River discharge, coastal metabolism, and the fate of carbon in the coastal zone

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Outline

- Introduction and major features of the coastal zone
- Land inputs (C, N, P)
- Metabolic balance and significance of coastal ecosystems in the global oceanic carbon cycle
  - The ecosystem approach: survey of the 5 main ecosystems
  - Other approaches: air-sea CO2 fluxes, mass balance
- Burial and export
- How do we go regional?

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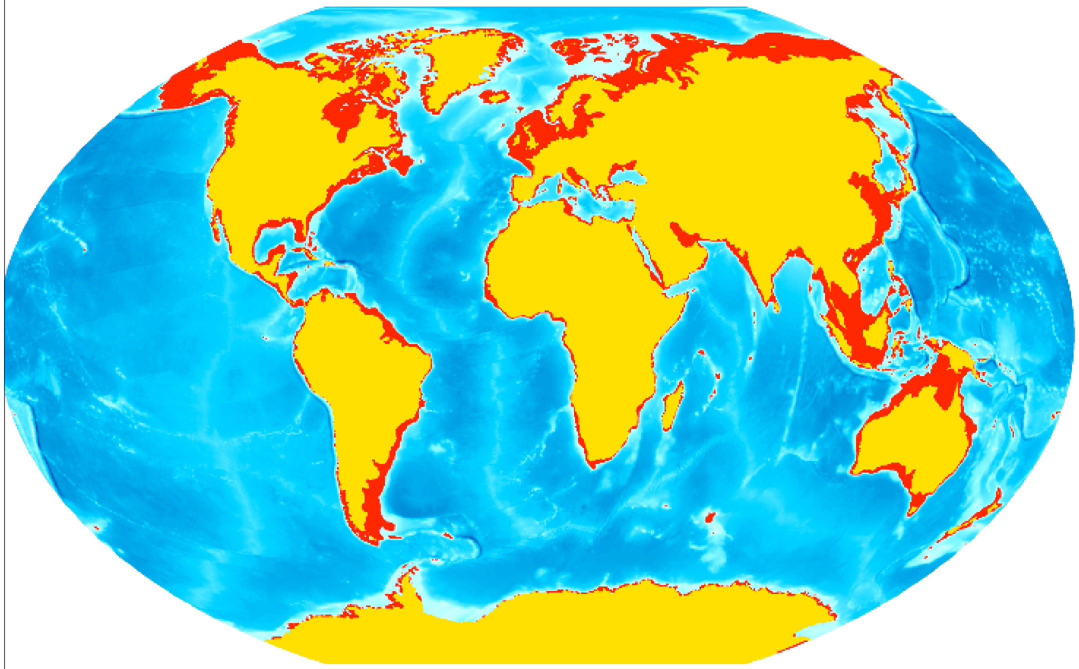
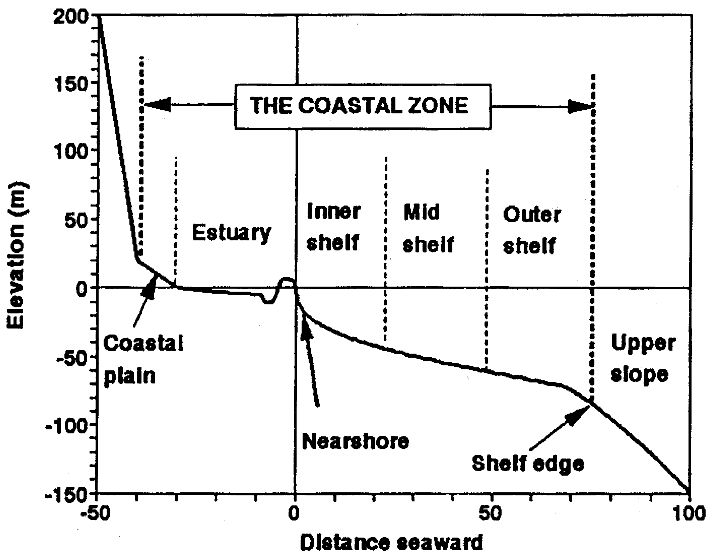
Definition and extent of the coastal zone





(Wright, unpublished)

- From the coastline to the continental margin, depth < 200 m
- Average width: 70 km; surface area: 26 10^6 km^2 or 7% of the surface of the global ocean.

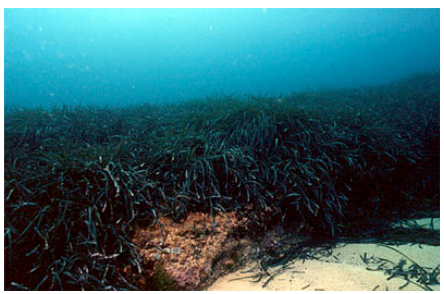
Coastal ecosystems: great physiographic and biological diversity

