Estuarine and Coastal Ocean Environments

Biogeochemical Systems -- OCN 401

16 October 2012

Reading: Schlesinger Chapter 8

Outline

1. **Introduction**
   - Definition of "Estuary"
   - Estuary distribution and importance
   - Water movement / classification of estuaries

2. **Mixing Processes in Estuaries**
   - Salinity distribution
   - Other compositional gradients

3. **Nutrient Loading in Estuaries**
   - Primary production and respiration response to N loading
   - Estuarine N budgets
   - Coastal eutrophication and hypoxia

4. **Estuarine Sediments**
   - Fates of sediments
   - Sedimentary sulfur cycle

5. **Salt Marshes**
   - Geomorphology & hydrology
   - Nutrient cycling

Definitions of “Estuary”

- Two major components involved:
  - Gradation from fresh (river) water to saline (ocean) water
  - Tidal influence
- One definition:
  - “An estuary is a semi-enclosed coastal water body that extends upstream to the effective limit of tidal influence, within which sea water is significantly diluted with freshwater from land drainage.”

- Estuarine ecosystems includes:

  - The river channel, to the maximum upstream extent of tidal influence

  - The adjacent coastal waters, to the maximum extent of freshwater flow

  - Salt marshes and tidal flats that develop along the shore line, built up from riverine sediments deposited as river flow rate slows once sea level is reached; subject to daily tidal inundation

- Estuaries are zones of mixing, displaying strong salinity gradients from land to sea

Estuary Distribution

- Estuaries are found around the global coastal zone, wherever rivers (large or small) enter the sea
- There are thousands of geographical features that fit the criteria
- Estuaries cover a global area of ~10^6 km^2
    - ~ 0.3% of the world ocean
    - ~ 4% of the world continental shelf

Why are such small oceanic features so important?

- Most materials entering the ocean from land do so through estuaries
- High primary production
- Used for fishing, shipping, recreation, aquaculture, etc
- Most people live in the coastal zone, many of them near estuaries
- Most human perturbation of the ocean (pollution, over-exploitation, dredging, etc.) occurs in estuaries

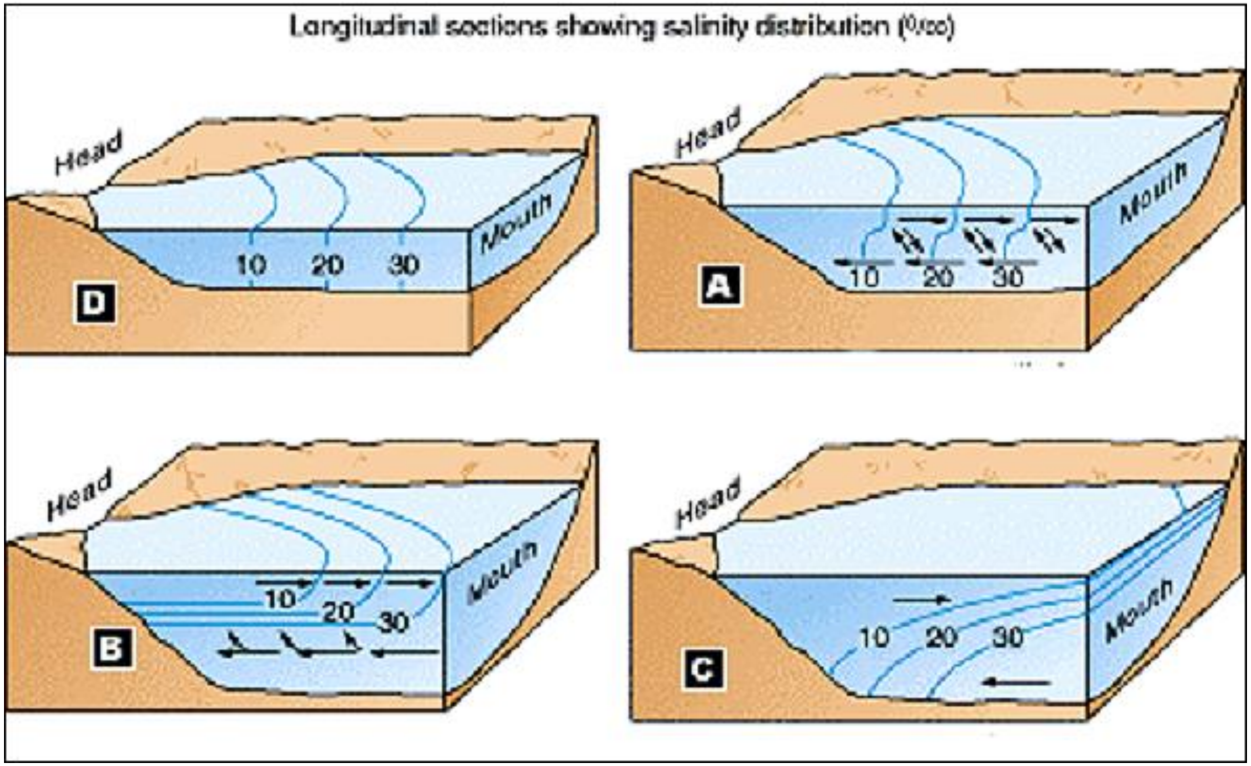
Water Movement in Estuaries

- River flow is essentially unidirectional
- As river water meets the sea, tidal oscillation introduces a bi-directional ("in-out") component to flow
  - This bi-directionality may be throughout the water column (well-mixed estuary)
  - Or there may be predominantly surface outflow and deep inflow (salt-wedge estuary)

Estuary Classification

Well-mixed estuary

Slightly stratified estuary



Highly stratified estuary

Salt-wedge estuary

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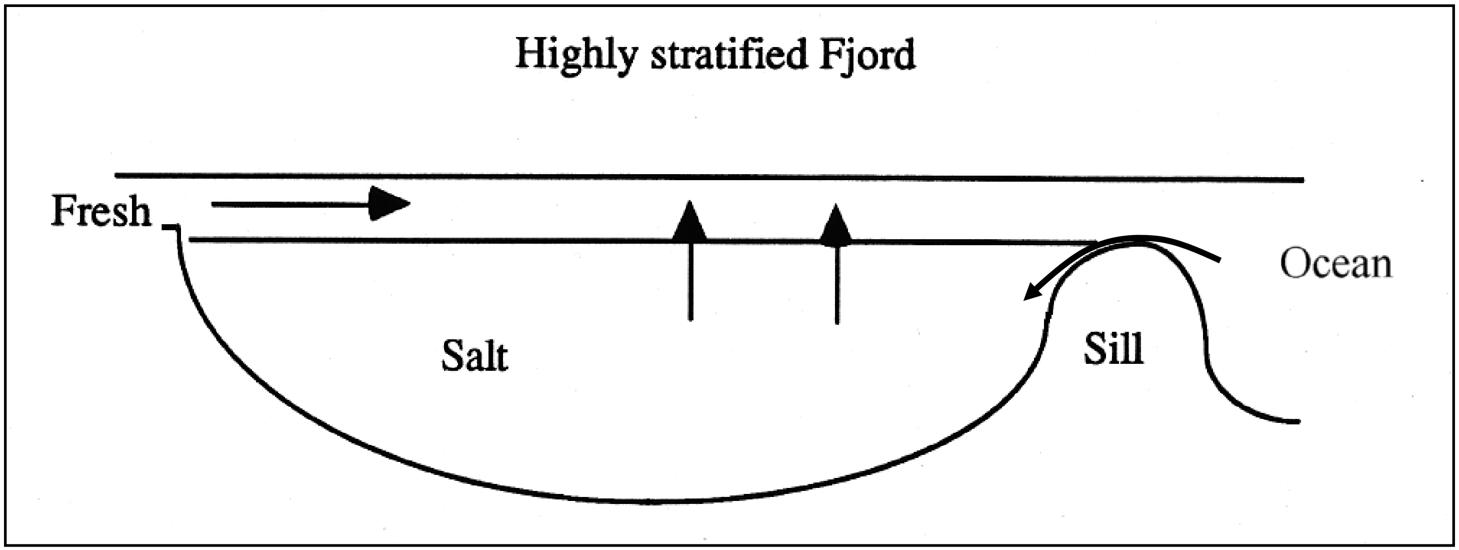
Water Flow in a Highly Stratified Estuary with a Sill



