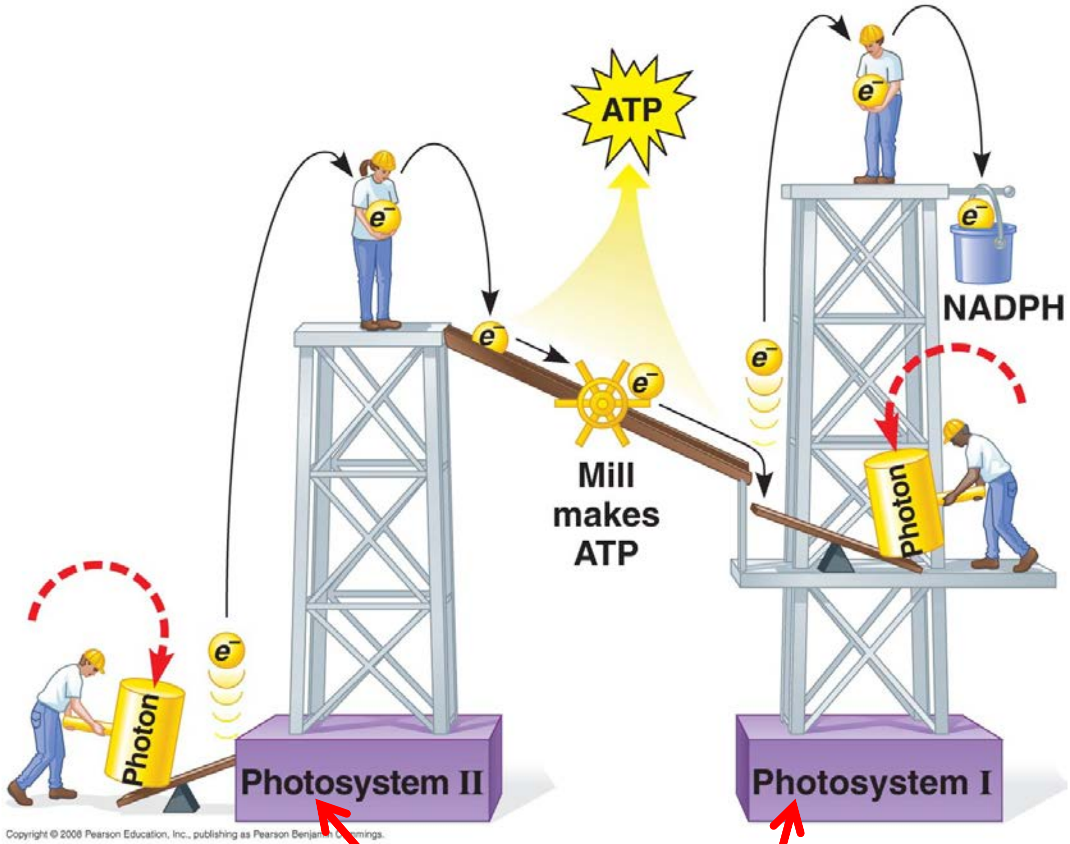


Light reactions:

$2H_2O + 2NADP^+ + 3ADP + 3Pi +$ **light** $\rightarrow 2NADPH + 2H^+ + 3ATP + O_2$

Dark reactions:

$3CO_2 + 9ATP + 6NADPH + 6H^+ \rightarrow C_3H_6O_3\text{-phosphate} + 9ADP + 8Pi + 6NADP^+ + 3H_2O$



What is the minimum quantum requirement for fixing one carbon?

A summary reaction for photosynthesis:

48 Photons (24@680 & 24@700) + 12 H_2O + 6 CO_2 + 30 ADP + 30 P_i

$\rightarrow$ 6 O_2 + 30 ATP + 36 H_2O + $C_6H_{12}O_6$

Thus, the overall photosynthetic process can be represented by

$$CO_2 + 2H_2O \xrightarrow{\sim 8h\nu} (CH_2O) + H_2O + O_2$$

Light Energy Used to Fix Carbon

Minimum requirement for fixation of one carbon is **8 quanta**. However, for a number of reasons, that limit is very unlikely to be reached.

