OCN 401-Biogeochemical Systems (10.02.14)

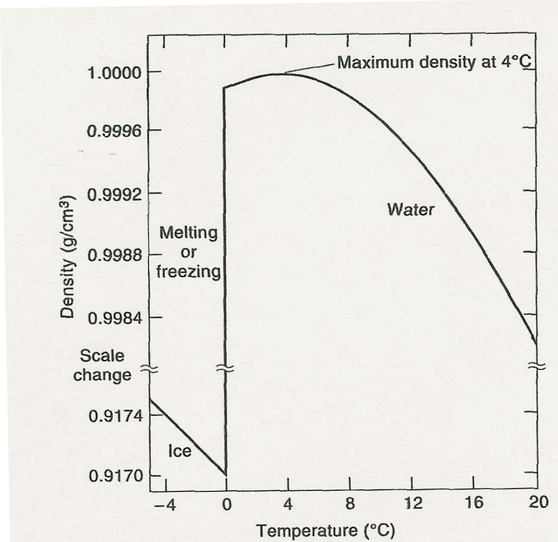
Lakes: Primary Production, Budgets and Cycling

Reading: Schlesinger, Chapter 8

Lecture Outline

1. Temperature / density relationship
   - Seasonal cycle of lake stratification
2. Primary Production and Nutrient Cycling in Lakes
   - Dissolved inorganic carbon speciation
   - Net primary production (NPP)
   - P and N in Lake Waters
3. Lake Budgets (C, N, P)
4. Eutrophication
5. Alkalinity and Acid Rain

The Physical Properties of Water: The Temperature-Density Relationship

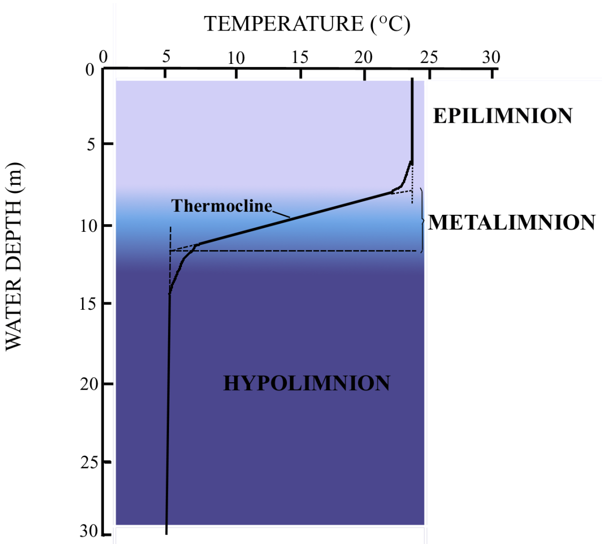


Berner & Berner Fig. 6.1

- Water is densest at 4 °C
- Both ice <u>and</u> warmer water are less dense
- Important implication: ice floats!
- If less dense water is overlain by denser water lake overturn occurs
- If denser water is overlay by less dense water, stable stratification occurs
- Lake chemistry and biology are affected by these physical processes.

Temperature structure for a typical temperate freshwater lake in summer

- Epilimnion: warm surface waters; light energy rapidly attenuates with depth
- Metalimnion: zone of rapid temperature change, or thermocline
- Hypolimnion: cooler, deep waters
- Many tropical lakes are permanently stratified
- Temperate lakes show seasonal break-down of temperature stratification & can mix from top to bottom.



Seasonal Cycle of Lake Stratification

Early spring (after ice melt):

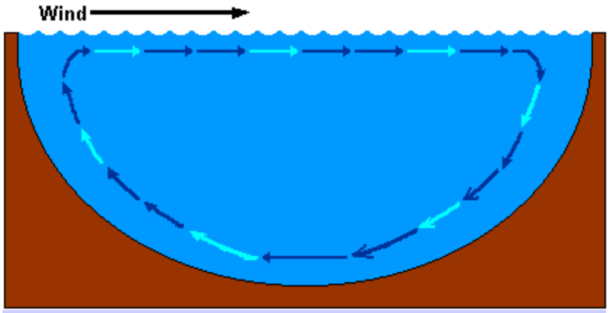


Figure 1 Complete mixing of water can occur when all water within the lake is generally the same temperature. Wind helps to drive this process.

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Late spring:

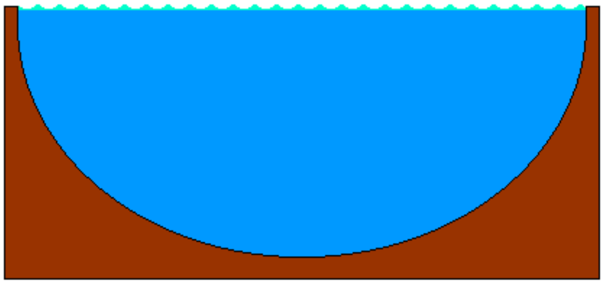


Figure 2 As summer approaches, the surface of the lake begins to get warmer. This creates a relatively warm surface layer over a relatively cool bottom layer. They are separated by a zone that changes temperature very rapidly with depth.

Summer:

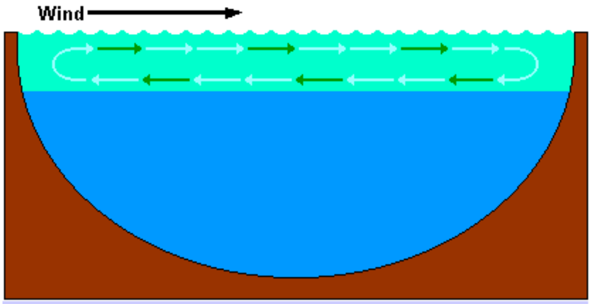


Figure 3 During summer density differences act as a barrier to complete mixing of the lake. This deprives the lake bottom of oxygen.