Courtesy: GBRMPA

Coral reefs
0.6 million km^2

Courtesy: davidluquet.com

Macrophytes
1.4 million km^2



Courtesy: davidluquet.com

Seagrass beds
0.6 million km^2

Courtesy: GBRMPA

Mangroves
0.2 million km^2

Courtesy: www.clas.uconn.edu

Salt--marshes
0.4 million km^2

Courtesy: davidluquet.com

Sediments
23.9 million km^2

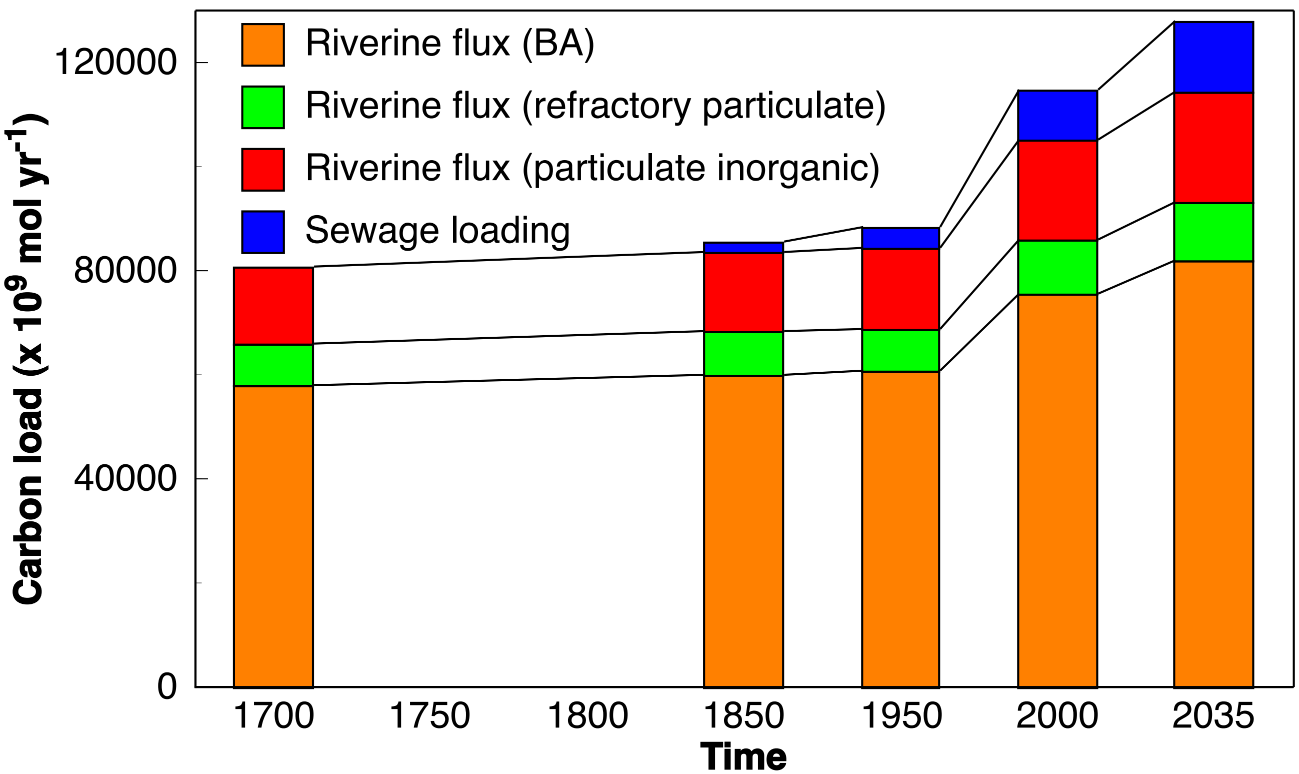
Costal Zone: Introduction (cont'd)

- Despite its relatively modest surface area, it plays a considerable role in the biogeochemical cycles because it:
  - receives massive inputs of terrestrial organic matter and nutrient
  - exchanges large amounts of matter and energy with the open ocean
  - constitutes one of the most geochemically and biologically active areas of the biosphere
- Additionally, the coastal zone:
  - represents 90% of the world fish catch (Pauly & Christensen, 1995).
  - its overall economic value is 43% of the value of the world's ecosystem services and natural capital (Costanza et al., 1997).
  - is the area of greatest human impact on the marine environment since 37% of the human population live within 100 km of the coastline (Cohen et al., 1997).

Inputs from land

- Freshwater inputs relatively well constrained (except SGD): about 40 km^3/yr
- **Inputs comprise**:
  - particulate material (sediment and organic matter)
  - dissolved material (organic matter and nutrients)
- **Two components** difficult to tease apart: natural and anthropogenic
- Inputs from runoff **highly variable** both in space and time:
  - geomorphology of watershed (area, elevation, slope)
  - climate (precipitation, temperature)
  - geology (soil type)
  - biology (type of vegetation)
  - anthropogenic activities (population density, land use, industry)
- **Non-point sources** locally important but global magnitude poorly known
- Inputs are **processed, stored or exported** (to the open ocean or back to land)

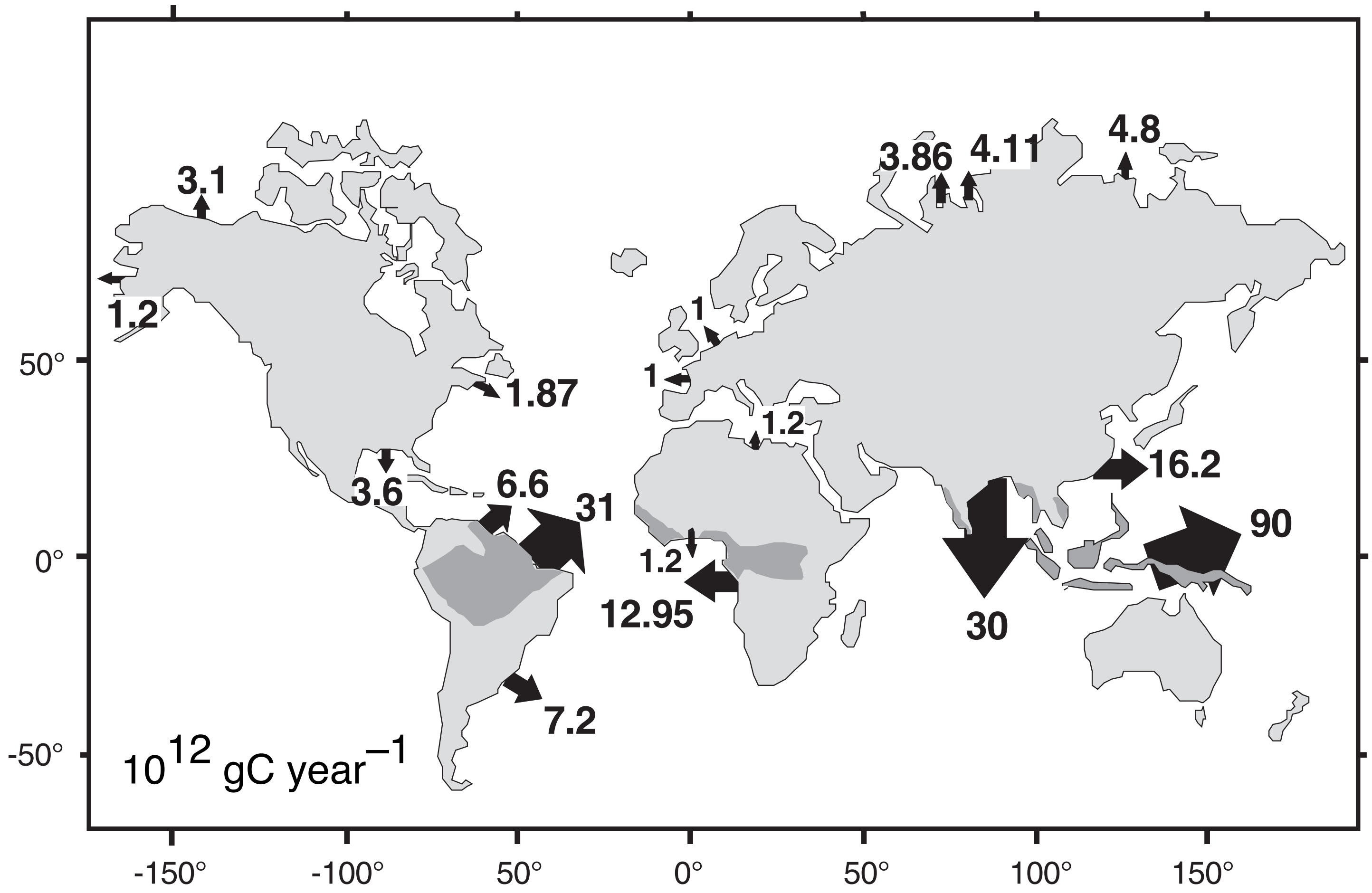
Past, present and future inputs of Carbon



