12.742 - Marine Chemistry Fall 2004

Lecture 13 - Primary Production: Water Column Processes

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- Somewhat different organization from years past - start with surface productivity and work our way down the water column
- Try to fold methods in as we go
- Electronic notes still missing many of the figures - also somewhat different order.

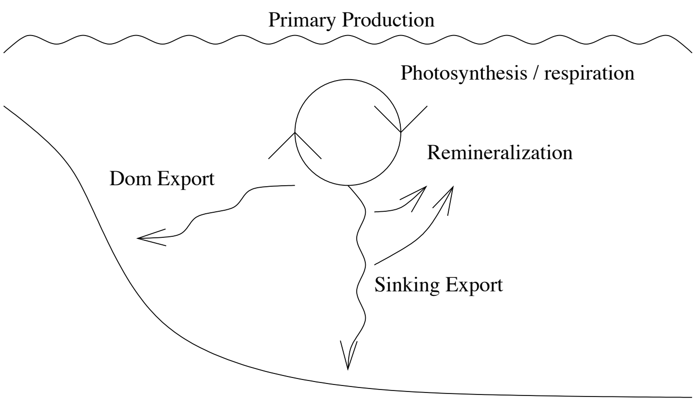


Figure 1.

- Formation and respiration of organic matter
- Formation and dissolution of $CaCO_3, SiO_3$
- Transport of dust, resuspended sediments, particles
- Scavenging onto particles
- Elemental stoichiometry
- Water column distributions
- Rates

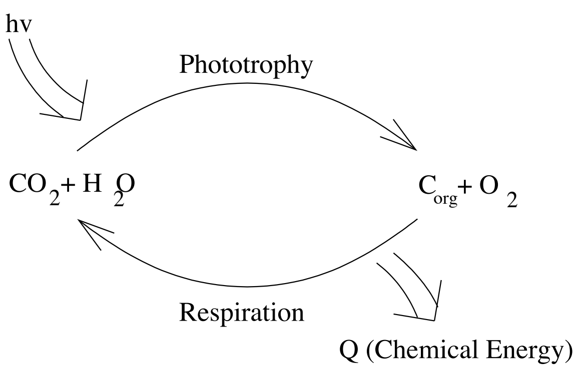


Figure 2.

- Categorize organisms by source of energy, inorganic electron donor and carbon source.
  - Chemo litho autotrophy
  - Chemo organo heterotrophy
  - Photo litho autotrophy

- Light absorbed by pigments.
  - mainly chlorophyll a
  - also accessory pigments (which absorb different wavelengths) including forms of chlorophyll (b, c1, c2) carotenoids, biliproteins

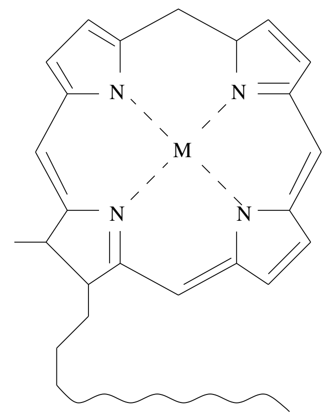


Figure 3.

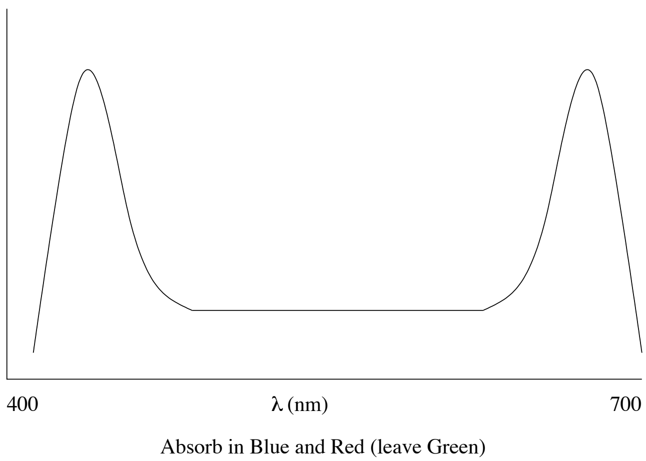


Figure 4.