- Dead organic matter sinks from the epilimnion to the hypolimnion
- The decay of this organic matter leads to O_2 depletion of the hypolimnion

Early autumn:

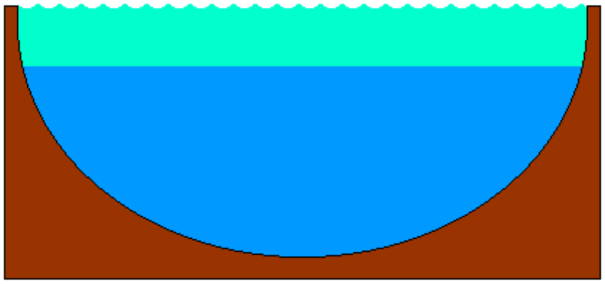


Figure 4 As seasonal temperatures decrease, so does the depth of the warm water layer known as the epilimnion. Conversely, the cold layer known as the hypolimnion increases in thickness.

Autumn:

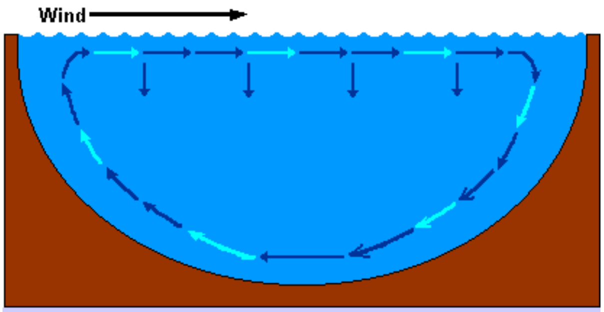


Figure 5 Complete mixing of water can occur when all water within the lake is generally the same temperature. In addition, the atmosphere cools the water at the lake's surface. This dense water sinks to the bottom and further contributes to lake mixing.

Winter:

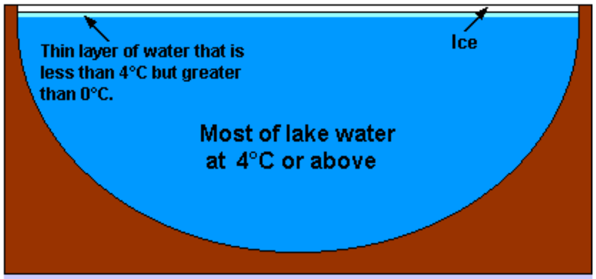
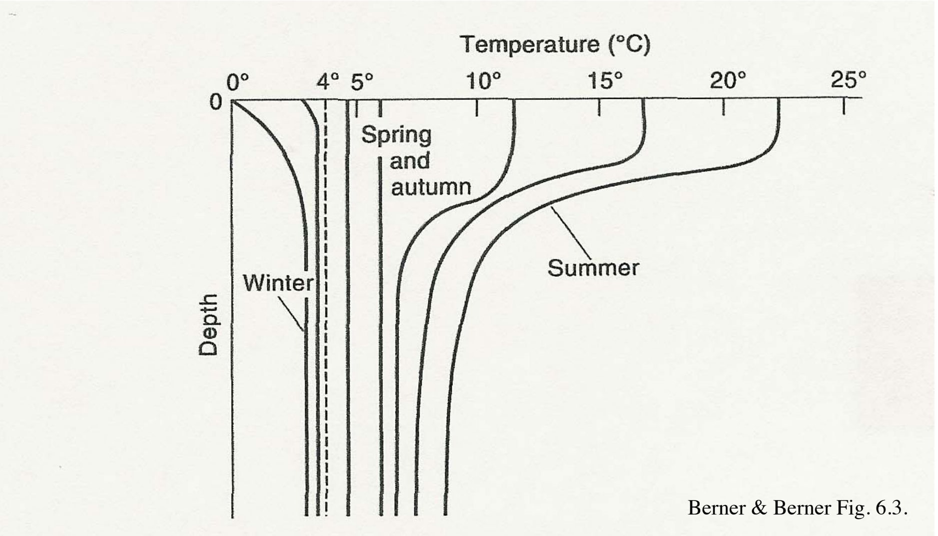


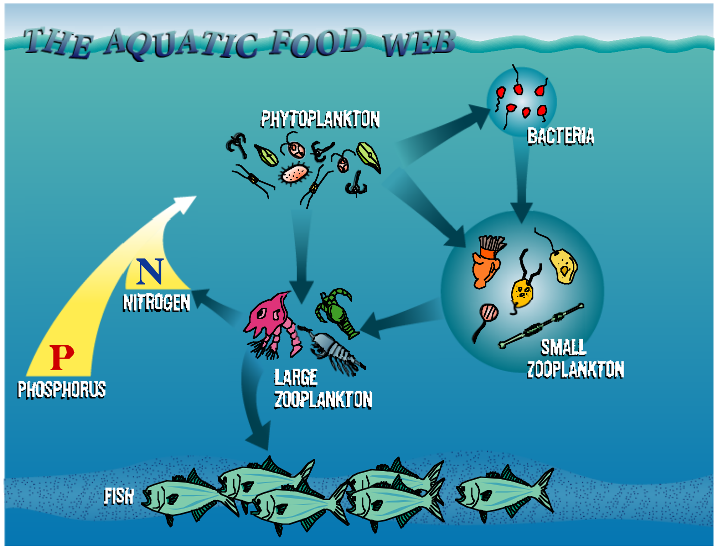
Figure 6 During the winter, ice prevents lake water mixing. Stratification can occur during this time of winter stagnation.

The Seasonal Cycle of Lake Stratification



Berner & Berner Fig. 6.3.