Biogeochemical Processes in Estuaries

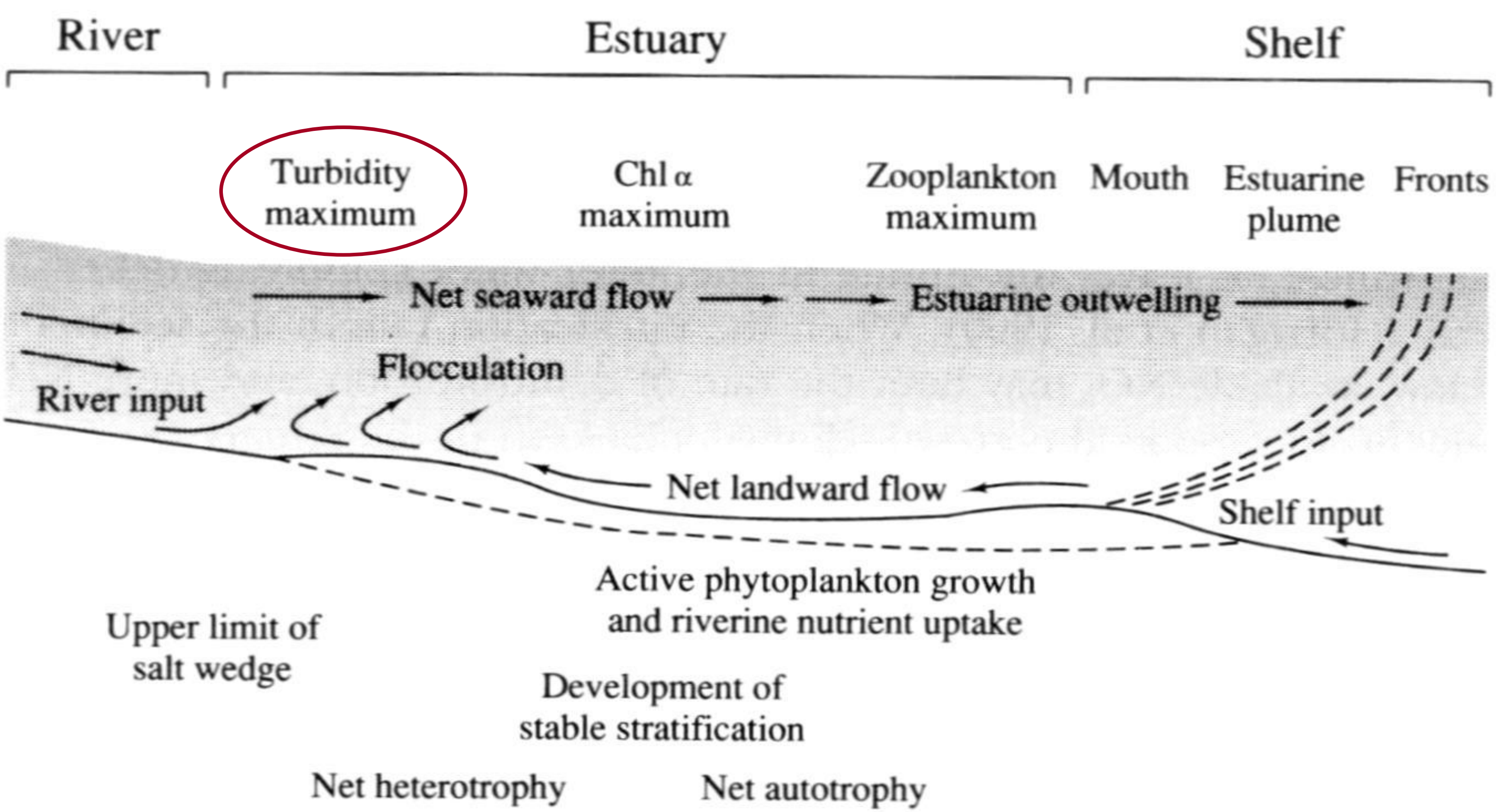


Figure 8.13 Conceptual model of the chemical and biological structure in estuaries. As the suspended load settles from the entering river waters and nutrients are made available, phytoplankton production increases, fueling an increase in zooplankton production and higher trophic levels. From Fisher et al. (1988).

Biogeochemical Mixing Processes in Estuaries

- Salinity gradients in estuaries are useful for studies of biogeochemical processes

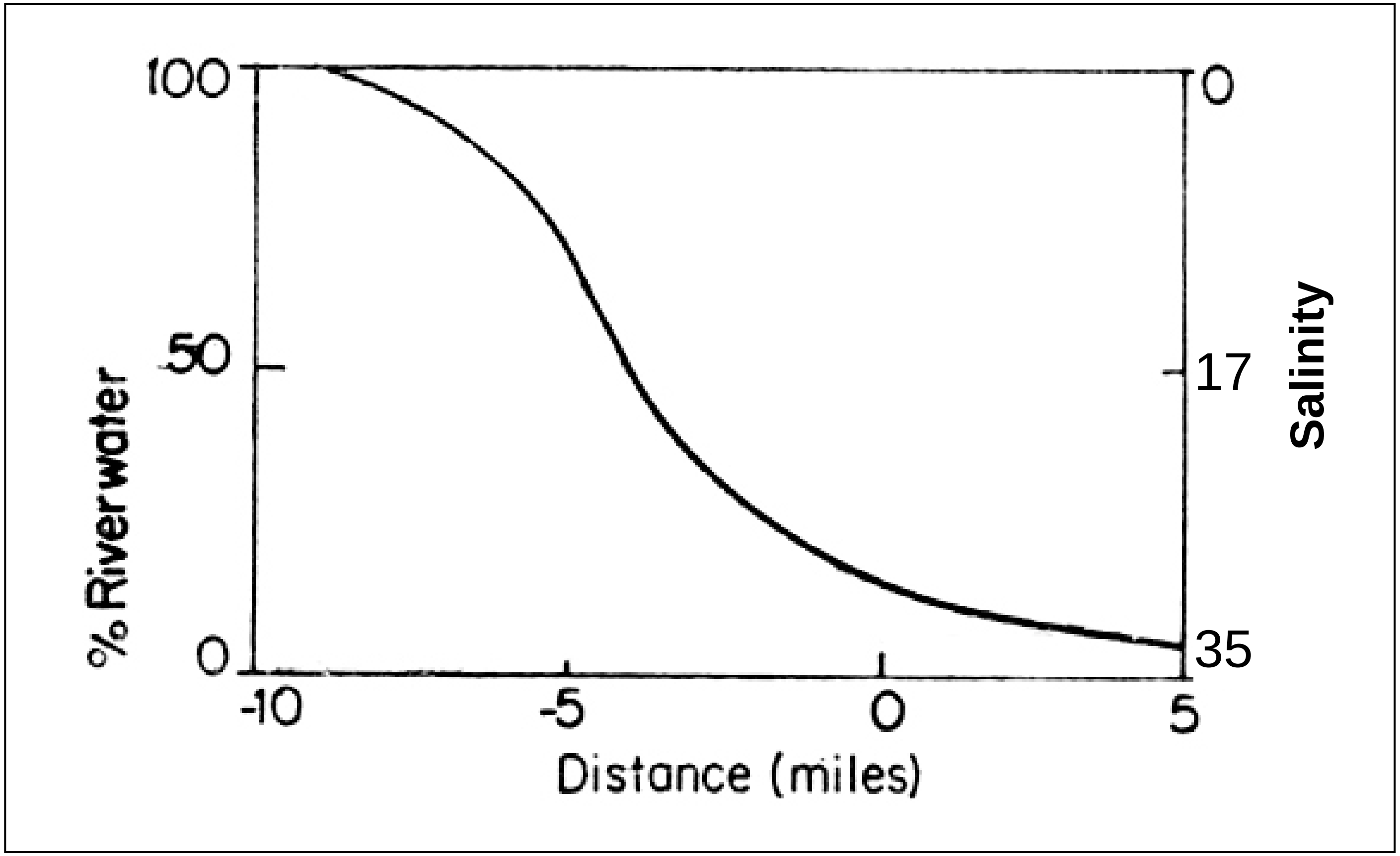
- Salinity (or Cl^- conc) can be used as a ***conservative*** tracer of estuarine mixing

- Other river concentrations change during mixing due to biological uptake, chemical reactions or exchange with sediments -- these chemical species behave in a ***non-conservative*** manner

- Changes in non-conservative species in excess of that expected from simple dilution with seawater are used to infer biogeochemical processes in the estuary.....