Energy received by PSII can be:

1. Used to fix carbon
2. Dissipated as heat
3. Fluoresced

Results of *F* & *R*

Area	P^b_{opt} gC gChl^{-1} h^{-1}	P_D mg C m^{-2} d^{-1}	Surface Chl *a* mg m^{-3}	Areal Chl *a* mg m^{-2}	*F*	*R*
Bay: Coastal	**9.13±2.17**	**475.99**	6.35	14.45	**4.4%**	**13.6**
Bay: Estuarine	**3.14±0.81**	**19.47**	4.80	0.96	**0.29%**	**37.3**
Louisiana Coast	6.6±0.3	1050	3.0	47.6	10.8%	**32.67**
BATS	5.16	462.04	0.11	21	6.4%	**49.07**
HOT	6.88	530	0.088	23.0	4.3%	**33.59**
Peru Coast	3.9−4.7	3580	2.55	111	34%	**37.98**

- **Coastal:** Relatively high P^b_{opt} values and low *R* ratios suggest the highly efficient usage of absorbed light by phytoplankton under replete nutrient levels and favorable temperatures;
- **Estuarine:** Low P^b_{opt} values and high *R* ratios suggest rather extreme light limitation and lowly efficient usage of absorbed light in photosynthesis;
- **More or less nutrient or light limitation in other areas, especially, open sea**