Temperature profiles over the year for a typical temperate lake Dashed line represents maximum density at 4°C



- Like terrestrial systems, P and N can be limiting nutrients in lakes.
- Unlike terrestrial systems, C can also be limiting, because it must dissolve according to equilibrium reactions of the CO_2 system:

$$CO_2 + H_2O \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^{2-} \qquad (7.23)$$

Dissolved Inorganic Carbon (DIC, ΣCO_2) Speciation

$$DIC = \Sigma CO_2 = [CO_2\,(aq)] + [HCO_3^-] + [CO_3^{2-}]$$

Bicarbonate ion

Carbonate ion

$$CO_2\,(g) \rightleftharpoons CO_2\,(aq)$$

$$CO_2\,(aq) + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$$

Thus, CO_2 speciation is pH dependent:

Bjerrum Plot for CO_2 speciation

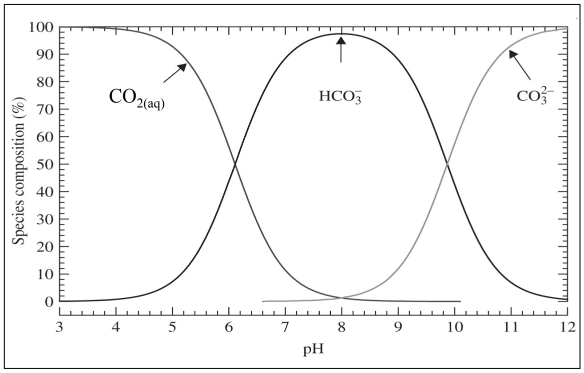
(Seawater values shown --- freshwater curves are shifted left)

Dominant species in freshwater as a function of pH:

CO_2(aq) dominates at pH < 4.3

HCO_3^- (bicarbonate) dominates between 4.3-8.3

CO_3^- (carbonate ion) dominates pH>8.3



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Methods of Measuring Primary Production

- Collect water sample
- Incubate water samples in clear & dark bottles
- Measure either:
  - Change in dissolved oxygen (O_2)
  - Production of ^{14}C-labeled POC (from ^{14}C-HCO_3 additions)
- Calculate results via O_2-evolution method:
  - Dark bottle: Respiration (for O_2 only):
  - Clear bottle: Net Primary Production (NPP = P – R)
  - Clear bottle – Dark bottle: Gross Primary Production (GPP) (for O_2 only)

Looking at PP and R in terms of Reactions

- Water incubated in clear bottles:
  - Oxygen evolution (photosynthetic O_2 production)

$$CO_2 + H_2O \rightarrow \boxed{O_2} + CH_2O \qquad \text{(eqn. 5.2)}$$

  - ^{14}C-labeled POC (C-uptake)

$$^{14}CO_2 + H_2O \rightarrow O_2 + \boxed{^{14}CH_2O}$$

- Calculate results via O_2-evolution method:
  - Dark bottle: Respiration (drop in O_2 is a measure of net respiration):

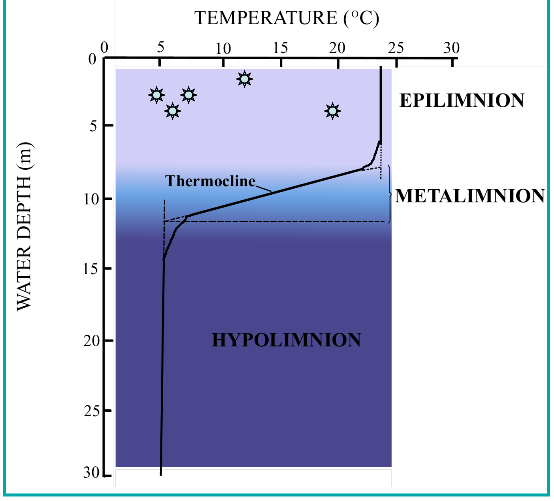
$$O_2 + CH_2O \rightarrow CO_2 + H_2O$$

  - Clear bottle: Net Primary Production (NPP = P-R):
    - photosynthesis in excess of respiration
    - assumes molecular equivalence between C-fixation and O_2 production
  - GPP = NPP – R (e.g., the sum of changes in light & dark bottles)

Primary Production and Nutrient Cycling

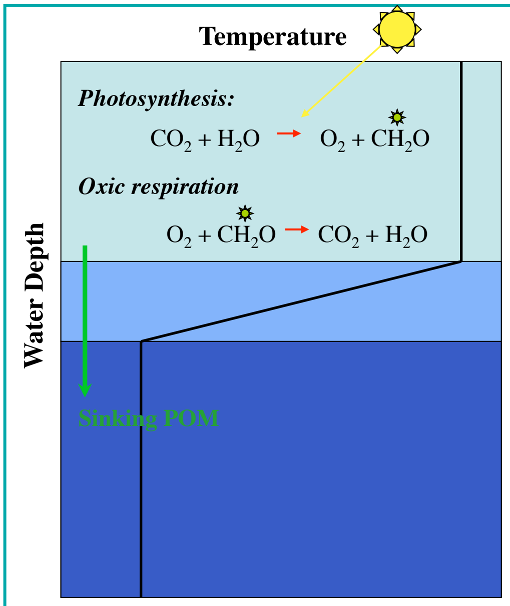
- Phytoplankton (free-floating algae) contribute most of the net primary production
- Phytoplankton are confined to surface waters due to light limitation
- NPP depends on external nutrient inputs to epilimnion and regeneration
- Epilimnion is oxic, so organic matter decomposes rapidly by aerobic respiration
- Low levels of nutrients are found in surface waters due to efficient phytoplankton uptake

Summer Stratification



Primary Production and Nutrient Cycling (cont’ d.)

- Dead organic matter sinks into the hypolimnion where it is decomposed by microbial respiration.
- Decay within hypolimnion consumes O_2 (low redox potential); since it is isolated from the atmosphere there is no opportunity for re-oxygenation.
- As a result of hypolimnion isolation, and of continual supply of dead organic matter and microbial respiration, O_2 is consumed and nutrients build up during the growing season.