- Input of natural C: 76.8 Tmol/yr (60% dissolved, 40% particulate)
- Additional anthropogenic is 8 Tmol/yr
- Dissolved load of inorganic C: mostly bicarbonate
- TOC: 31-36 Tmol/yr, large contribution of wet tropical rivers

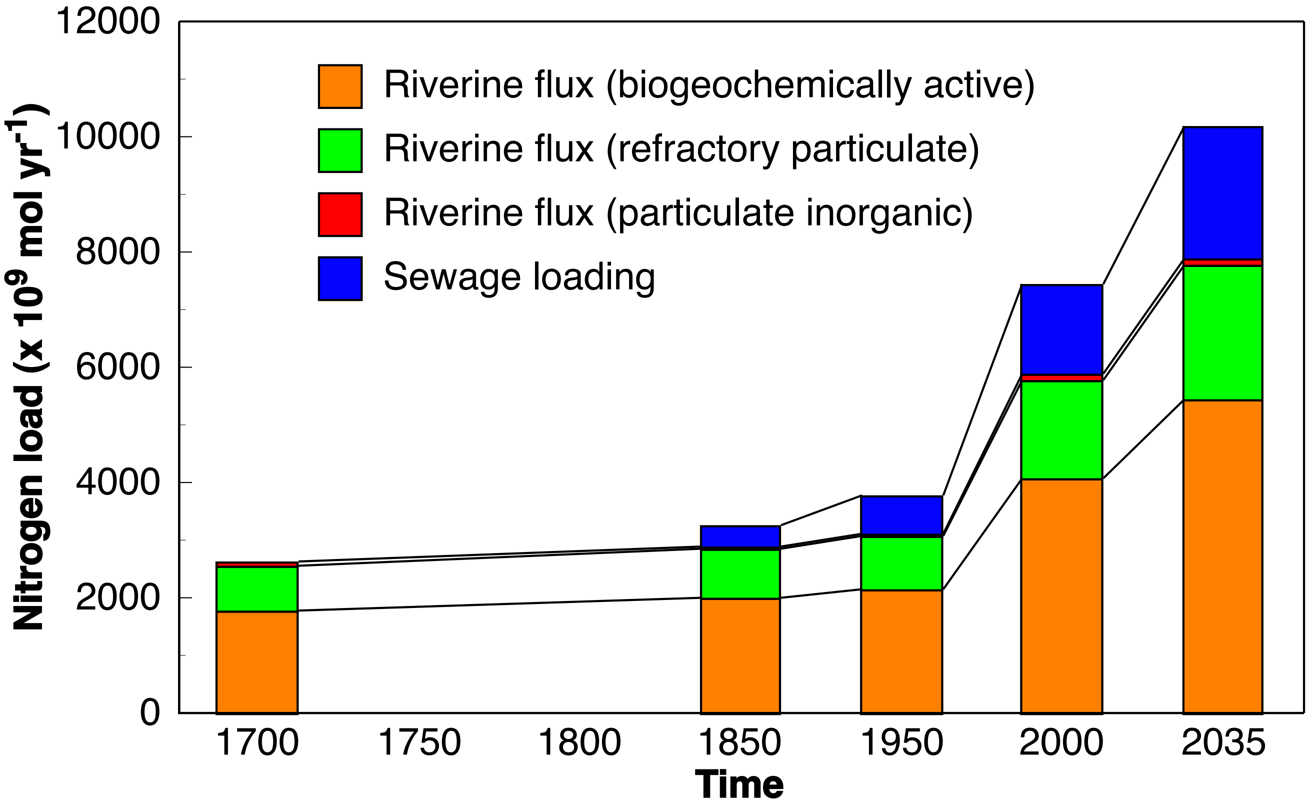
Source: Mackenzie et al. (2002)

Annual discharge of total organic carbon of major world rivers to the oceans



Source: Schlünz & Schneider (2000)