Effect of Temperature

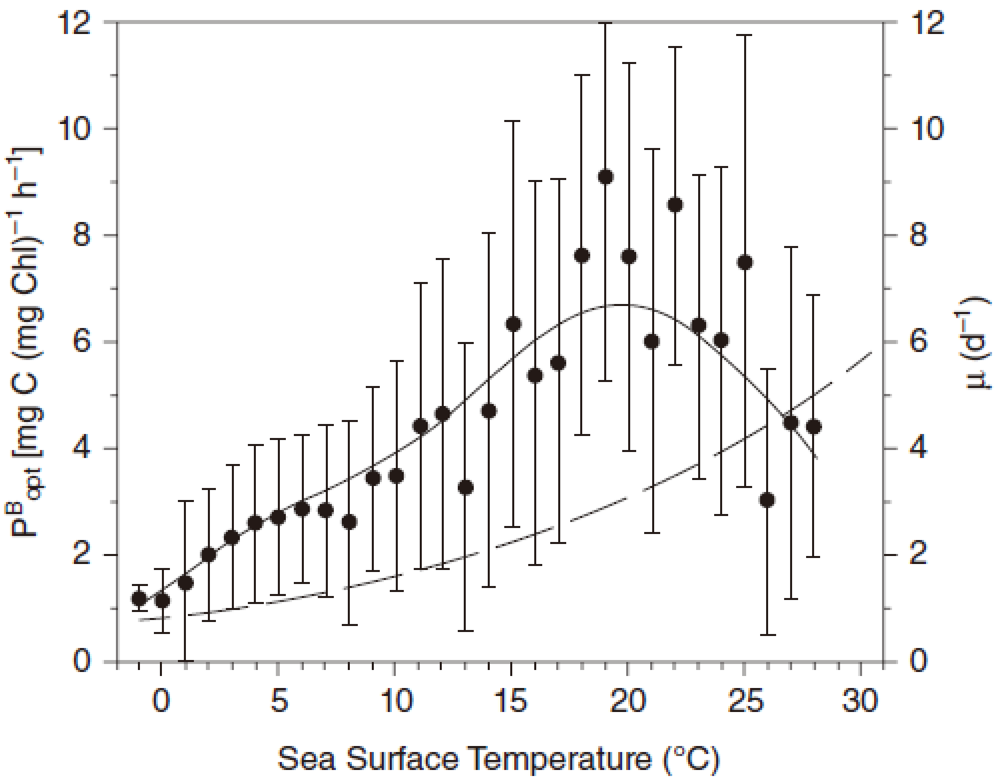
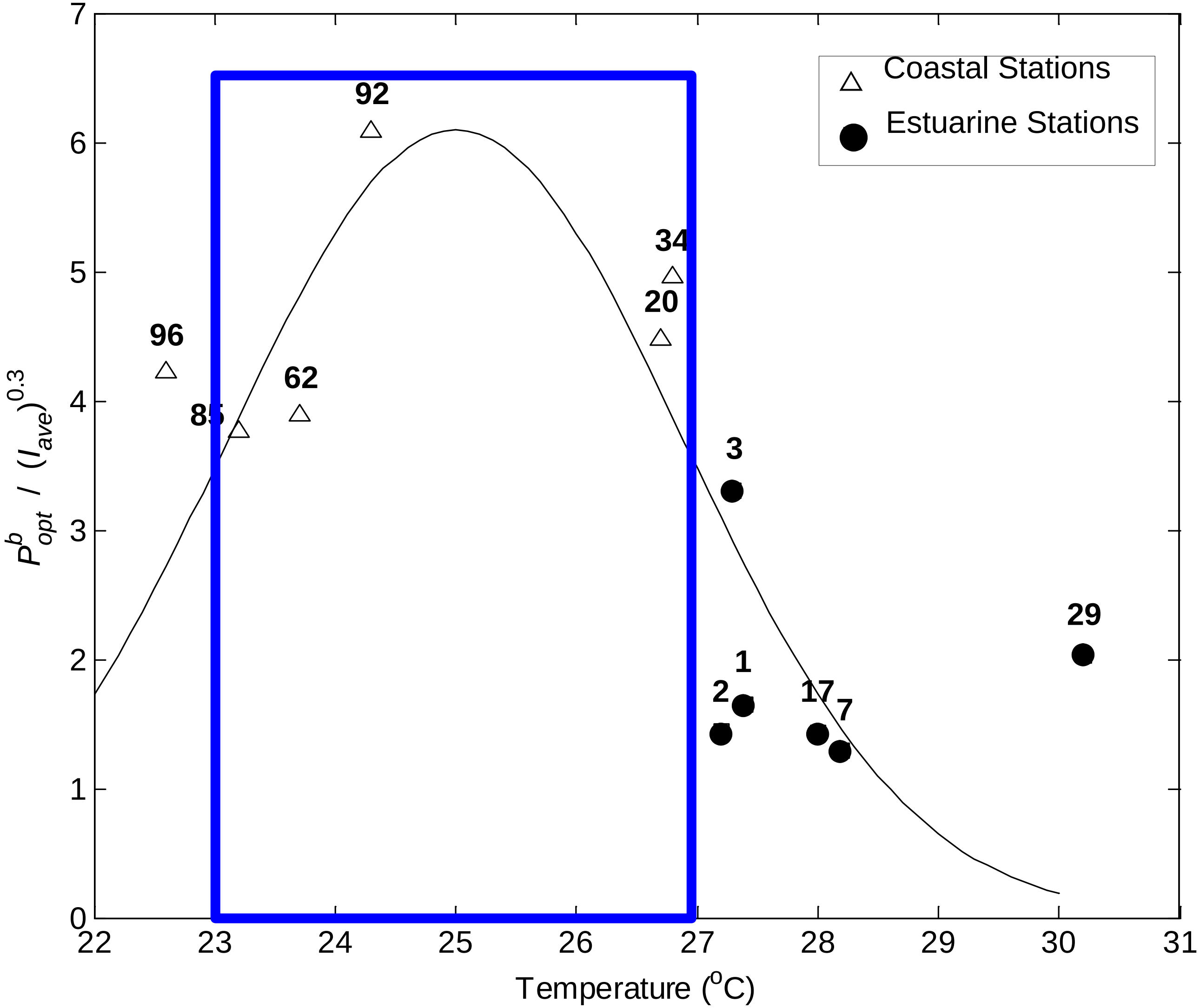


Fig. 3.10 Measured (•; ± SD) and modeled median value (solid curve) of the photoadaptive parameter, P^B_{opt}, as a function of sea-surface temperature. Dashed curve indicates the theoretical maximum specific growth rate (μ; d^{-1}) of phytoplankton described by Eppley (1972), which is used in a variety of productivity models. (After Behrenfeld & Falkowski 1997a.)