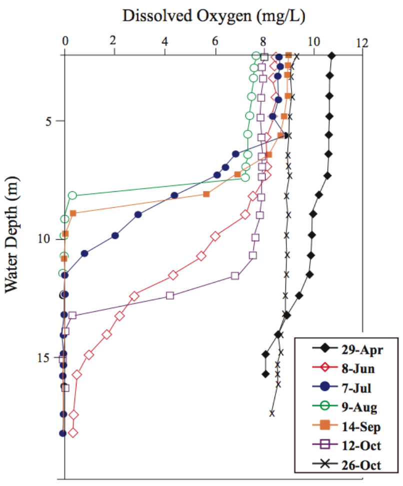
Photosynthesis:

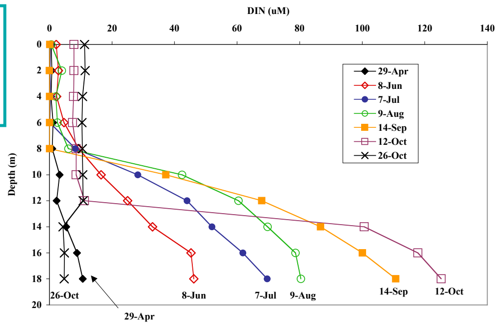
$CO_2 + H_2O \rightarrow O_2 + CH_2O$

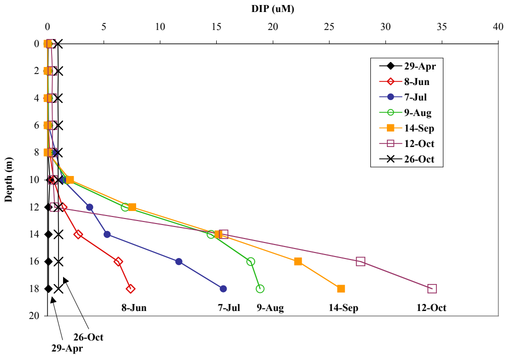
Oxic respiration

$O_2 + CH_2O \rightarrow CO_2 + H_2O$

Seasonal Evolution of O_2, DIN, and DIP in a temperate lake in Massachusetts







Lake Productivity is Linked to Nutrient Concentration

Comparison of lakes of the world:

- Most lakes appear to be *P-limited*.
- Other factors can be important (e.g., other nutrients, sunlight).

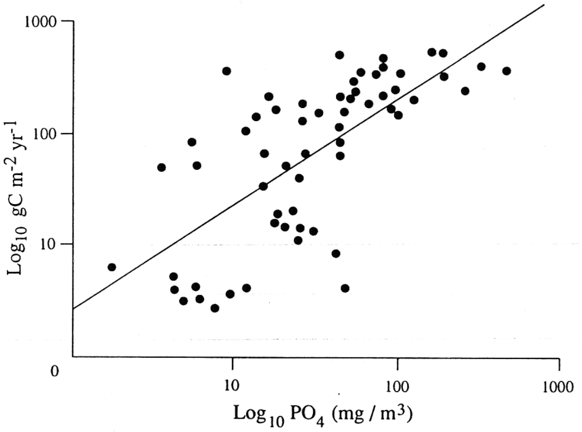


Fig. 7.10. Relationship between NPP and phosphate concentration of lakes of the world (Shindler 1978).

Nutrients Cycling in Lakes

- Natural P inputs to lakes is small.
  - Retention in terrestrial watersheds: vegetation and soil
  - P associated with soil minerals not bioavailable
- Large proportion of P is in plankton biomass; small proportion is “available” (dissolved in lake water).
- P-turnover in the epilimnion is dominated by bacterial decomposition of organic matter (internal recycling)
  - Produced POM and DOM
- Phytoplankton and bacteria excrete phosphatases to convert DOP to bioavailable PO_4^{3-}.
- When N is limiting, shift from green to blue-green algae (cyanobacteria) that fix N_2

Export of POM from the Epilimnion

- Export ratio = percentage of PP that sinks to the hypolimnion.
- Export ratio is 10-50% of NPP in 12 US lakes.
- Greater fractional export in lower productivity lakes.
- High P in hypolimnion is returned to the surface during seasonal mixing.
- P-Turnover is incomplete, some P is lost to sediments.

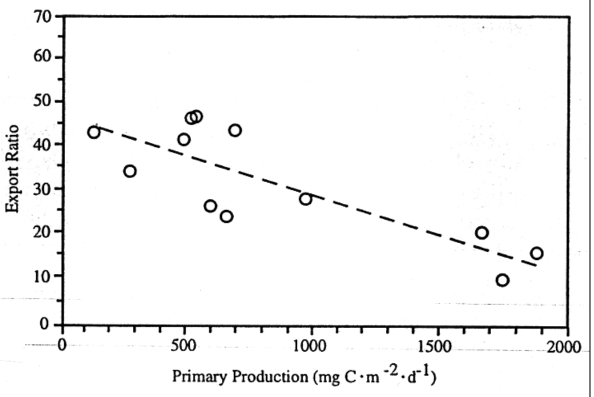
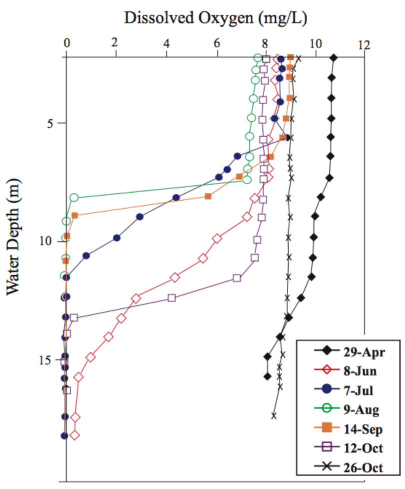
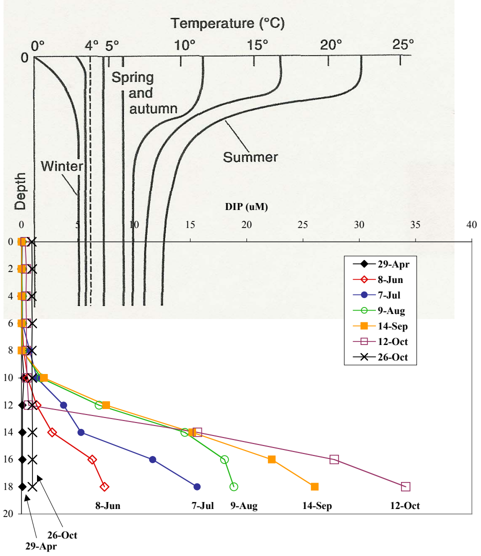


Fig. 8.13 % of phytoplankton PP that sinks to hypolimnion (export ratio) as a function of lake net primary productivity; after Baines and Pace 1994).