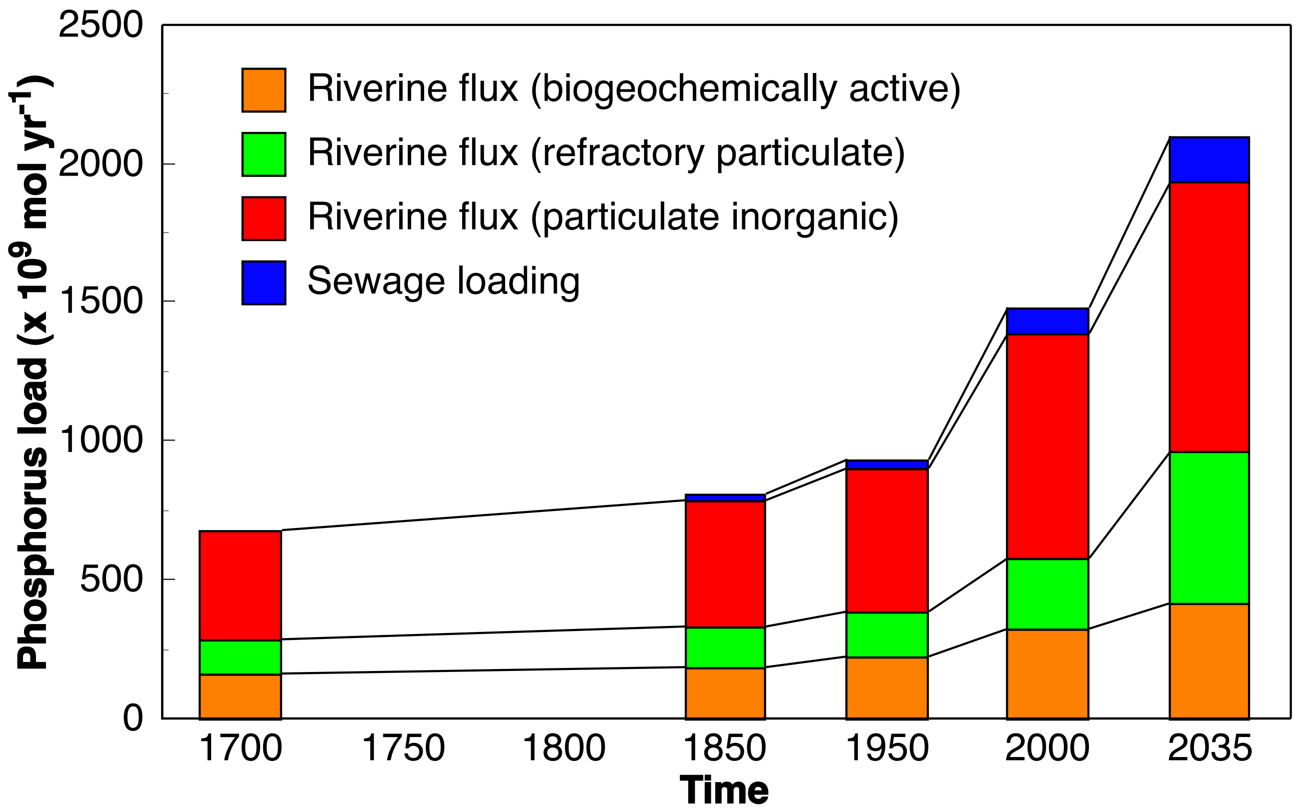
Past, present and future inputs of Nitrogen



- pristine-1970: about 50% increase of DIN
- 1970-1990: additional 180% increase
- 2000-2035: total N increase of 37%, half of which in the form of sewage (labile)

Source: Mackenzie et al. (2002)

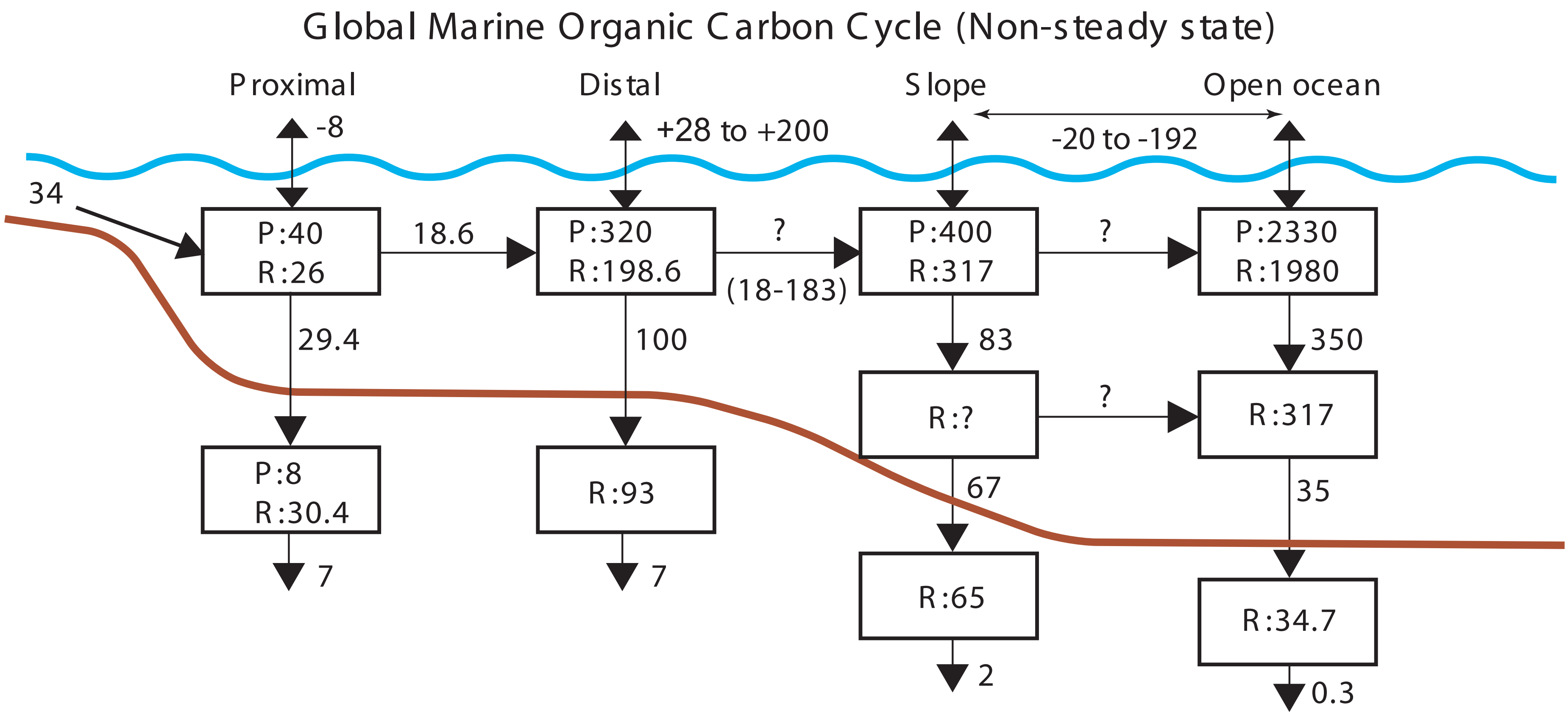
Past, present and future inputs of Phosphorus