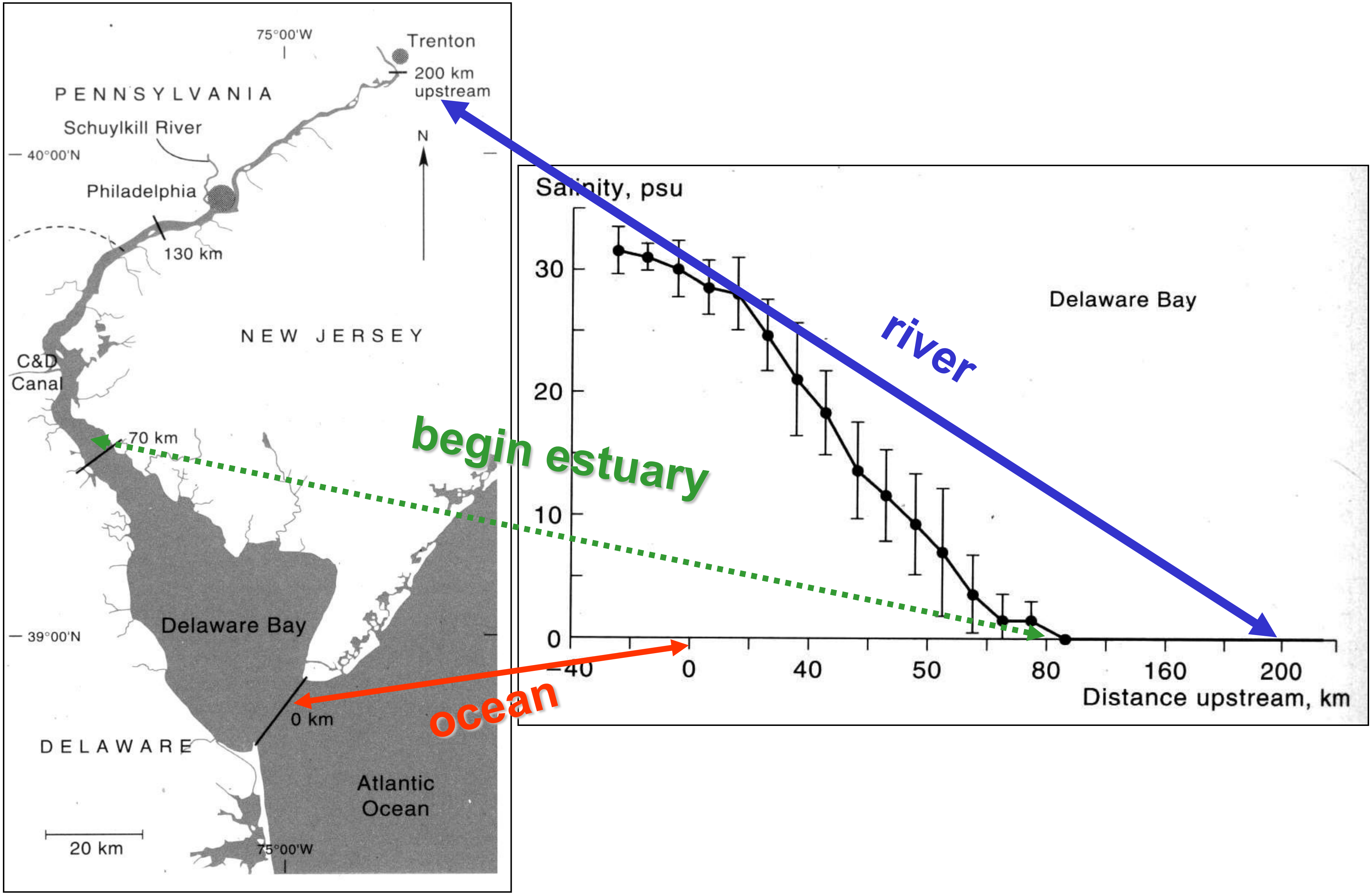
Salinity Distribution in Estuaries

Percent river water and seawater
along typical estuary:

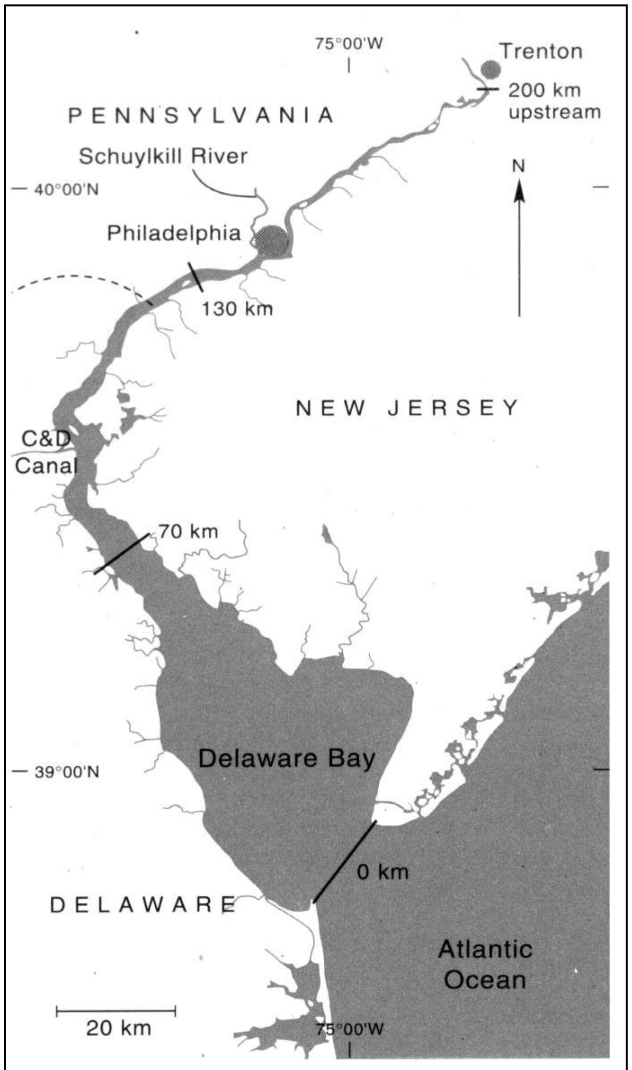


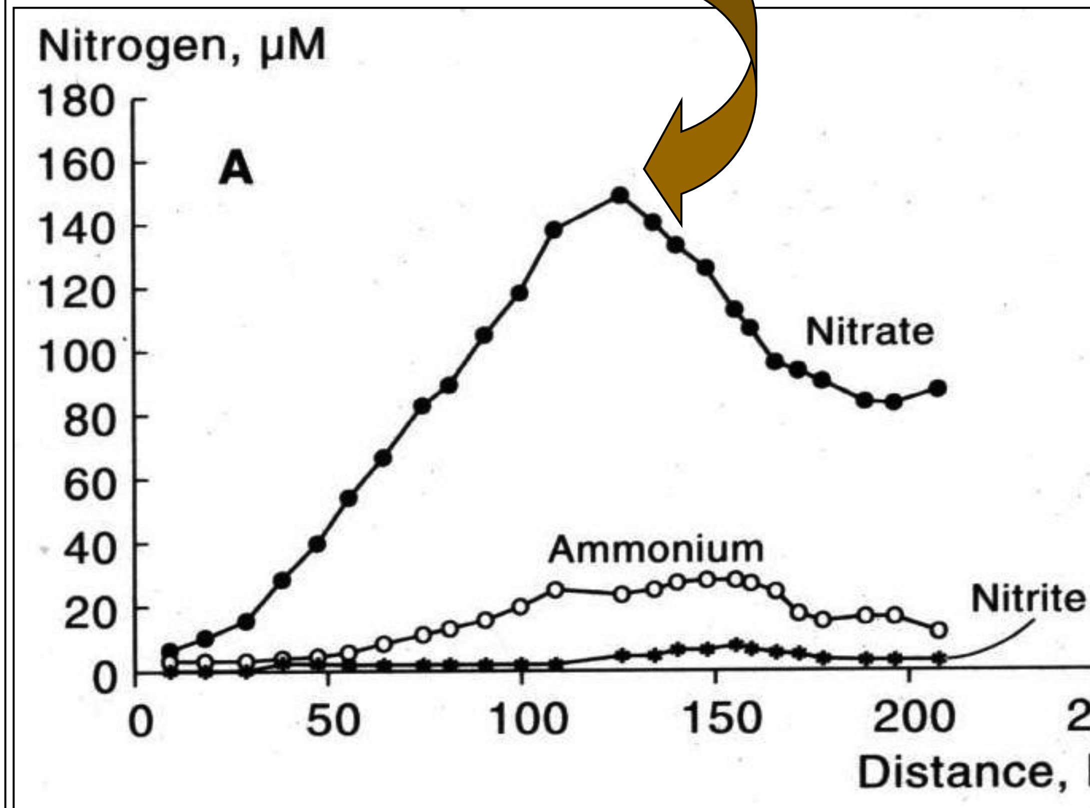
Distance = 0 at mouth of estuary

Compositional Gradients in Estuaries



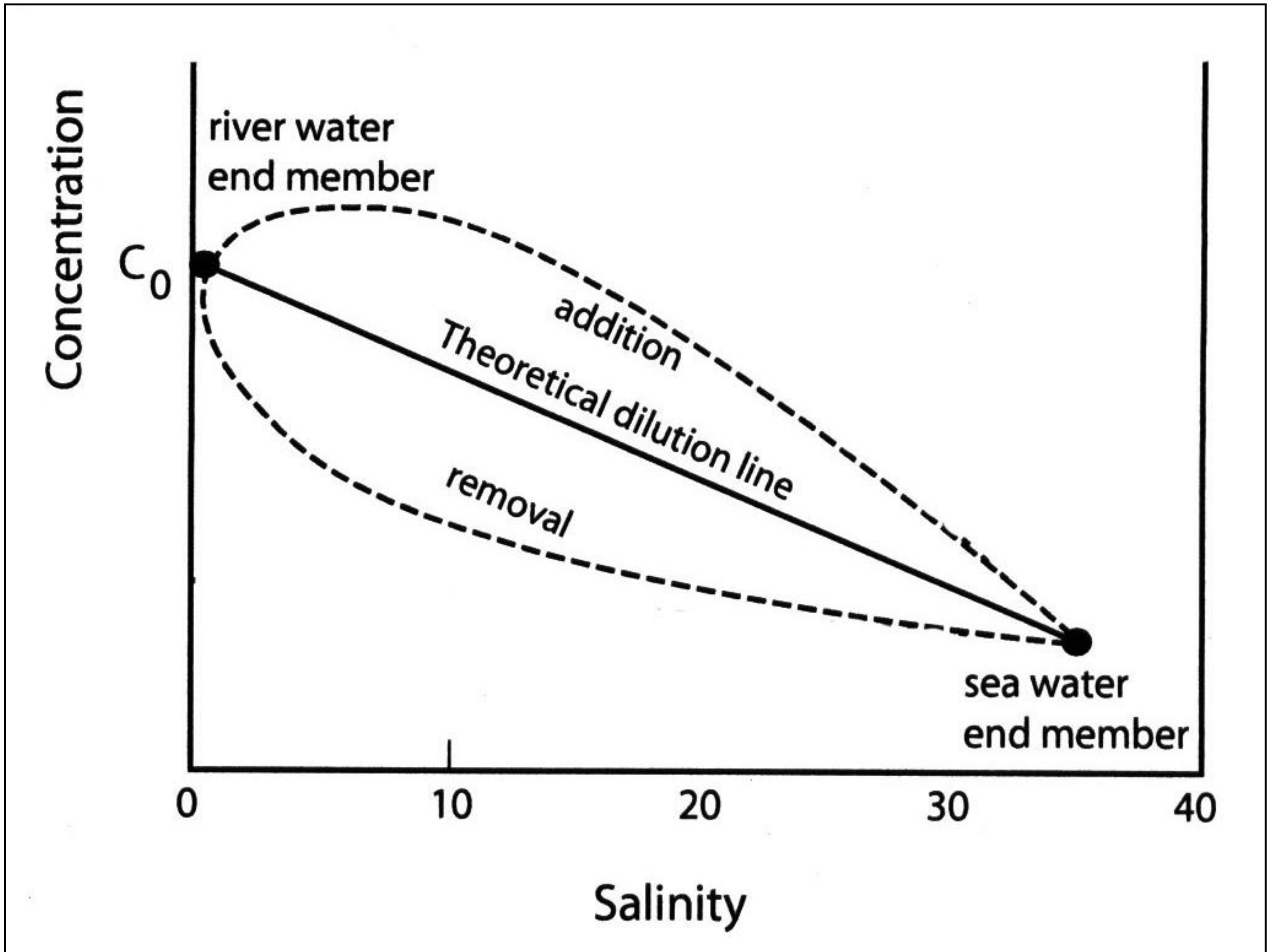
Philadelphia waste load





But what about less obvious cases (*e.g.*, river and ocean concs ≠ 0)?

Use ***estuarine mixing curve*** to determine if estuary is a net <u>source</u> or <u>sink</u> for a chemical species:



Example: dissolved CO_2 is high in rivers, low in ocean

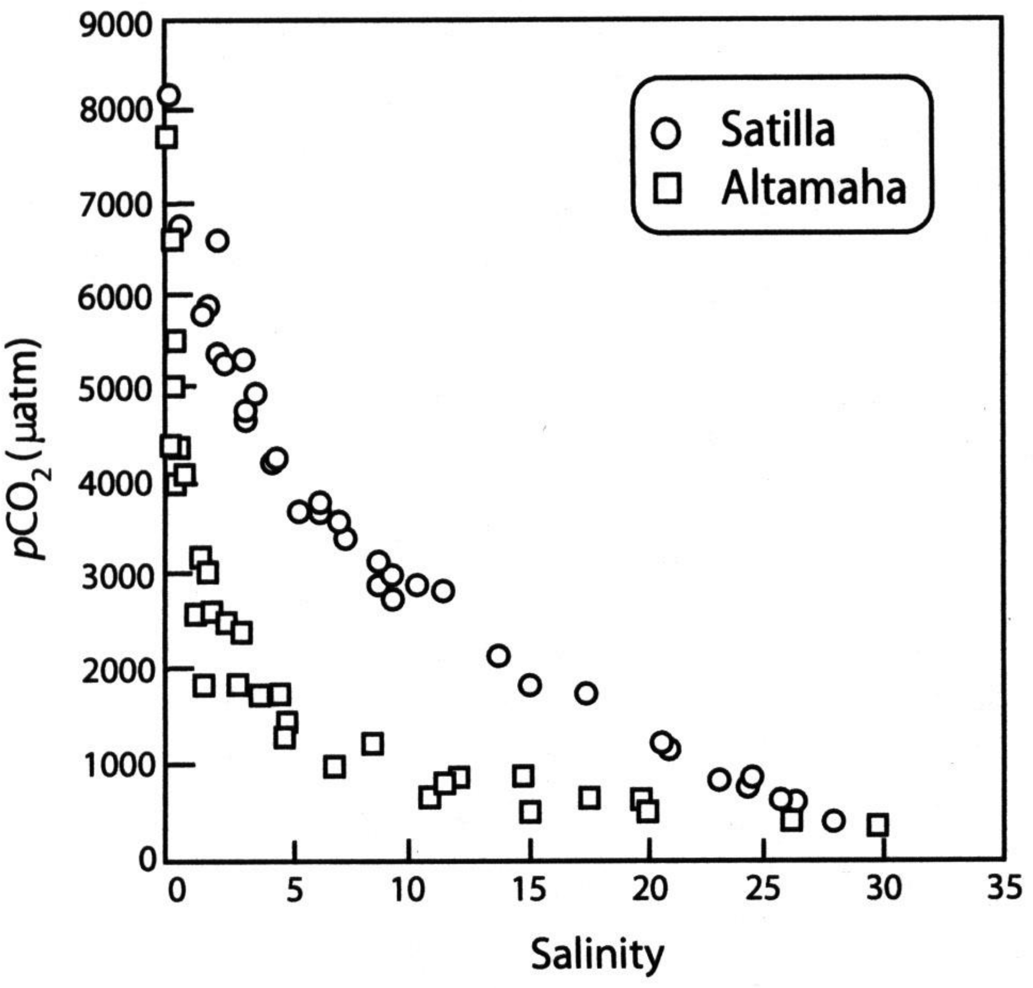


Figure 5.3 Calculated values of partial pressure of CO_2 (pCO_2), based on dissolved inorganic carbon (DIC) and pH data, versus salinity in estuarine waters of the Satilla and Altamaha Rivers (USA). (Modified from Cai and Wang, 1998.)