Consequence of POM Export: Nutrient build-up in Hypolimnion

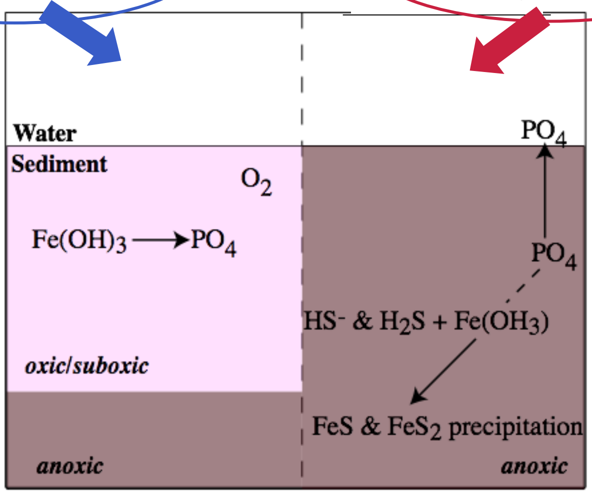




Role of Sediments in P-Cycling

Oxic hypolimnion
Oxic surface sediments

Anoxic hypolimnion
Reducing sediments



Water

PO_4

Sediment

O_2

$Fe(OH)_3 \longrightarrow PO_4$

PO_4

HS^- & $H_2S + Fe(OH_3)$

oxic/suboxic

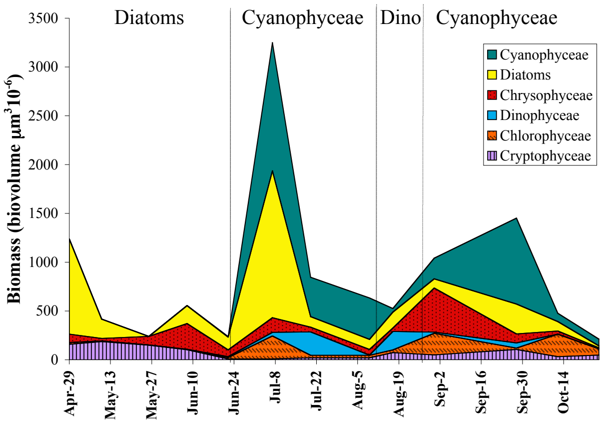
FeS & FeS_2 precipitation

anoxic

anoxic

Role of N-Fixation in Epilimnion

Green Algae → Blue-green Algae



- Both P & N are depleted in epilimnion.
- Encourages blue-green algal growth, because they are N-fixers.
- Pollutant P encourages blue-green algal growth, can account for >80% of N-input to phytoplankton.
- N-input via N-fix’n maintains P-limitation

Lake Carbon Budgets

- NPP within the lake is “autochthonous” production.
- Note importance of macrophytes (i.e., rooted plants), which reflects the extent of shallow water.
- Organic carbon from outside the lake is “allochthonous” production.

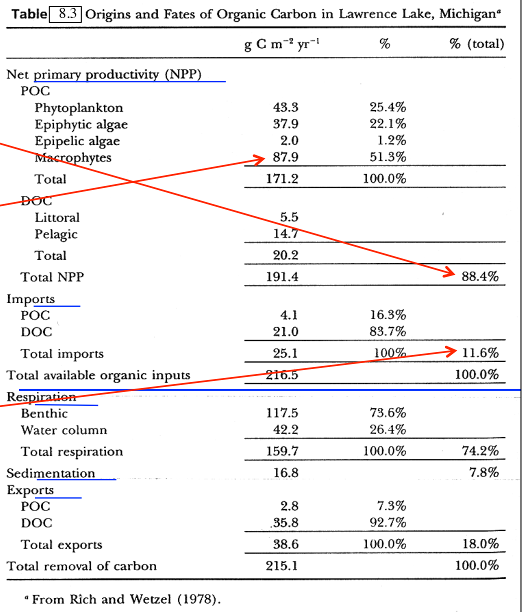


Table 8.3 Origins and Fates of Organic Carbon in Lawrence Lake, Michigan[a]

	g C m^{-2} yr^{-1}	%	% (total)
Net primary productivity (NPP)			
POC			
Phytoplankton	43.3	25.4%	
Epiphytic algae	37.9	22.1%	
Epipelic algae	2.0	1.2%	
Macrophytes	87.9	51.3%	
Total	171.2	100.0%	
DOC			
Littoral	5.5		
Pelagic	14.7		
Total	20.2		
Total NPP	191.4		88.4%
Imports			
POC	4.1	16.3%	
DOC	21.0	83.7%	
Total imports	25.1	100%	11.6%
Total available organic inputs	216.5		100.0%
Respiration			
Benthic	117.5	73.6%	
Water column	42.2	26.4%	
Total respiration	159.7	100.0%	74.2%
Sedimentation	16.8		7.8%
Exports			
POC	2.8	7.3%	
DOC	35.8	92.7%	
Total exports	38.6	100.0%	18.0%
Total removal of carbon	215.1		100.0%

[a] From Rich and Wetzel (1978).

- In lakes with lower chlorophyll concentrations (i.e., lower productivity), respiration exceeds production.

- This reflects the increased importance of allochthonous carbon inputs.
- Lake waters are often supersaturated with respect to CO_2 relative to the atmosphere.