- pristine-1970: about 100% increase of DIP
- 1970-1990: additional 180% increase
- 2000-2035: total increase of 41%

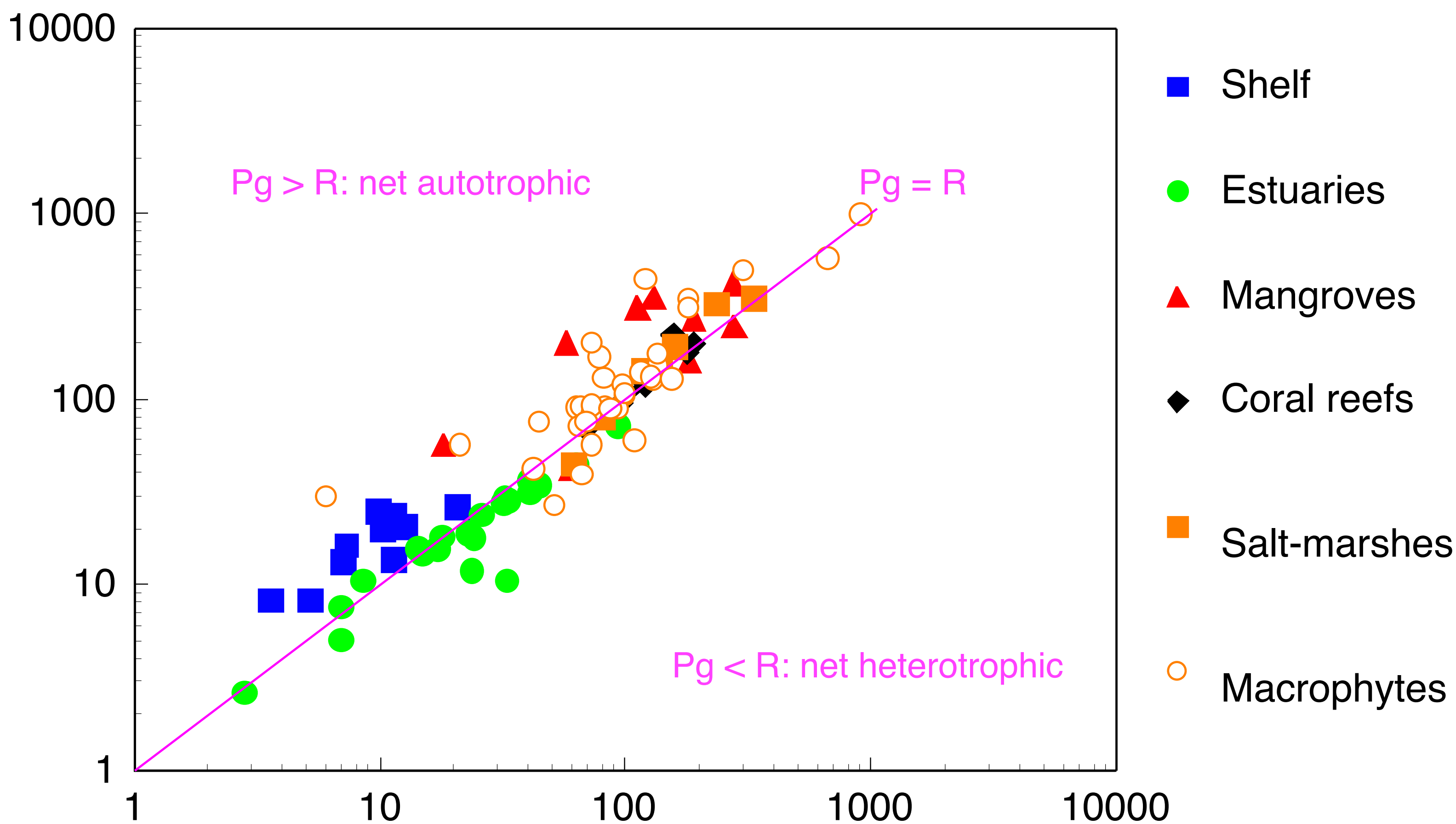
Source: Mackenzie et al. (2002)