(Miller & Wheeler, 2012)

Falkowski and Raven [1997] reported that increasing temperatures can stimulate photosynthesis through a direct effect on Calvin cycle enzymatic activity up to an optimal temperature after which rates in photosynthesis can decline due to inactivation and denaturation of enzymes [Raven and Geider, 1988].

Light-conditioned P^b_{opt} vs Temperature



Coastal: 9.13±2.17

Estuarine: 3.14±0.81

Maximum: 12.48

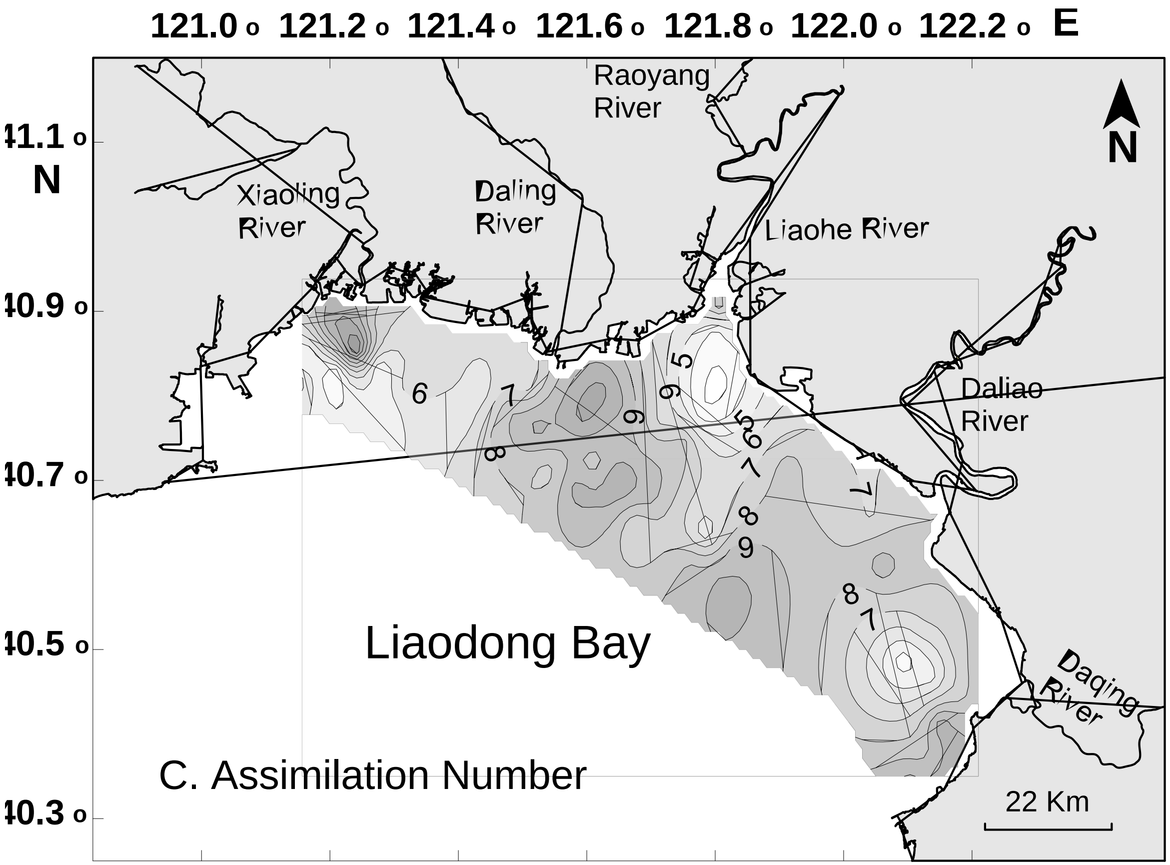
$$\frac{P^b_{opt}}{(I_{ave})^{0.3}} = Ae^{(BT - CT^2)}$$