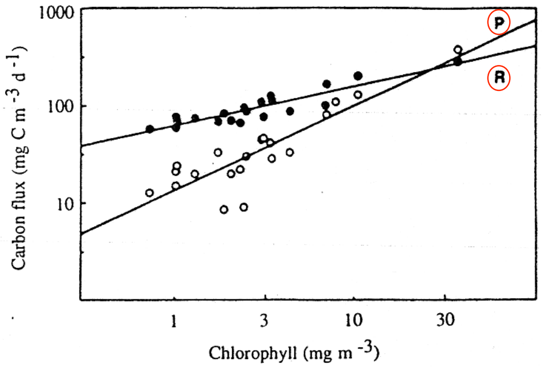
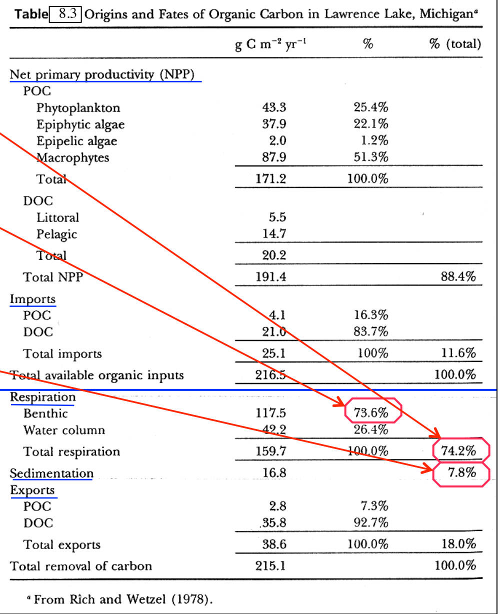


Fig. 7.12. Mean summertime plankton respiration (R) and photosynthesis (P) in surface waters of lakes as a function of chlorophyll concentration, an index of overall lake productivity (del Georgio & Peters, 1994).

Lake Carbon Budgets (cont’ d).

- 74% of organic inputs are respired in the lake
- 74% of that respiration occurring in the sediment. (Deeper lakes have more respiration in the water column.)
- 7.8% of OC is stored in sediments, similar to terrestrial systems, but from a much lower NPP that is typical on land; reflects inefficiency of respiration, as compared to non-saturated soils.



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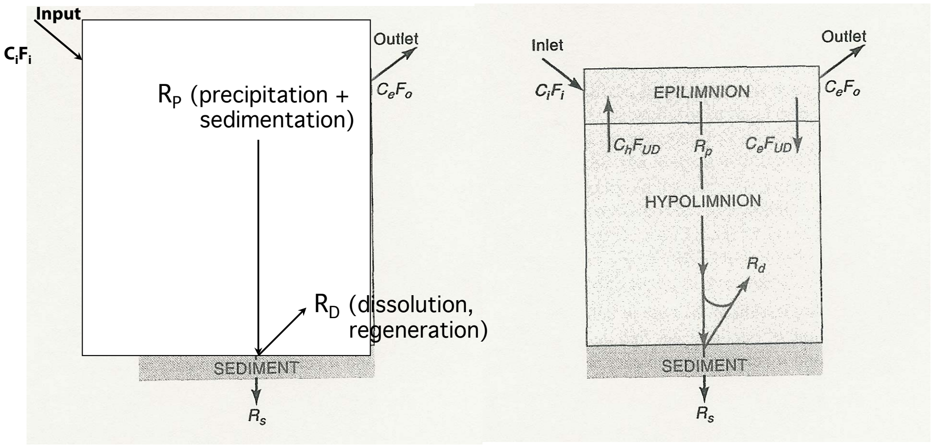
Lake Nutrient Budgets

- **Inputs**: precipitation, runoff, N-fixation, groundwater
- **Losses**: sedimentation, outflow, release of gases, groundwater
- Thus, nutrient budgets require an accurate water budget for the system
- Comparison of nutrient residence time with water residence time gives an indication of the importance of internal biotic cycling
  - Most lakes show a substantial net retention of N and P.
  - Lakes with high water turnover, however, may show relatively low levels of N and P storage.
- Many lakes show near-balanced budgets for Mg, Na, Cl, because these elements are highly soluble and non-limiting to phytoplankton.

One- and Two-box Models for Lakes

(after Berner and Berner, Figs. 6.5 and 6.6)



$\Delta M/\Delta t = C_iF_i - C_eF_o + R_D - R_P$

where $R_S = R_D - R_P$

$T_r = [C]$ moles ÷ C_iF_i moles/yr

F_U = rate of water transfer from hypolimnion to epilimnion

F_D = rate of water transfer from epilimnion to hypolimnion

Lake Nutrient Budgets, cont.

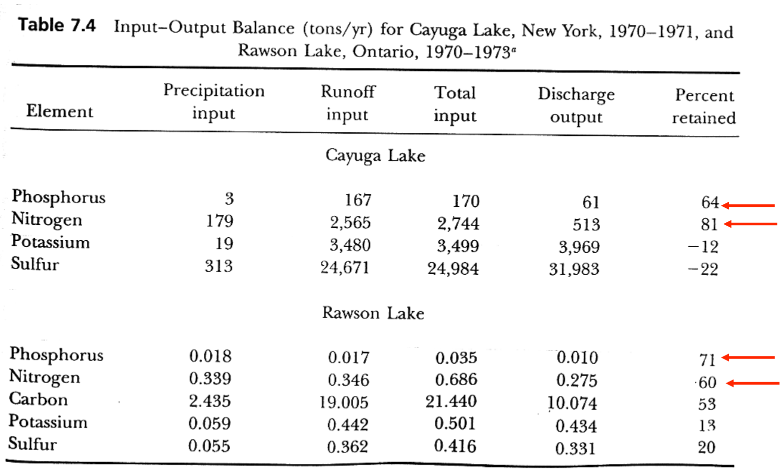


Table 7.4 Input–Output Balance (tons/yr) for Cayuga Lake, New York, 1970–1971, and Rawson Lake, Ontario, 1970–1973[a]