Ecosystem metabolism: Recent box model



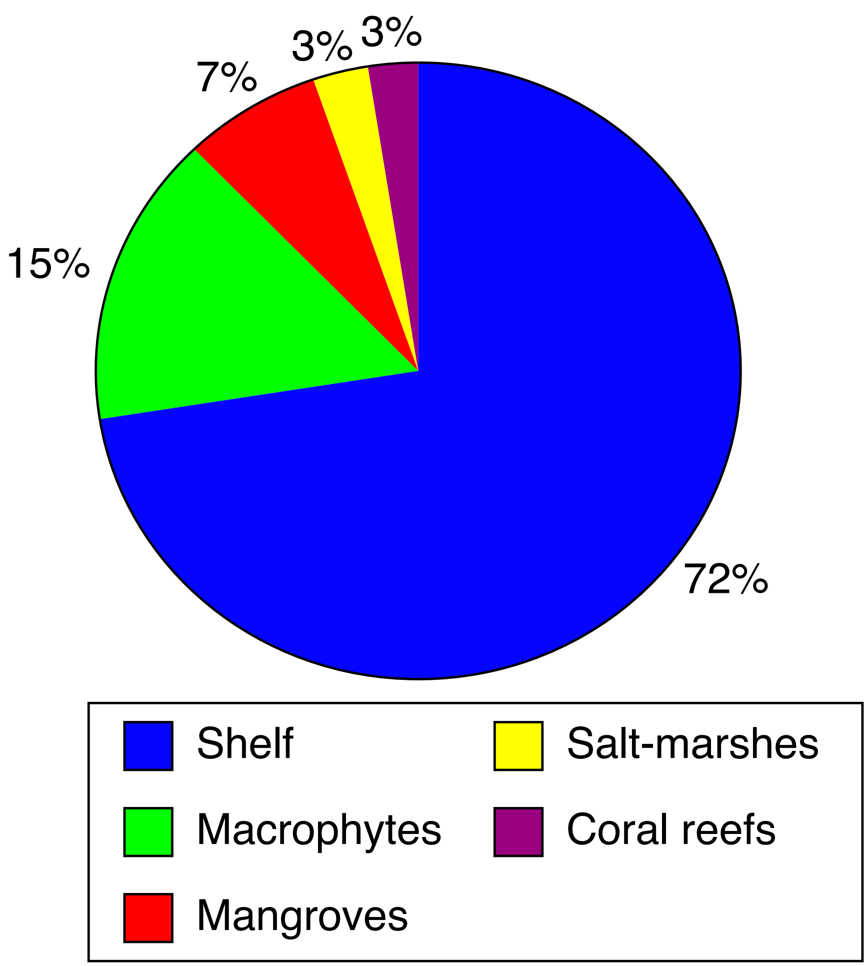
Source: Mackenzie et al. (2004)

1st approach: ecosystem metabolism



Source: Gattuso et al. (1998)

Significance of coastal ecosystems in the global carbon cycle— Ecosystem approach



- All coastal ecosystems appear to be net autotrophs (GPP/R > 1; NEP > 0) except estuaries which exhibit a negative NEP and are net heterotrophs.
- These data can be upscaled to provide an estimate of coastal metabolism. There are limitations:
  - metabolic data are scarce for some ecosystems
  - not weighted averages
  - NEP often estimated as GPP - R
- GPP = 789 Tmol C/yr relatively close to previous estimates of 500 Tmol C/yr since the later did not take into account mangroves and macrophyte-dominated ecosystems (Smith & Hollibaugh, 1993; Wollast, 1998).
- NEP = 235 TmolC/yr.

Source: Gattuso et al. (1998)

Ecosystem studies: conclusion (cont'd)

- Anthropogenic disturbance (loading of nutrients and organic C) could shift the coastal ocean towards a more autotrophic or a more heterotrophic state.
- Increased carbonate precipitation and increased heterotrophy (or decreased autotrophy) resulted in a source of CO_2 which was smaller than the rise of atmospheric CO_2. The present coastal ocean is therefore a sink for atmospheric CO_2 (Mackenzie et al.).
- The main areas for which data are lacking are:
  – the respiration rate of coastal waters
  – the fate of C imported from land and an estimate of the export of organic carbon from the coastal ocean to the open ocean (see Bauer and Druffel, 1998)

Drawbacks of the ecosystem metabolism approach

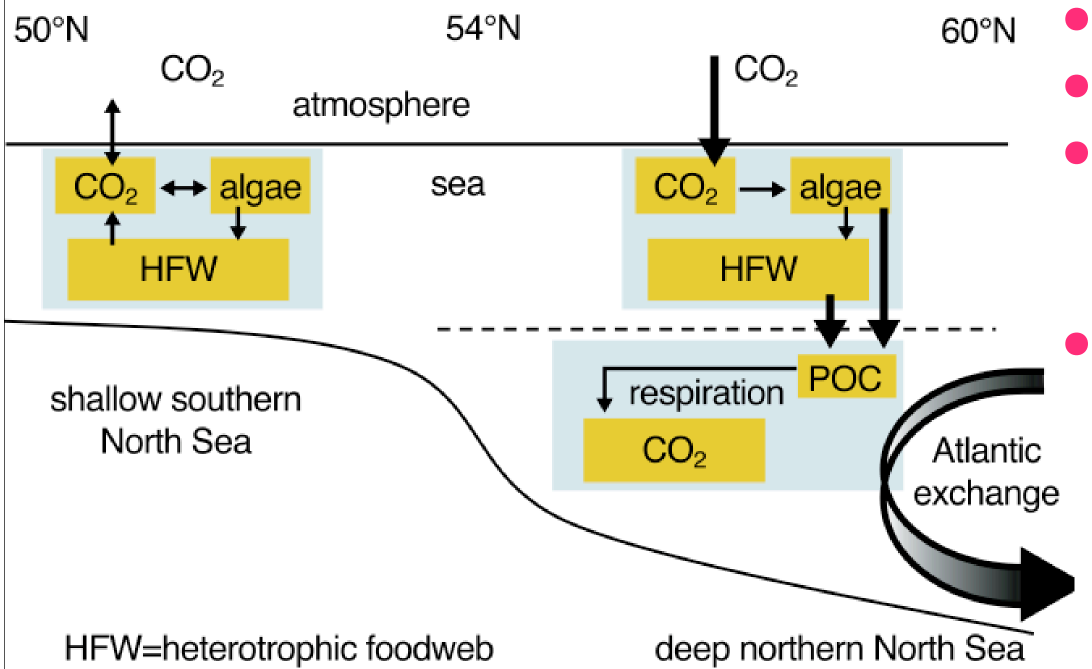
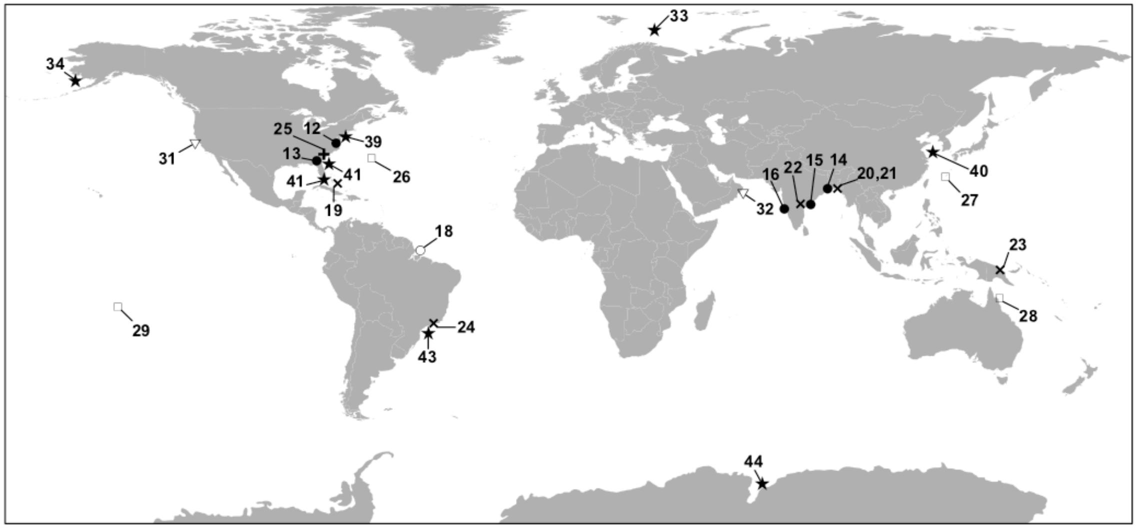