  - Chlorophyll has conjugated double bonds - non-localized π orbital electrons, can absorb solar radiation, bump up to higher electron state
  - PAR - photosynthetic available radiation (350 – 700 nm)
  - Convert light energy into electron energy
  - Light harvesting pigment-protein complexes involved in electron transfer, funneling excited electrons to reaction sites.

- Two types of reactions
  - Light reactions
    Photosystems I and II - redox/electron exchange
    ATP - adenosine triphosphate
    Photosystem I - reduction of $NADP \rightarrow NADPH_2$
    Nicotinamide adenine dinucleotide phosphate (NADP)
    Photosystem II - liberation of O_2 from water
    Interconnected photosystem II $\rightarrow$ photosystem I (photosynthetic unit)
    Light reactions (light into energy and reducing power),

$$2H_2O + 2NADP^+ \xrightarrow[8\,h\nu]{} O_2 + 2NADPH + 2H^+ \qquad \text{Delta G} = +105.5 kcal/mol$$

Coupled with phosphorylation reaction,

$$4ADP + 4P_i \rightarrow 4ATP$$

- Dark reactions
  Calvin/Benson cycle - biochemistry ($CO_2 \rightarrow$ carbohydrate)

$$2H^+ + CO_2 + 2NADPH \rightarrow (CH_2O) + 2NADP^+$$

  which requires $3ATP$:

$$3ATP \rightarrow 3ADP + 3P_i$$

  where (CH_2O) is a generic carbohydrate. The net reaction is:

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

- Respiration by phytoplankton (light and dark)
  - Use stored organic matter to regenerate energy

$$CO_2 + H_2O \leftrightharpoons CH_2O + O_2$$

  - Forward reaction - Gross Primary Production (GPP)
  - Reverse reaction - respiration (autotroph)
  - Net Primary Production (NPP) = GPP - autotroph respiration
  - Typically respiration small: ≤ 0.1 GPP, but can be higher in tropical oligotrophic ~ 0.4 GPP
- What limits/controls primary production?
  - autotroph biomass (grazing, excretion, mortality)
  - light
  - nutrients
  - temperature (growth rates versus photosynthesis)
- So where is most of the biomass (phytoplankton)?
  - Photosynthetic Quotient $\left[-\frac{O_2}{CO_2}\right]$

$$CO_2 + H_2O \leftrightharpoons CH_2O + O_2 \qquad PQ \sim 1$$

    requires ~ 532 kJ.
    But PQ for algae is > 1 because of production of proteins and lipids (carbohydrates, DNA)
    Eg: fatty acid $CH_3 - (CH_2)_{10} - COOH$

$$C_{12}H_{24}O_2 + 17O_2 \leftrightharpoons 12CO_2 + 12H_2O \qquad PQ \sim \frac{17}{12} \approx 1.42$$

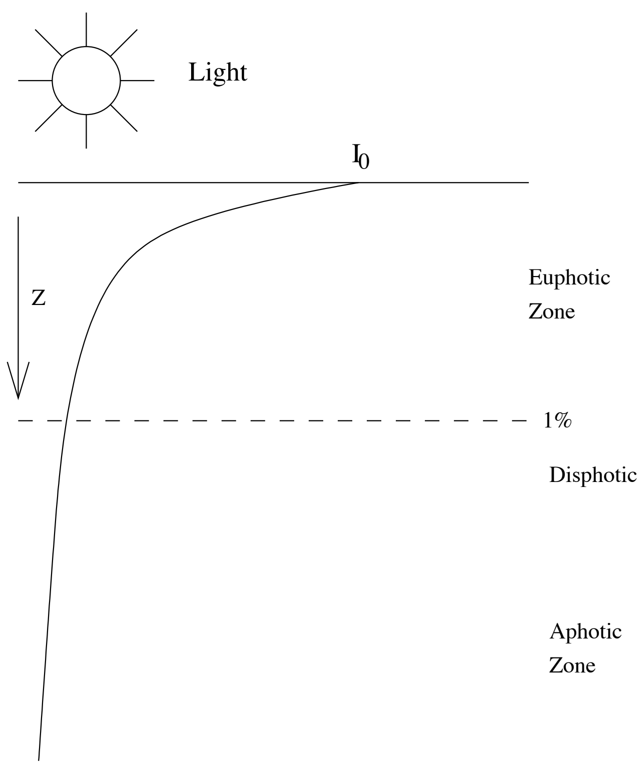
  - Alfred Redfield in the 1930s-1950s examined the elemental composition of marine phytoplankton (now call “Redfield ratios”)