Element	Precipitation input	Runoff input	Total input	Discharge output	Percent retained
Cayuga Lake					
Phosphorus	3	167	170	61	64
Nitrogen	179	2,565	2,744	513	81
Potassium	19	3,480	3,499	3,969	−12
Sulfur	313	24,671	24,984	31,983	−22
Rawson Lake					
Phosphorus	0.018	0.017	0.035	0.010	71
Nitrogen	0.339	0.346	0.686	0.275	60
Carbon	2.435	19.005	21.440	10.074	53
Potassium	0.059	0.442	0.501	0.434	13
Sulfur	0.055	0.362	0.416	0.331	20

- Most lakes show a net retention of N and P
- Biogeochemical control on geochemistry of system

Lake Nutrient Budgets: N fixation

- Lakes with high rates of N fixation show large apparent accumulations of N.
  - 80% of N input to Amazon River is via N-fix'n
- However, the loss of N by denitrification >> input of N by fixation
- Denitrification removes fixed N as N_2O and (especially) N_2.
- Anammox is another pathway for removal of fixed N:

$$NH_4^+ + NO_2^- = N_2 + 2H_2O$$

Lake Classification

- Oligotrophic lakes are:
  - low productivity systems
  - nutrient depleted
  - frequently geologically young
  - typically deep, with a cold hypolimnion

- Eutrophic lakes are:
  - high productivity systems
  - nutrient rich
  - dominated by nutrient inputs from the surrounding watershed
  - often shallow and warm
  - may be subject to “cultural eutrophication”

Lake Classification (cont’d).

- Nutrient input to oligotrophic lakes is typically dominated by precipitation.
- Eutrophic lakes derive nutrients mainly from the surrounding watershed.

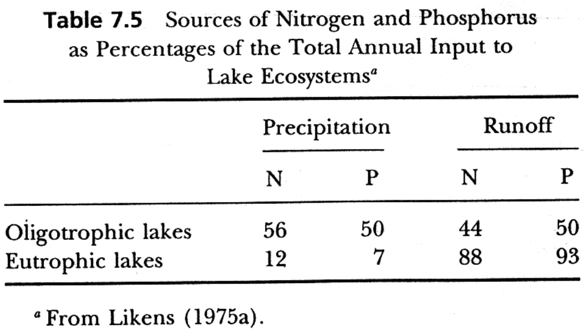


Table 7.5 Sources of Nitrogen and Phosphorus as Percentages of the Total Annual Input to Lake Ecosystems[a]

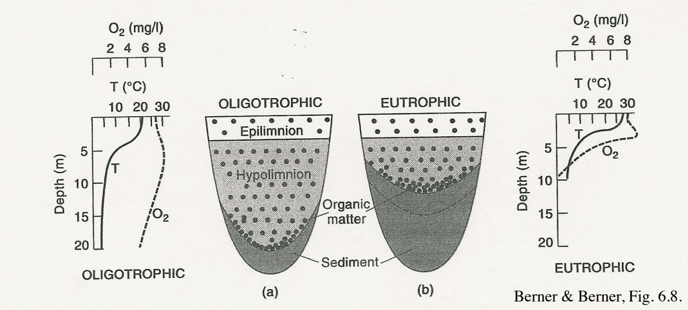
	Precipitation		Runoff	
	N	P	N	P
Oligotrophic lakes	56	50	44	50
Eutrophic lakes	12	7	88	93

[a] From Likens (1975a).

- Sedimentation will convert oligotrophic to eutrophic lakes, by a process known as eutrophication; an aging sequence of a lake.

- Nutrient status is the most useful criterion for distinguishing oligotrophic vs. eutrophic lakes.

- ***Eutrophication*** is a natural process by which accumulation of sediment causes:
  - lake shallowing
  - decrease in volume of hypolimnion
  - increasing extent of O_2 drawdown
- Positive feedback
  - lower O_2
  - less nutrient retention in sediments
  - higher productivity
  - higher rain of organic matter to hypolimnion



Berner & Berner, Fig. 6.8.

- ***Cultural eutrophication***: human activity accelerates eutrophication.

Cultural Eutrophication (Berner and Berner)

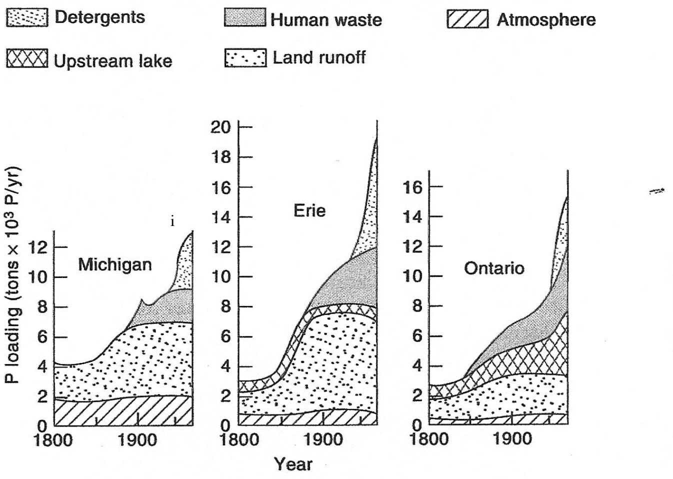


Figure 6.10. Historical loading of total phosphorus (in 10^3 tons/yr) from 1800 to 1970 for three Great Lakes, Michigan, Ontario, and Erie, based on model calculation. [From Stumm and Morgan, 1981, after S. C. Chapra, "Total Phosphorus Model for the Great Lakes," *Journal of Div. of Environmental Engineering* 103(EE2): 153. Copyright © 1977. American Society Civil Engineering, reprinted by permission of the publisher.]

- Berner & Berner, Fig. 6.10.

Lake Classification (cont’d).