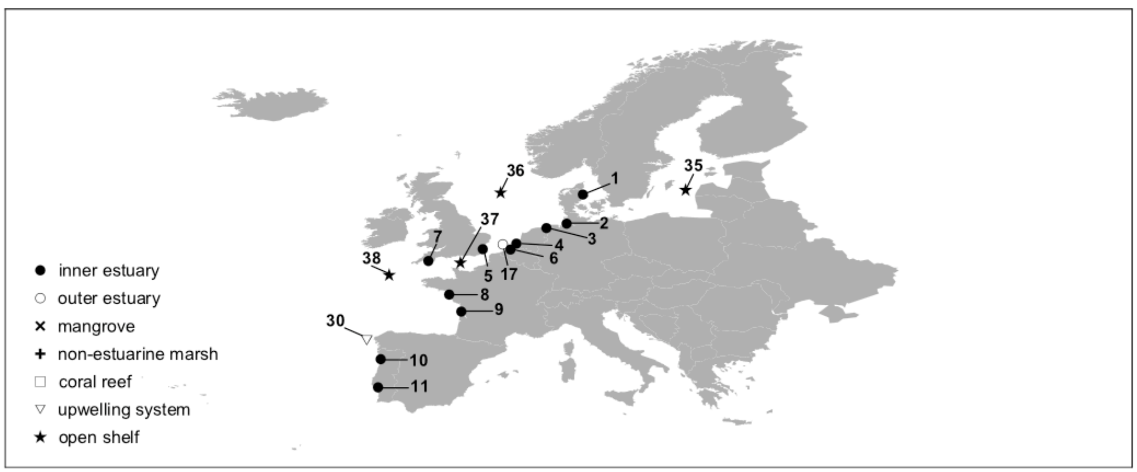
Figure 1. South-north section through the North Sea. In the shallower southern region production and respiration processes occur in the mixed layer, whereas in the northern region respiration processes mainly occur in the separated subsurface layer, which is subjected to exchange circulation with the North Atlantic Ocean. The dashed line indicates the thermocline, and the darkening of the arrow implies the increase of dissolved inorganic carbon in the North Atlantic Ocean water circulated through the North Sea [after 10].

- Paucity of data
- Continental shelf pumping
- No way to separate R of allochthonous and autochthonous organic matter
- No direct information on burial

Source: Thomas et al. (2004)

2nd approach: air-sea CO_2 fluxes





Excluding estuaries and salt-marshes:

- coastal ocean is a sink for atmospheric CO2 (-1.2 mol m^{-2} yr^{-1})
- uptake of atmospheric CO_2 by the global ocean increases by 24%.

Including estuaries and salt-marshes:

- coastal ocean is a source for atmospheric CO_2 (+0.38 mol m^{-2} yr^{-1})
- uptake of atmospheric CO_2 from the global ocean decreases by 12%.
- CO is a CO_2 source at high and subtropical and tropical latitudes, and a moderate sink at temperate latitudes.

Upscaling hampered by limited data coverage and poorly constrained estimate of the surface area of inner estuaries.

Source: Borges (sbm)

3rd approach: mass balance
Fate of river-derived organic matter

- Organic carbon delivery is only about 0.7% of terrestrial NPP (36 x 10^{12} vs 5 x 10^{15} mol/yr)
- Less than 10% of the total suspended material reaches the deep sea (Eisma et al., 1995)
- Three possible fates:
  - Accumulate in sediment (burial)
  - Oxidized
  - Accumulate in the water column
    - reservoir of oceanic TOC ~ 140 x 10^{15} mol (S&H93)
    - inputs of ~ 36 x 10^{12} mol/yr (Schlünz & Schneider, 2000)
    - doubling time of 4000 yr if it did not react, hence OC enters other reservoirs

Partly from Smith & Hollibaugh (1993)

Organic carbon burial in the coastal ocean

Component	10^{12} mol C/yr
Vegetated habitats	
Mangroves	2.0
Salt-marsh	5.0
Seagrass	2.3
Total	**9.3**
Depositional areas	
Estuaries	6.8
Shelf	3.8
Total coastal	**19.8**
Deep sea burial	0.5
Total oceanic burial	**20.3**