- Anderson proposed

$$C_{106}H_{175}O_{42}N_{16}P + 150O_2 \leftrightharpoons 106CO_2 + 16HNO_3 + H_3PO_4 + 78H_2O$$

- Main primary producers:
  - by phylogeny (genomics, metabolics, and cellular form) - phylogenitvely rich/diverse taxonomy $2 \cdot 10^4$ species (?) cyanobacteria (prokaryote), eukaryotes (green and red algae), red (diatom, dinoflagellates)
  - by size (important later for grazing, export, etc) - haptophytes (coccolithophorids), chrysophytes (Note: pico - $0.2 - 20$ μm, nano - $2.0 - 20$ μm, micro - $20 - 200$ μm, meso - $200 - 2000$ μm, micro - > 2000 μm
  - guild/geochemical function group - nitrogen fixers, calcifiers, silicon shells, etc

  Spatial distribution based on field surveys and satellite remote sensing



  - Primary production in clearest open ocean waters down to ~ 125 m.
  - Turbid coastal a few meters to 10s of meters
  - Light absorption - depends upon water, suspended material, dissolved organisms, biology, etc.

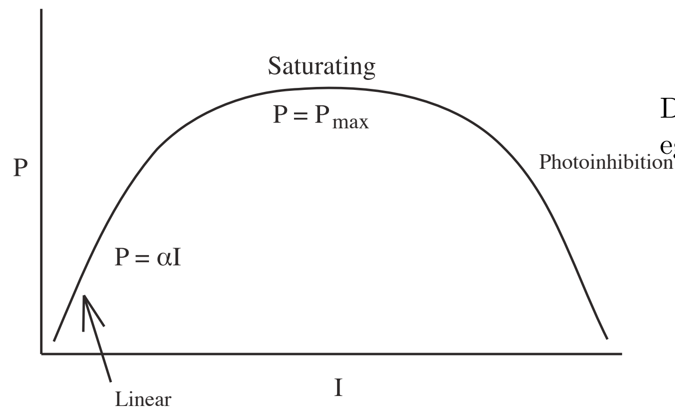
Figure 5.

Lights falls off with depth $I(\lambda, z) = I_0(\lambda)e^{-k(\lambda)z}$ (For PAR, exponential is only an approximation)

$k = k_w + k_c Chl + other absorbers$, PAR ~ 0.5 total irradiance

Change spectral character of light (strip out all of the red, for example)

Photosynthesis - irradiance curves



Different function forms - "models" eg.

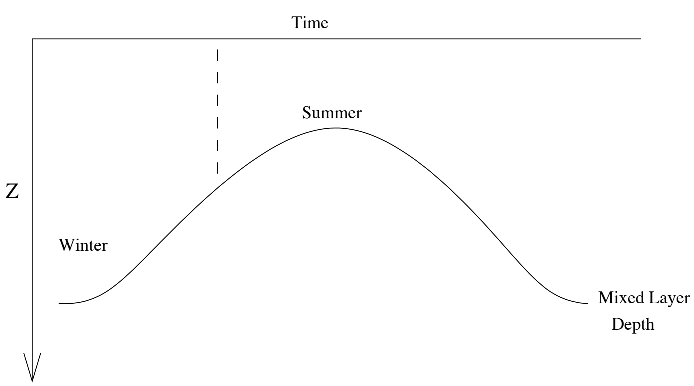
$$P = P_{\max}\left[1 - e^{-\alpha I/P_{\max}}\right]$$

$$\lim_{a\to 0} e^a = 1 + a\left(+\mathcal{O}(a^2)\right)$$

$$\Rightarrow P \to P_{\max}\left(1 - \left(1 - \frac{\alpha I}{P_{\max}}\right)\right)$$

Figure 6.