Nutrient Loading in Estuaries

- Nutrients naturally higher in river water than open-ocean water
- Further elevated by activities in the river catchments (*e.g.*, agriculture, fertilizer runoff)
- Also elevated by local inputs within the estuaries (*e.g.*, human waste discharge, street runoff)
- Estuary systems respond to nutrient loads

Primary Production Response to N Loading

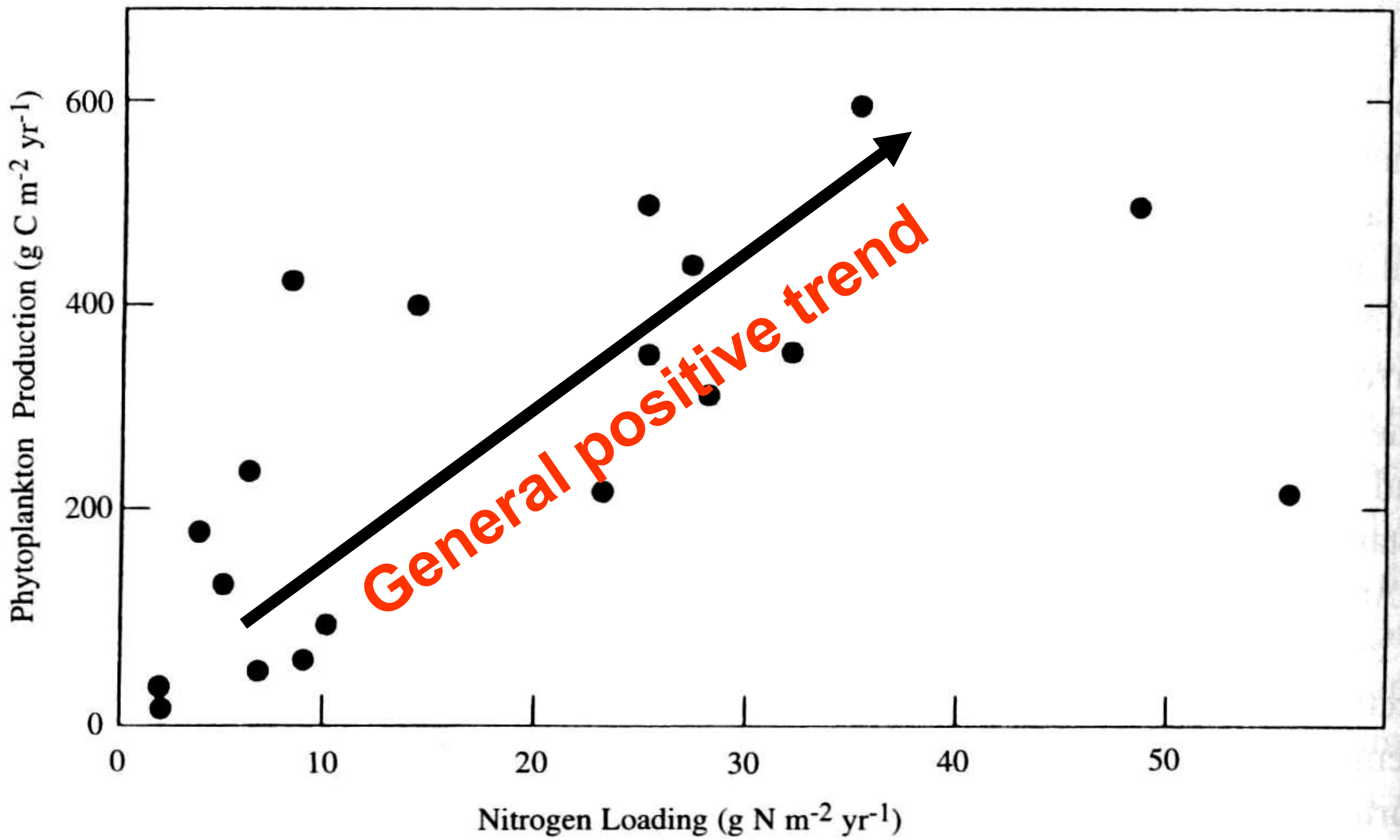


Figure 8.14 Annual phytoplankton productivity in estuaries as a function of the new inputs of nitrogen to their waters. From Boynton et al. (1982).

As Primary Production Increases, Respiration Tends to Exceed Production

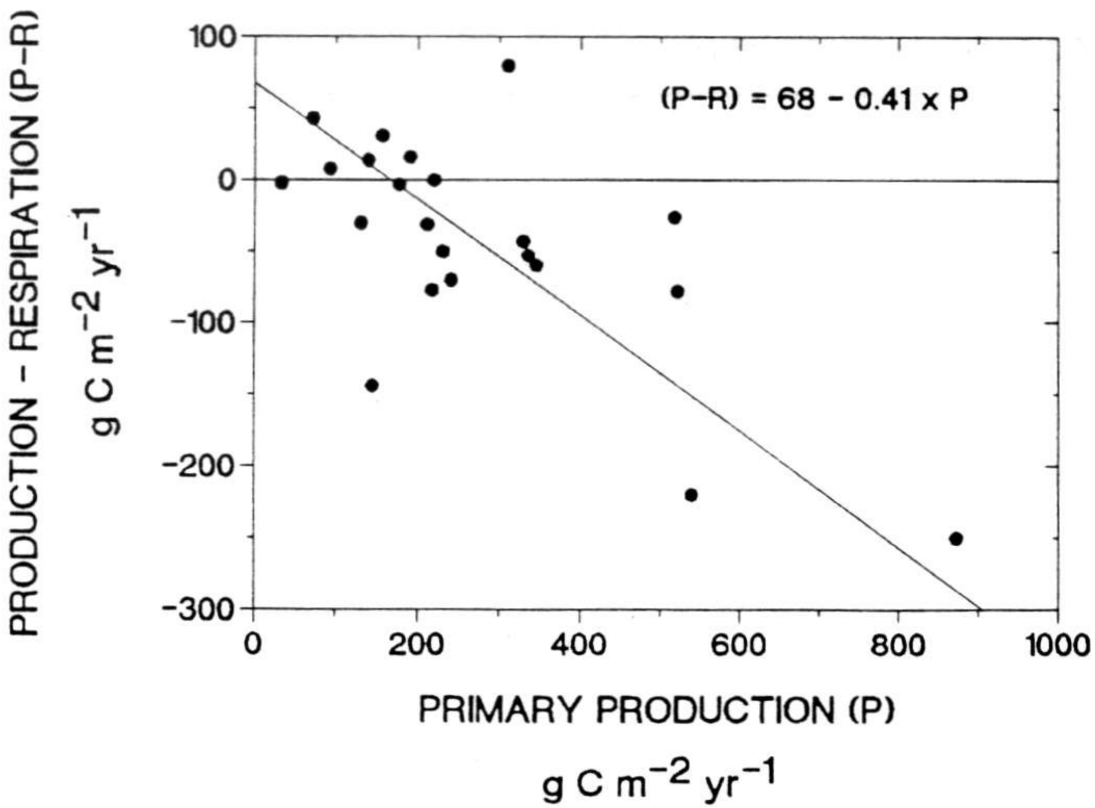


Figure 1. Relationship between primary production (*P*) and net ecosystem metabolism (*P-R*) for the 22 estuarine and continental shelf sites listed in Table 5.