$R^2 = 0.60$

$p = 0.003$

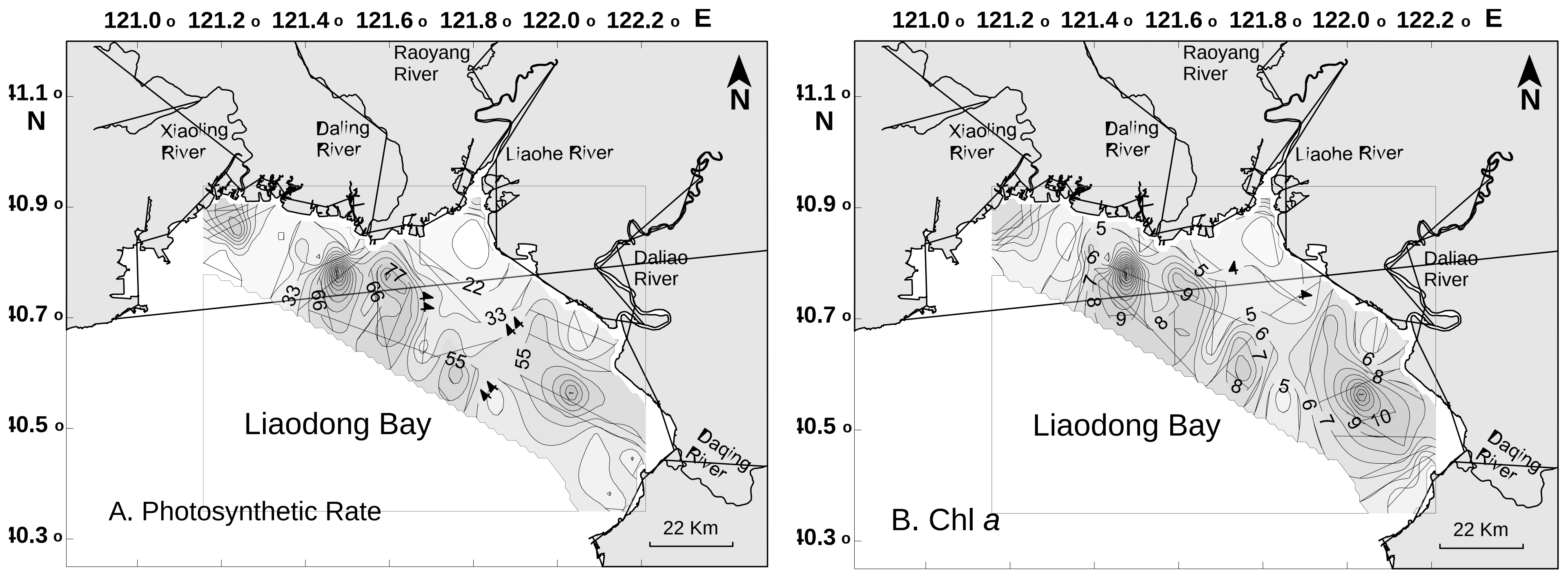
Patchiness of phytoplankton & PP

$$\frac{P^b_{opt}}{(I_{ave})^{0.3}} = \mathrm{A}e^{(\mathrm{B}T\text{-}\mathrm{C}T^2)}$$



Mean AN: 7.63 ± 2.42
Median AN: 7.74

(g C g^{-1} Chl *a* h^{-1})



- **Two large patches** of high biomass and production with dimensions on the order of 10 km reflect the effects of water temperature and variation of light penetration restricted by water turbidity.

Shaofeng Pei, et al. (2017). "**Patchiness of phytoplankton and primary production in Liaodong Bay, China**." *PLoS ONE* **12**(2): e0173067.

Shaofeng Pei, et al. (2018). “**Study on chemical hydrography, chlorophyll-*a* and primary productivity in Liaodong Bay, China**.” *Estuarine, Coastal and Shelf Science*.

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Preliminary Conclusions

- **Areal production in Liaodong Bay appears to be controlled by a combination of temperature and light, probably not nutrients.**
- **Two large patches** of high biomass and production with dimensions on the order of 10 km reflect the effects of water temperature and variation of light penetration restricted by water turbidity.
- **Light-conditioned P^b_{opt} values were modeled as a function of the temperature with a satisfactory fit to our field data** (R^2 = 0.60, p = 0.003).
- **The ratios of light absorbed to photosynthesis can help us estimate/understand the efficiency of usage of absorbed light by phytoplankton under various environments**

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Thanks.