Light and mixing



Trigger spring bloom when have enough "average" light (when mixing depth shoals to the critical depth Z_{CR})

$$\frac{1}{kZ_{\text{CR}}}\left(1 - e^{-kZ_{\text{CR}}}\right) = \frac{R_0}{P_0} = \frac{I_c}{I_0}$$

Figure 7.

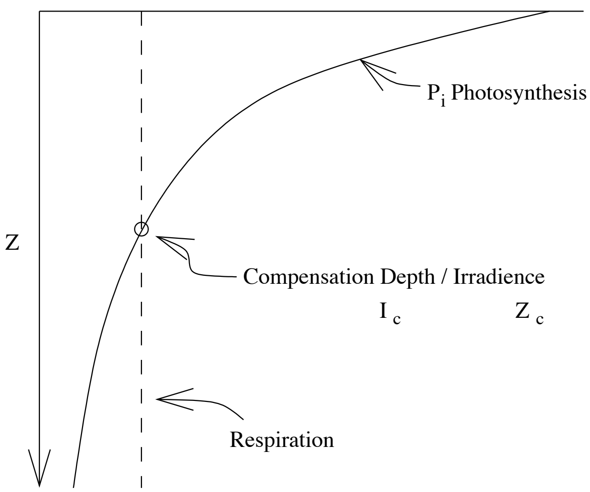


Figure 8.

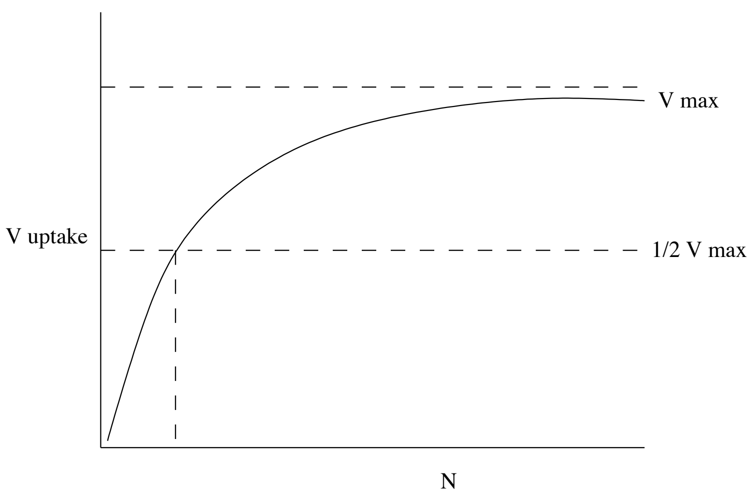
at the compensation irradiance, I_c, $P_c = R_c$ (autotroph production equals community respiration)

$$I_c = I_0 e^{-kZ_c} \qquad P = \alpha I, P_0 = \alpha I_0$$

At critical depth, total integrated respiration = integrated production
Harold Sverdrup first identified critical depth Z_{CR} defined as depth where depth integrated respiration = depth integrated production.

$$R_0 Z_{\text{CR}} = \int_0^{Z_{\text{CR}}} dz\, \alpha I_0 e^{-kz}$$

- Nutrient limitation N



$$V_{\text{uptake}} = V_{\max} \cdot \frac{N}{N + k_N}$$

Figure 9.