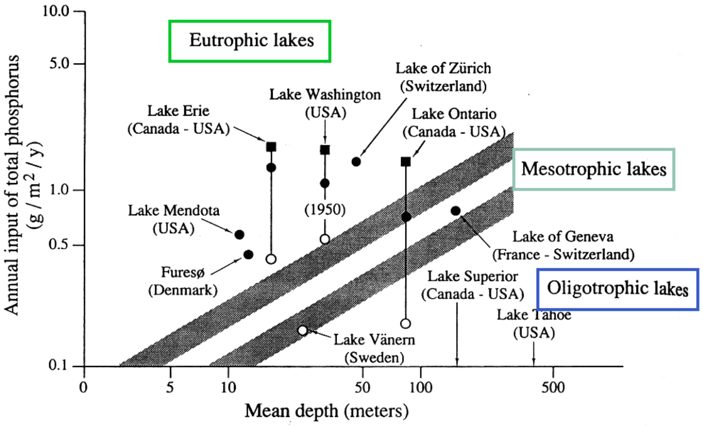


Figure 7.13 The position of important lakes relative to the annual receipt of phosphorus and their mean depth, differentiating oligotrophic and eutrophic lakes. For lakes that have undergone significant pollution, the change from previous conditions (○) to present conditions (●) is shown. From Vollenweider (1968).

Alkalinity and Acid Rain Effects

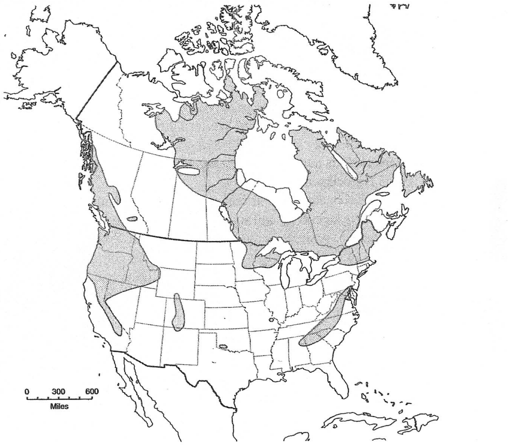
- Alkalinity is roughly equivalent to the imbalance in charge from cations and anions:

  Alkalinity = Σ cations – Σ anions

- Any charge imbalance is “corrected” by changes in equilibrium in the DIC system: $HCO_3^- + H^+ = H_2CO_3$.
- Thus, Alkalinity = $[HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+]$

- Alkalinity increases by processes that consume SO_4^{2-}, NO_3^- or other anions, or that release DIC.
- Alkalinity decreases by processes that consume cations or DIC
- Acid rain decreases alkalinity due to addition of H^+.

Sensitivity of Lakes to Acid Rain Effects

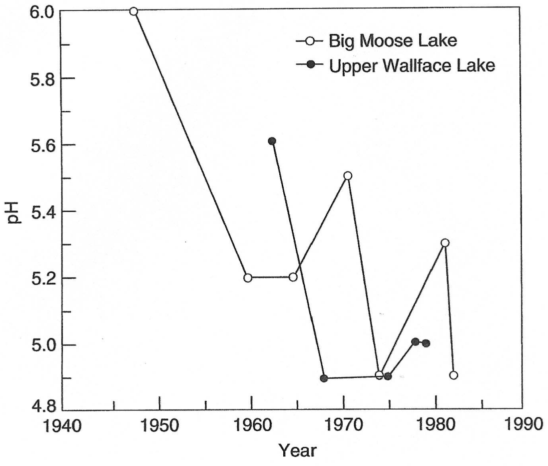


(a)

Figure 6.16. Lake Acidification in North America. (a) Regions in North America containing lakes that would be sensitive to potential acidification by acid precipitation (shaded areas). These areas have igneous or metamorphic bedrock geology which results in dilute lakes with low HCO_3^- concentrations (<0.5 mEq HCO_3^-/l). Unshaded areas have calcareous or sedimentary bedrock geology. (From J. N. Galloway and E. B. Cowling, "The Effects of Precipitation on Aquatic and Terrestrial Ecosystems, A Proposed Precipitation Chemistry Network," *Journal of the Air Pollution Control Association* 28(3): 233. Copyright © 1978. J. of the Air Pollution Control Assoc. Reprinted by permission of the publisher.]

(after Berner and Berner, Fig. 6.16.)

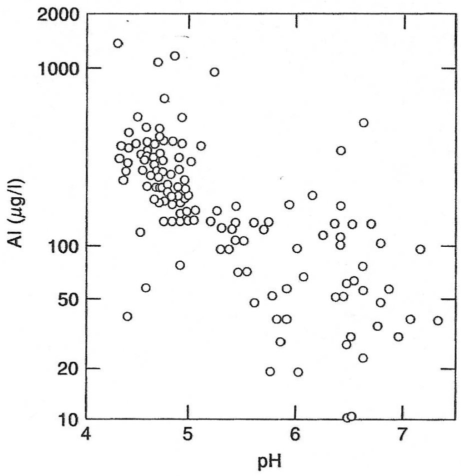
Acid Rain Effects



Berner & Berner Fig. 6.15. Changes in pH with time in lakes located in the Adirondack Mountains of New York State

Changing atmospheric conditions can alter lake ecosystem processes

Acid Rain Effects



Berner & Berner Fig. 6.18. Highly acidic weathering dissolves Al from kaolinite, plagioclase and gibbsite; these phases are not dissolved during normal weathering.

Lecture Summary / Main Points

- Physical properties of water, seasonal climate changes, and the surrounding landscape and geology exert profound control on nutrient cycling and NPP in lakes
- Primary production is closely linked to nutrient supply
- Nutrient and carbon budgets provide a key means of assessing lake biogeochemical cycling
- Eutrophication is a natural process, which can be accelerated by anthropogenic activities
- Acid rain has had profound impacts on some lakes; underlying geology is a major factor in lake sensitivity