Apparently reflects importance of sedimentary organic matter loading

Estuarine Nitrogen Budgets

- Pristine river waters generally have low levels of bioavailable N (NO_3 and NH_4)

- Bioavailable N is stripped from river water as it passes over salt marshes (discussed later)

- N-filtering by salt marshes is so efficient, rainfall can be a significant contributor to estuarine waters

- Most of the bioavailable N in estuaries is not new, but is recycled from mineralization of OM within estuarine water column and sediments

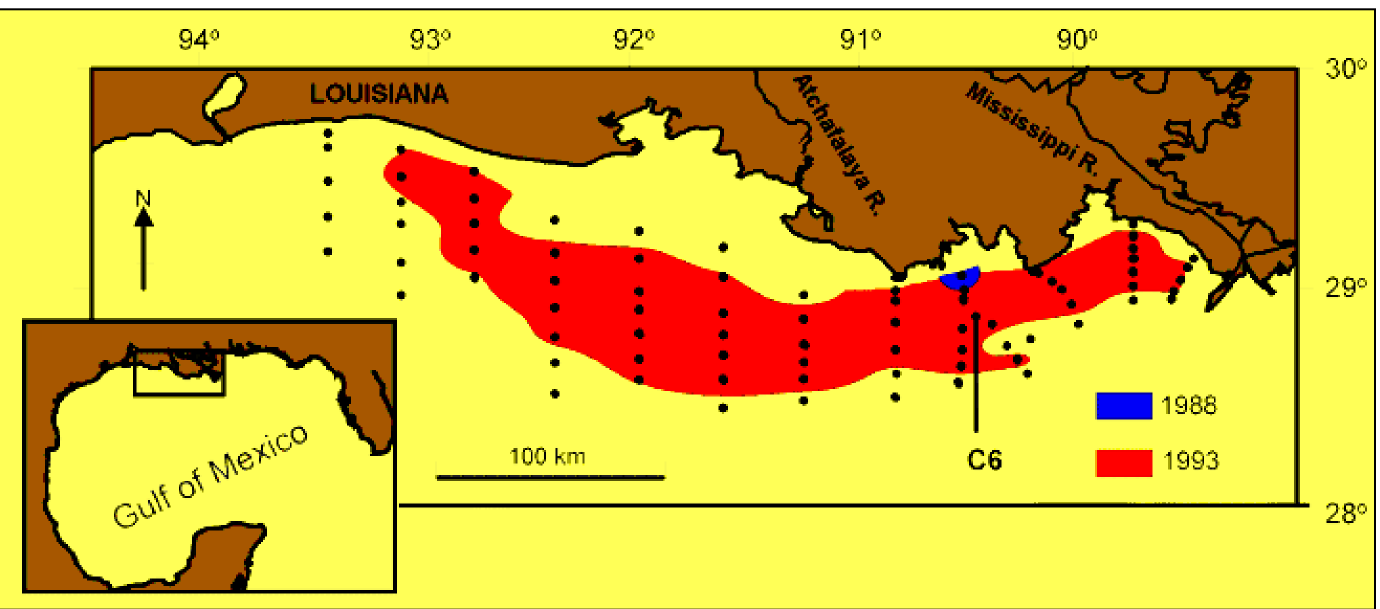
- As with eutrophied lakes, cessation of excess nutrient input may not have immediate effect -- because of sediment storage of N and P. Thus, bottom sediments can be a source of N and P long after pollutant input ceases.

Nutrient Loading and Coastal Eutrophication

- Increases in nutrients in the Mississippi River (high levels of N and P from agricultural fertilizer use in the Mississippi River Basin) results in enhanced nutrient transport to the Gulf of Mexico

- As with lake eutrophication, excess nutrients promote excessive primary productivity, which leads to a greater input of reactive OM to sediments

- Summer stratification segregates bottom waters from surface waters, and bottom waters become depleted in O_2:



Areal extent of ***bottom water hypoxia*** (<2 mg/L)

1988 – drought
1993 – flood

nigec.ucdavis.edu/publications/ar/annual98/southcentral/project63.html

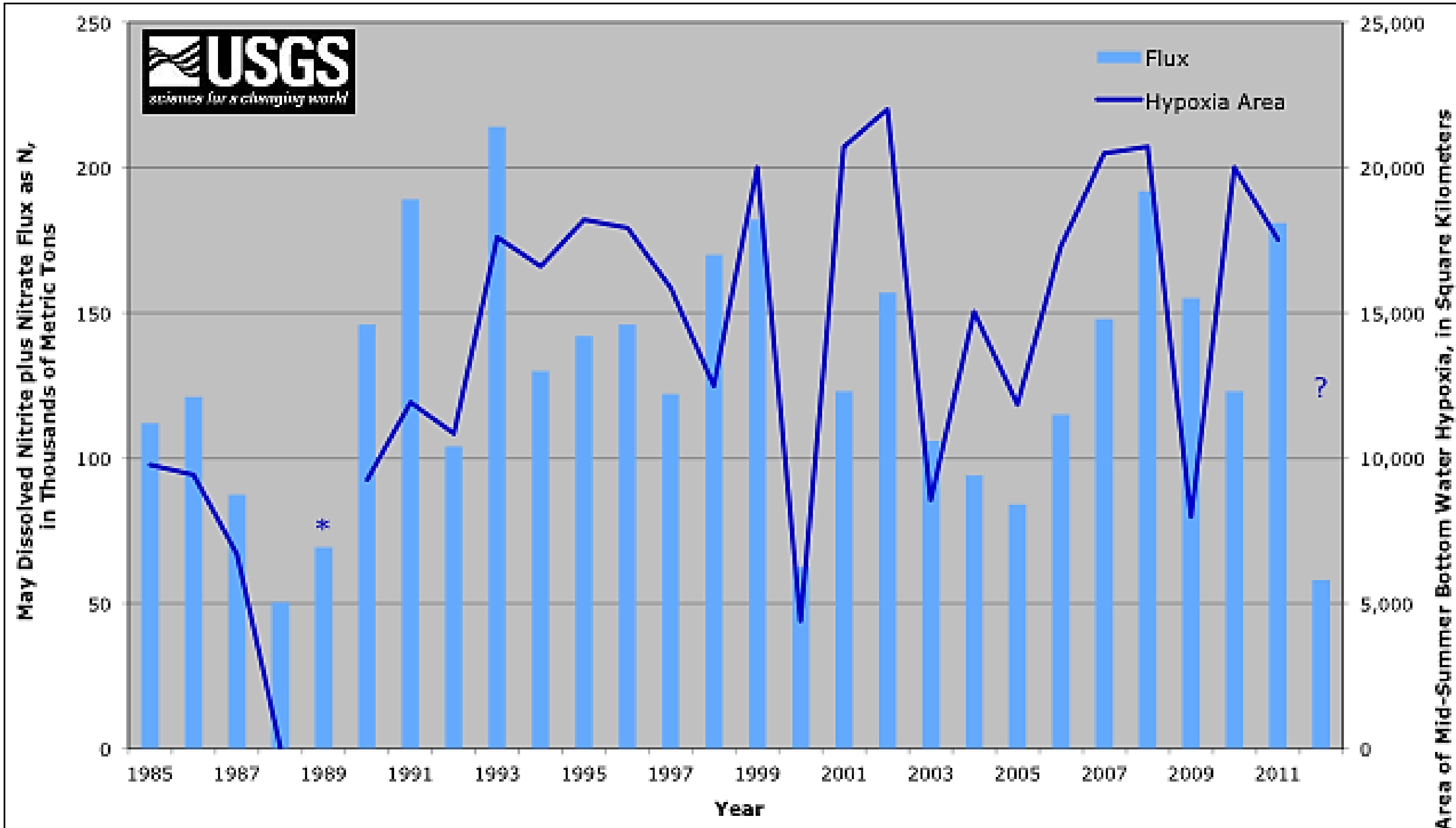


Figure 1. May dissolved nitrite plus nitrate flux to the Gulf of Mexico and area of mid-summer bottom water hypoxia (dissolved oxygen concentrations of less than 2 miligrams per liter) in the northern Gulf of Mexico. Hypoxia area data from Nancy N. Rabalais, Louisiana Universities Marine Consortium. *No hypoxia area data for 1989.