- Complications
  - Many different possible limiting nutrients N, P, Si (diatoms), also, trace elements $Fe, Co, Zn, \ldots$
  - Multiple forms of nutrients $\underbrace{NH_4^+}_{\text{most easily used}}$, $\underbrace{NO_3^-}_{\text{dominant form in ocean}}$
  - Dissolved organic matter as source of nutrients
  - Nutrient inhibition (eg. NH_4^+ on nitrate)
  - Multiplicative i.e. Liebig's law of minimum; nutrient-light co-inhibition

- Temperature limitation T

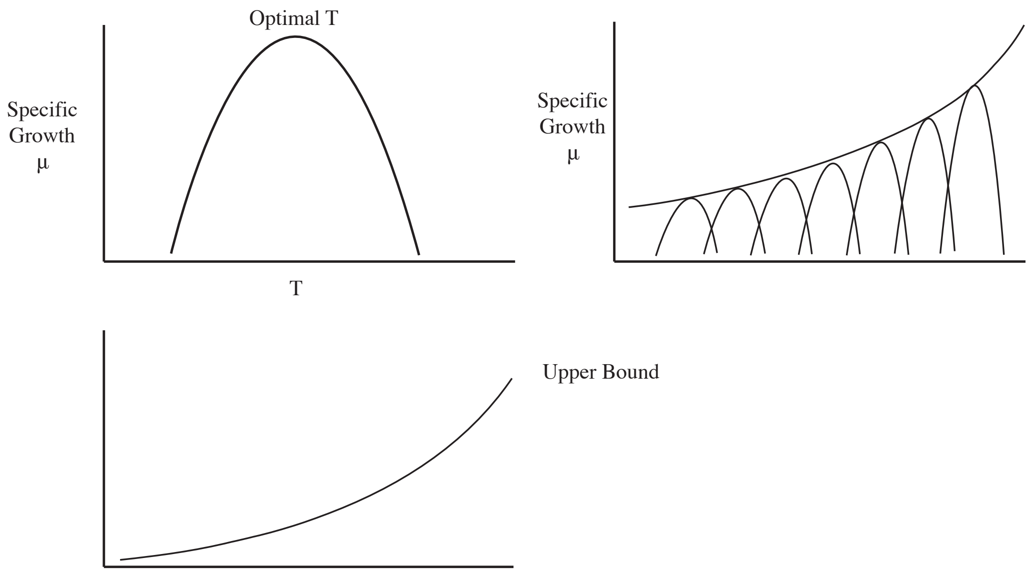


Figure 10.

Eppley curve [1972] for maximum autotroph specific growth ratesμ (1/day)

$\mu(T) = \frac{0.6}{d} 1.066^{T(\text{deg. } C)}$

alternative temperature curves defined with form similar to Arrehnius relationship

