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

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

Bohai Sea

121.0 121.2 121.4 121.6 121.8 122.0 122.2

40.3

40.5

40.7

40.9

41.1

N

o o o o o o o E

Raoyang River

Daliao River

Liaodong Bay

22 Km

SPM (mg L$^{-1}$)
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

\[ \Sigma PP = C_{surf} \times Z_{eu} \times P_{opt}^b \times DL \times F \]

(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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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 (\(P_{opt}^b\)). 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 \(P_{opt}^b\). Our results indicate that the accuracy of productivity algorithms in estimating PP\(_{eu}\) is dependent primarily upon the ability to accurately represent variability in \(P_{opt}^b\). We developed
Questions to study

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

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.
Primary Productivity Calculation at 12 Stations

\[ P_Z = \frac{(A_{POC} + A_{DOC})_{light} - (A_{POC} + A_{DOC})_{dark}}{A_{TC} \times T_{inc}} \times DIC \times 1.05 \]

- \( P_Z \) (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.
- \((A_{POC}+A_{DOC})_{light}\) and \((A_{POC}+A_{DOC})_{dark}\) = 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:

\[ P = \frac{P_M I}{K_I + I} \]

\( P \) (gC m\(^{-3}\) h\(^{-1}\)) = photosynthesis rate;
\( P_M \) (gC m\(^{-3}\) h\(^{-1}\)) = light-saturated \( P \);
\( P_M / Chl \) (gC g\(^{-1}\) Chl h\(^{-1}\)) = assimilation number (\( P_{opt}^b \));
\( I \) (mol quanta m\(^{-2}\) d\(^{-1}\)) = irradiance at a specific water depth;
\( K_I \) (mol quanta m\(^{-2}\) d\(^{-1}\)) = half-saturation constant;

(Falkowski & Raven, 2007; Lalli & Parsons, 1997)
• 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 \( (P_D, \text{ in gC m}^{-2}\text{ h}^{-1}) \) 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 ($P_{\text{opt}}^b$) & $P_D$

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

- Significant difference in $P_{\text{opt}}^b$ and $P_D$ between coastal and estuarine stations;
- $P_{\text{opt}}^b$ and $P_D$ in coastal zone is much higher than estuary;
- What are the controlling factors for the differences in $P_{\text{opt}}^b$, $P_D$ & 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?

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

Relationships between S and concentrations of \( \text{NO}_2 + \text{NO}_3 \), P, and Si, and between S and T at the 66 stations in Liaodong Bay
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 … …
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:

\[ L = \int_{0}^{\infty} K_{Chl}Chl \cdot I_0 e^{-(K+K_{Chl}Chl)Z} = \frac{K_{Chl}Chl \cdot I_0}{K + K_{Chl}Chl} \]
• 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 (\( R = \frac{Photons}{C} \), in mol quanta mol\(^{-1}\) C) can be calculated by dividing \( L \) by \( P_D \):

\[ R = \frac{L}{P_D} = \frac{K_{Chl} Chl \cdot I_0}{P_M \ln(1 + I_0 / K_I)} = \frac{K_{Chl} \cdot I_0}{P_{opt} \ln(1 + I_0 / K_I)} \]
**Results of **\( F & R \) (=Photons/C)

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<tr>
<th>Area</th>
<th>( P_{opt}^b ) gC gChl⁻¹ h⁻¹</th>
<th>( P_D ) mg C m⁻² d⁻¹</th>
<th>Surface Chl a mg m⁻³</th>
<th>Areal Chl a mg m⁻²</th>
<th>( F )</th>
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<td>0.96</td>
<td>0.29%</td>
<td>37.3</td>
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**\( F \):** 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:
\[ 2H_2O + 2NADP^+ + 3ADP + 3Pi + \text{light} \rightarrow 2NADPH + 2H^+ + 3ATP + O_2 \]

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 H₂O + 6 CO₂ + 30 ADP + 30 Pᵢ
→ 6 O₂ + 30 ATP + 36 H₂O + C₆H₁₂O₆

Thus, the overall photosynthetic process can be represented by

CO₂ + 2H₂O $\xrightarrow{\sim8hv}$ (CH₂O) + H₂O + O₂
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 $F$ & $R$

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- **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**
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].

(Miller & Wheeler, 2012)
Light-conditioned $P_{opt}^b$ vs Temperature

Coastal: $9.13 \pm 2.17$

Estuarine: $3.14 \pm 0.81$

Maximum: $12.48$

$$\frac{P_{opt}^b}{(I_{ave})^{0.3}} = A e^{(BT-CT^2)}$$

$R^2 = 0.60$

$p = 0.003$
Patchiness of phytoplankton & PP

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

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. (2018). “Study on chemical hydrography, chlorophyll-α 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 $P_{\text{opt}}^b$ 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.
Thanks.