USGS **2012 Preliminary Mississippi-Atchafalaya River Basin Flux Estimate**

http://toxics.usgs.gov/hypoxia/mississippi/oct_jun/index.html

Low O_2 has caused extreme biogeochemical shifts in the highly productive, commercially important Louisiana Shelf

Sediments in Estuaries

- Big rivers (*e.g.*, Amazon, Mississippi, Columbia, etc), and smaller rivers with little or no estuary area, discharge most of their sediment to the open continental shelf or the upper slope
  - This is the fate of most <u>global</u> river sediment discharge
- BUT the sediment in smaller rivers with significant estuaries is trapped in those estuaries because of slow water flow
  - This is what happens along most of the world coastlines
  - Sediment reactions in estuaries and elsewhere differ from water column reactions because of low redox conditions in the sediments

Sulfur Cycle in Coastal Seds

Active S cycle in estuarine sediments due to:

- High conc of SO_4^{2-} in seawater (28 mM)
- Large inputs of land- and estuary-derived organic matter

Permanent burial of reduced S-bearing minerals

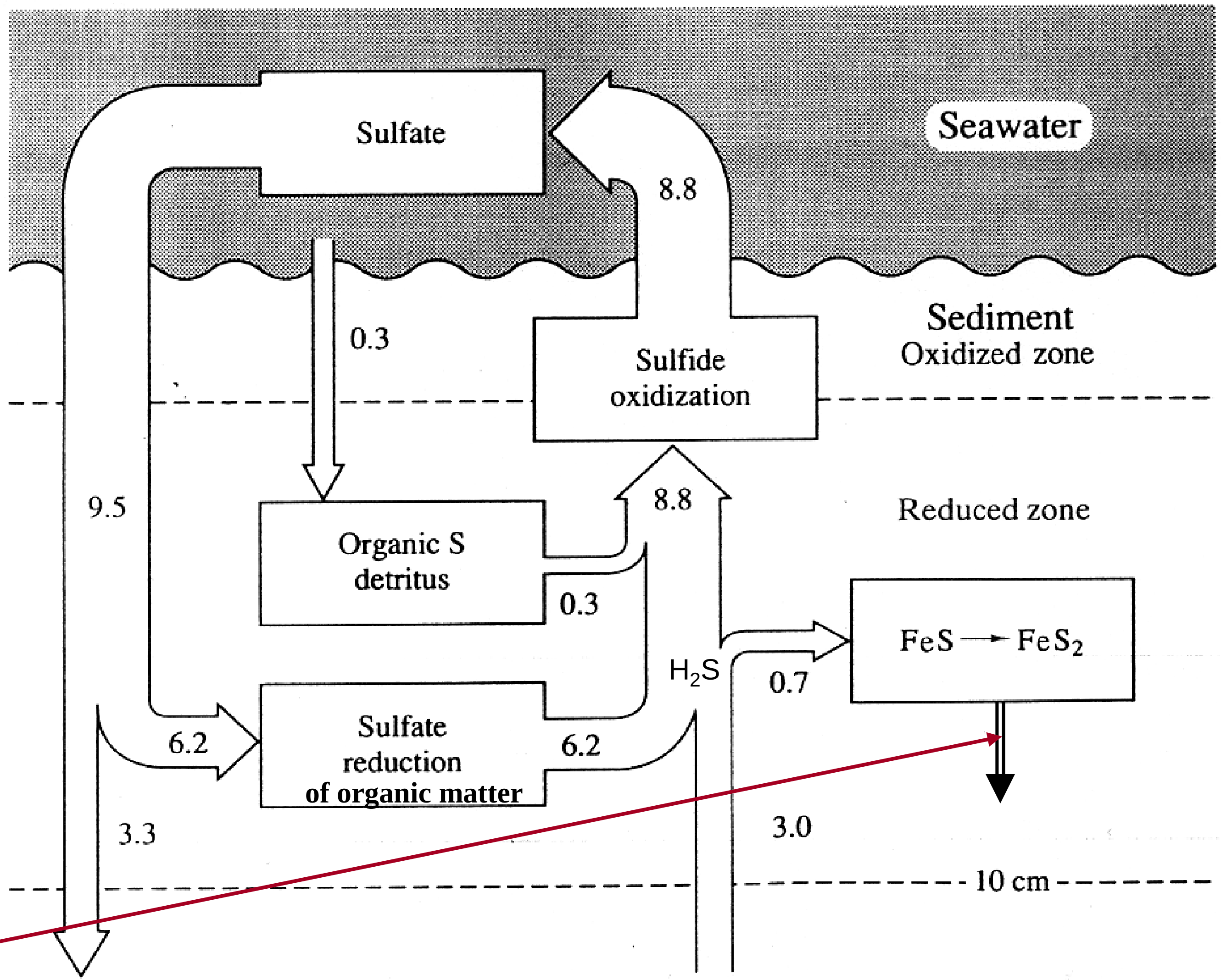


Figure 8.10 Transformations of sulfur in a coastal marine sediment. Note that of 6.2 g S m^{2-} yr^{-1} undergoing sulfate reduction, only 0.7 g S m^{-2} yr^{-1} is permanently stored in the sediment as pyrite or other reduced minerals. From Jørgensen (1977).

Salt Marshes

Definition: A relatively flat intertidal area along the margin of an estuary where fine-grained sediment is deposited and salt-tolerant grasses grow

Salt marshes are among the most biologically active area on earth

Salt Marshes - Geomorphology

Extent of channelization depends on the tidal range (more tide → more channels)

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Salt Marshes – Geomorphology & Hydrology

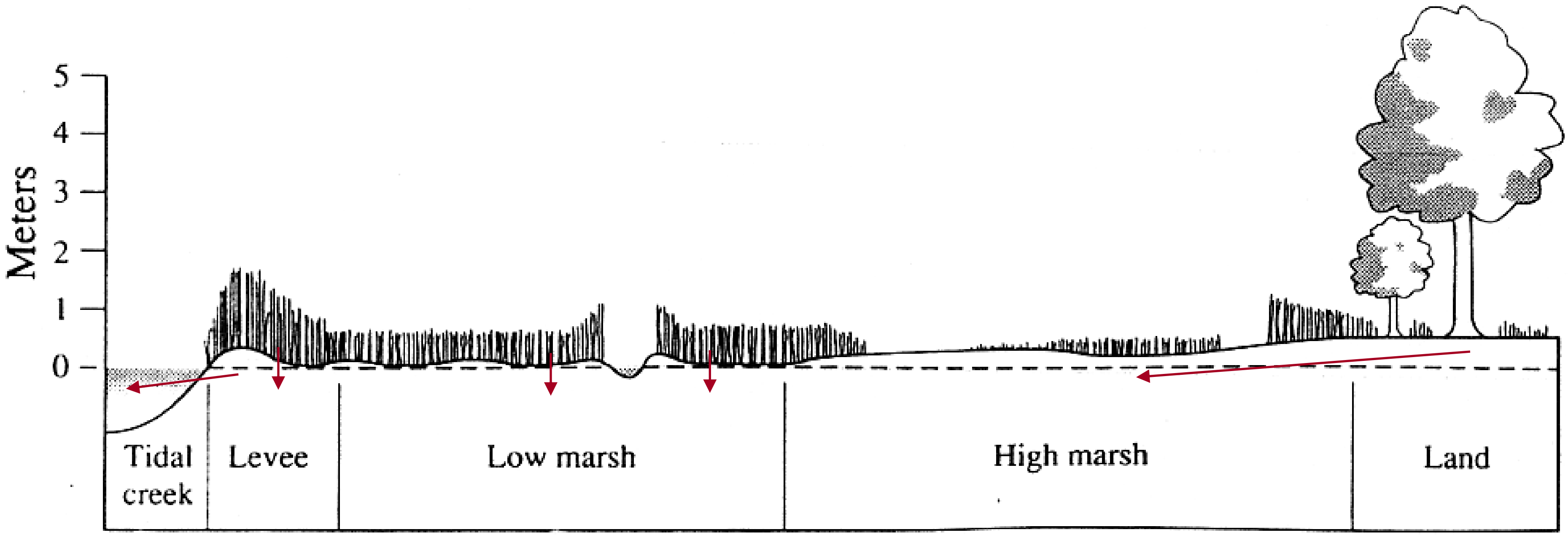
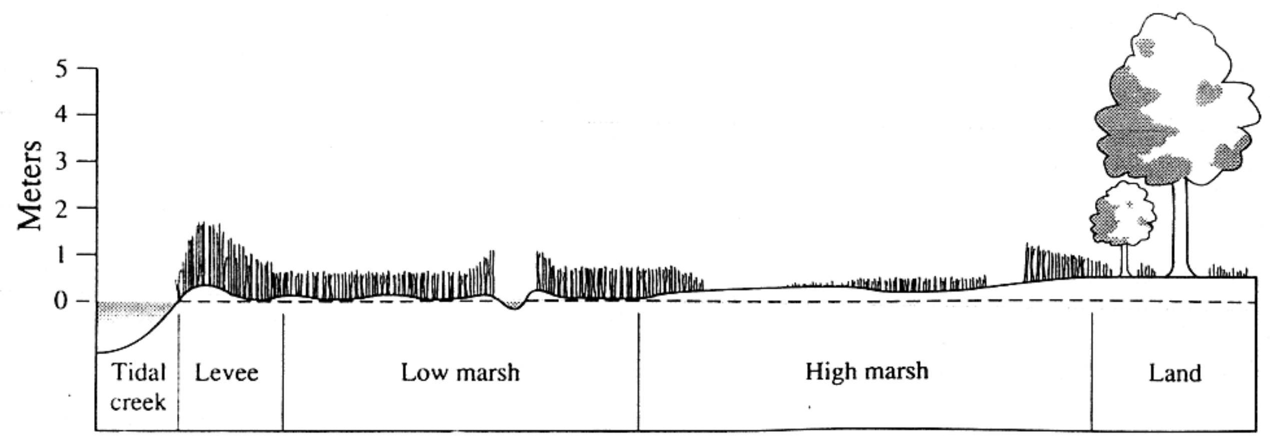


Figure 8.9 Schematic cross section through a salt marsh, showing the relationship between various components of the salt marsh ecosystem and the open waters of the estuary. From Wiegert et al. (1981).