- Time-Space variations

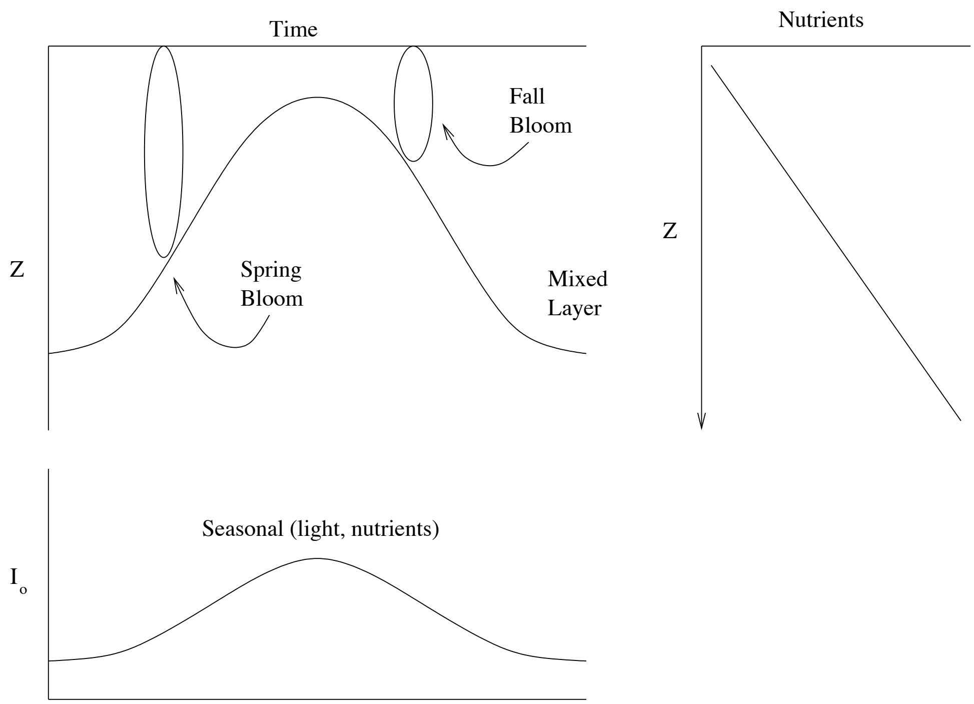


Figure 11.

during spring, have increased light (solar, mixed layer depth) and higher nutrients (from deep winter mixing)

Balance of light versus nutrient limitation depends upon location

- Variations with depth

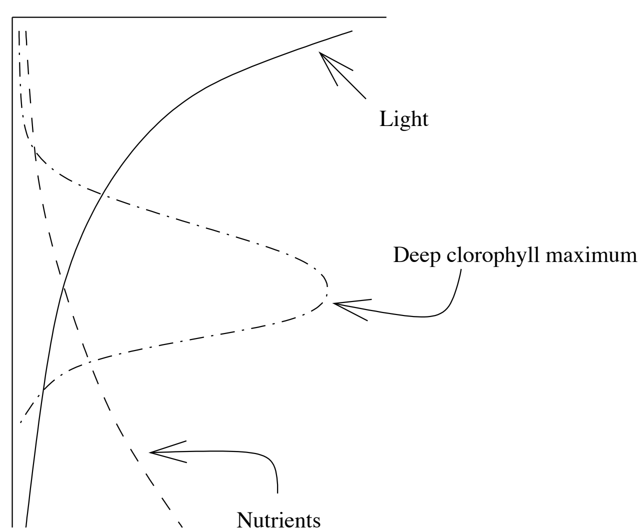


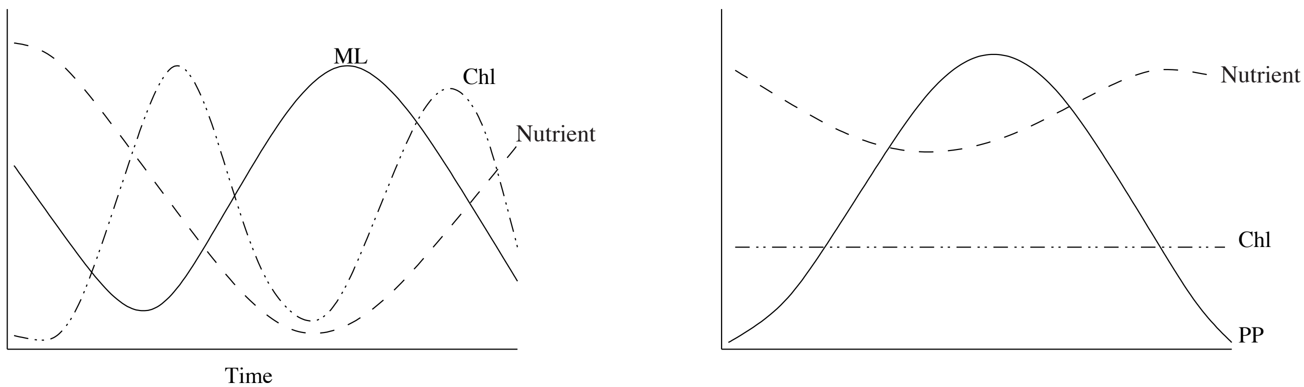
Figure 12.

Deep chlorophyll maximum (cell abundence and chl/cell, photoadaptation, photoacclimation)

Globally

- Spatial maps of chlorophyll (proxy for biomass)
- Primary determinant is nutrient supply
- Regions of upwelling (equatorial divergence, coastal upwelling, subpolar gyres)
- Regions of deep seasonal mixing (eg. North Atlantic spring bloom)

Stratified regions have relatively low biomass (subtropical gyres)



Atlantic

Figure 13.