Tide-induced flushing, combined with groundwater flow from land, leads to large amounts of import & export with tidal creeks



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- Tidal flows:
  - low tide - low salinity flow due to flushing of marsh by freshwater runoff from land
  - high tide - marsh is inundated with seawater, highest salinities observed
- Salt marsh soils undergo daily cycle of changing aeration and, thus, redox state:
  - high tide - soils are inundated, anaerobic conditions may develop
  - low tide - soils drain, high redox potential re-established in surface sed

- Salt marsh vegetation exists in dynamic equilibrium between rate of sediment accumulation and rate of sea level rise (or coastal subsidence):

  - as deposits accumulate, erosion and OM oxidation increase, slowing rate of further accumulation

  - as sea level rises, marsh is inundated more frequently, and accumulation rate of sediment and peat increases

- When rate of sedimentation does not kept up with sea-level rise, marshland is lost

- Sea level rise due to global warming could accelerate loss of marshland

Salt Marshes as Filters & Transformers of Nutrients

Table 8.7 Annual Flux of Carbon and Nutrients from Salt Marshes to Coastal Waters[a]

Marsh	Organic Carbon ($g\ C\ m^{-2}\ yr^{-1}$)			Nitrogen ($g\ N\ m^{-2}\ yr^{-1}$)			Phosphorus ($g\ P\ m^{-2}\ yr^{-1}$)	
	DOC	POC	TOC	NH_4^+	NO_3^-	Total	PO_4	TP
Great Sippewissett, Massachusetts		−76[b]		−4.2	−3.8	−24.6	−0.6	
Flax Pond, Long Island, New York	−8.4	+61	+53	−2.0	+1.0		−1.4	−0.3
Canary Creek, Delaware	−38	−62	−100	+0.7	+1.9	−1.2	<-0.1	
Gott's Marsh, Patuxent River, Maryland		−7.3		−0.4	−0.9	−3.7		−0.3
Ware Creek, York River, Virginia	−80	−35	−115	−2.9	+2.3	−2.8	−0.1	+0.7
Carter Creek, York River, Virginia	−25	−116	−142	−0.3	+0.3	−4.0	−0.6	0
Dill Creek, South Carolina		−303					−6.4	
North Inlet, South Carolina			−431					
Barataria Bay, Louisiana	−140	−25	−165					

[a] From Nixon (1980).
[b] Negative values are losses from marsh to estuary

- Salt marshes receive NO_3 from rivers and groundwater, and convert it to DON, PON, and NH_4
- Despite long-term storage of OM, most salt marshes are sources of C, N and P to estuaries

Nitrogen Cycling in Salt Marshes

Table 8.8 Nitrogen Budget for the Short *Spartina alterniflora* Areas of Great Sippewissett Marsh, Massachusetts[a]

	Nitrogen (g N m^{-2} yr^{-1})	Percent of annual plant N demand
Intersystem cycling		
Gains		
N-fixation	12.1	50.0–54.0
Precipitation	0.8	3.0–3.6
Import	0.9	3.7–4.0
Total	13.8	57.0–61.6
Losses		
Denitrification	4.1–5.6	16.9–25.0
Accretion	3.7–4.1	15.3–18.3
Export	2.0–3.2	8.3–14.3
Total	9.8–12.9	40.5–57.6
Intrasystem cycling		
Remineralization	14.9–16.3	61.6–72.8
Translocation	1.4	5.9–6.3
Total	16.3–17.7	67.4–79.0

[a] Gains and losses are from the vegetated sediment system. From White and Howes (1994).

- Salt marshes are often N-limited
- Flooded, anaerobic sediments of salt marshes allow significant rates of denitrification
- In most salt marshes, NH_4 is the dominant N-form, since nitrification rates are low, and denitrifiers remove much of the NO_3
- Contribution of new inputs and recycled N in salt marshes are about equal -- different from upland ecosystems where new inputs are much lower (~10%)
- N-fixation by cyanobacteria and soil bacteria may contribute significantly to salt marsh N-budgets

Salinity Effects on Salt Marsh Biogeochemistry

Salt marshes can exist over a wide range of salinities, so there will be large variations in the biogeochemistry of different marshes

Organic matter oxid	Oxidant	Reductant
Aerobic oxidation	O_2	H_2O
Manganese reduction	MnO_2	Mn^{2+}
Nitrate reduction	HNO_3	N_2
Iron reduction	Fe_2O_3	Fe^{+2}
Sulfate reduction	SO_4^{2-}	S_2^-
Methanogenesis	CO_2	CH_4

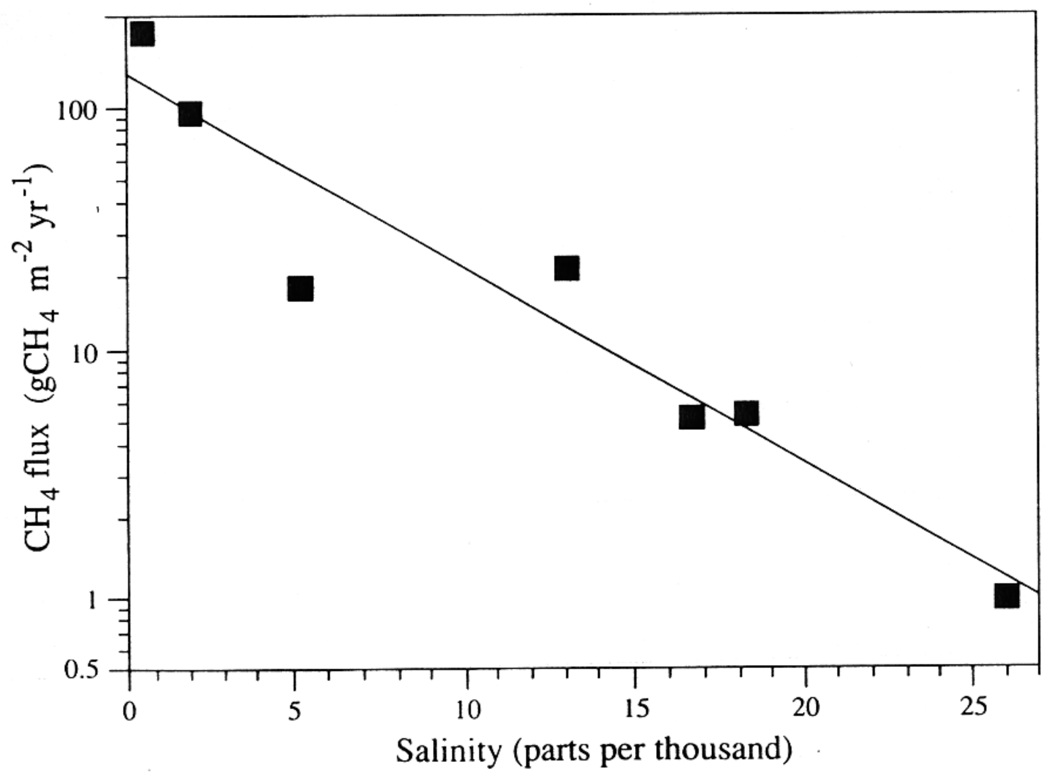

Figure 8.11 Annual methane lost from salt marsh soils as a function of salinity. From Bartlett et al. (1987).

Estuaries – an overview

- Water flow slows as rivers enter estuaries, and exchange via mixing with coastal ocean becomes important
- Salinity changes occur and are accompanied by changes in chemistry (nutrients, pH, O_2, redox, etc.)
- Sediment trapping (and subsequent organic matter oxidation) occurs because of slowed flow
- Nutrient (N and P) and organic loads to estuaries are typically high and are often influenced by pollution sources
- Primary production is typically elevated, but estuaries may be either net autotrophic or heterotrophic