- Previous estimates: 8.3 x 10^{12} mol/yr
- Role of marine vegetation grossly underestimated
- Total burial is 2-fold higher than previously anticipated
- About 98% of burial occurs in the coastal ocean

Source: Duarte et al. (2004; Biogeosciences Discussions)

Metabolism and export

GPP
500 (S&H)
1907 (D&W)

Land inputs
34 (S&H)
36 (S&S)

R
507 (S&H)
1150 (R&W) + 620 (M)=1770

Burial
9 (S&H)
20 (D)

Export
18 (S&H)
151 (range previous estimates: 40-500)

D: Duarte et al. (2004)
D&W: del Giorgio & Williams (in press)
M: Middelburg et al. (in press)
R&W: Robinson & Williams (in press)
S&H: Smith & Hollibaugh (1993)
S&S: Schlünz & Schneider (2000)

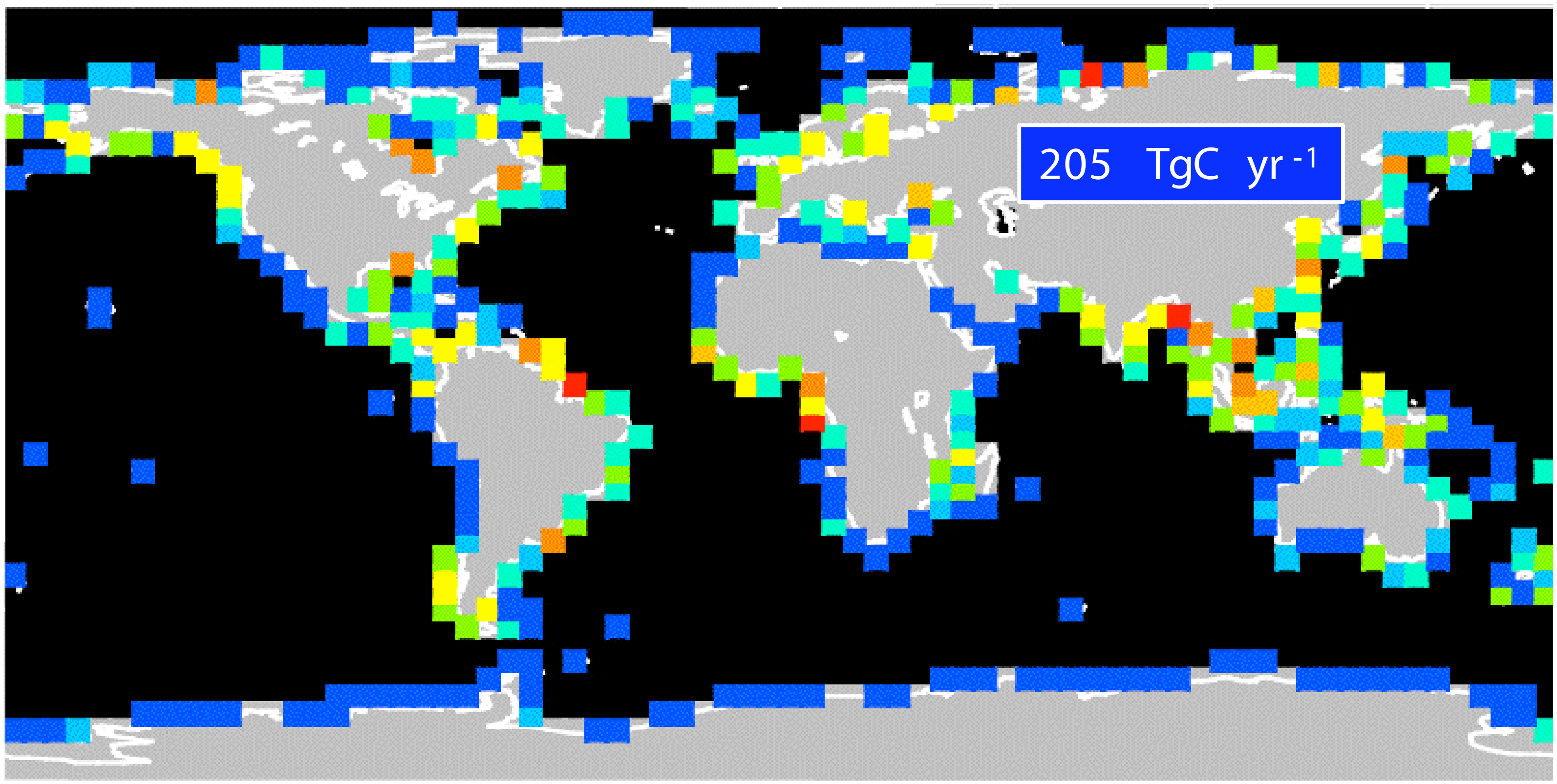
Latest estimates on inputs and fate of organic C
(Schlünz & Schneider, 2000)

Organic carbon source	Global Flux (10^{12} gC year$^{P\ 1}$)	Burial (%)	Burial (10^{12} gC year$^{P\ 1}$)
Global marine primary production	36,500 [a]		
Coastal ocean	6,900 [b]	0.8 [e]	55.2
Open ocean	29,600	0.03 [e]	8.8
River input	434 [c]	10 [c]	43.4 [c]
Aeolian input	320 [d]	10	32
Total			139.4

[a] Antoine et al. (1996)
[b] Wollast (1991)
[c] This paper
[d] Romankevich (1984)
[e] Berger et al. (1989)

- Note that burial in CZ is underestimated
- About 65% of the riverine POC flux is refractory (labile fraction already processed on land in soils and aquifers)
- 11.6 x 10^{12} mole/yr should be buried rather than 3.6 x 10^{12}
- Where do the remaining 90% go?
  - Amazon data not representative
  - Contribution of terrestrial organic carbon in offshore sediments underestimated. Subject to intense debate

Spatially-explicit model: DOC



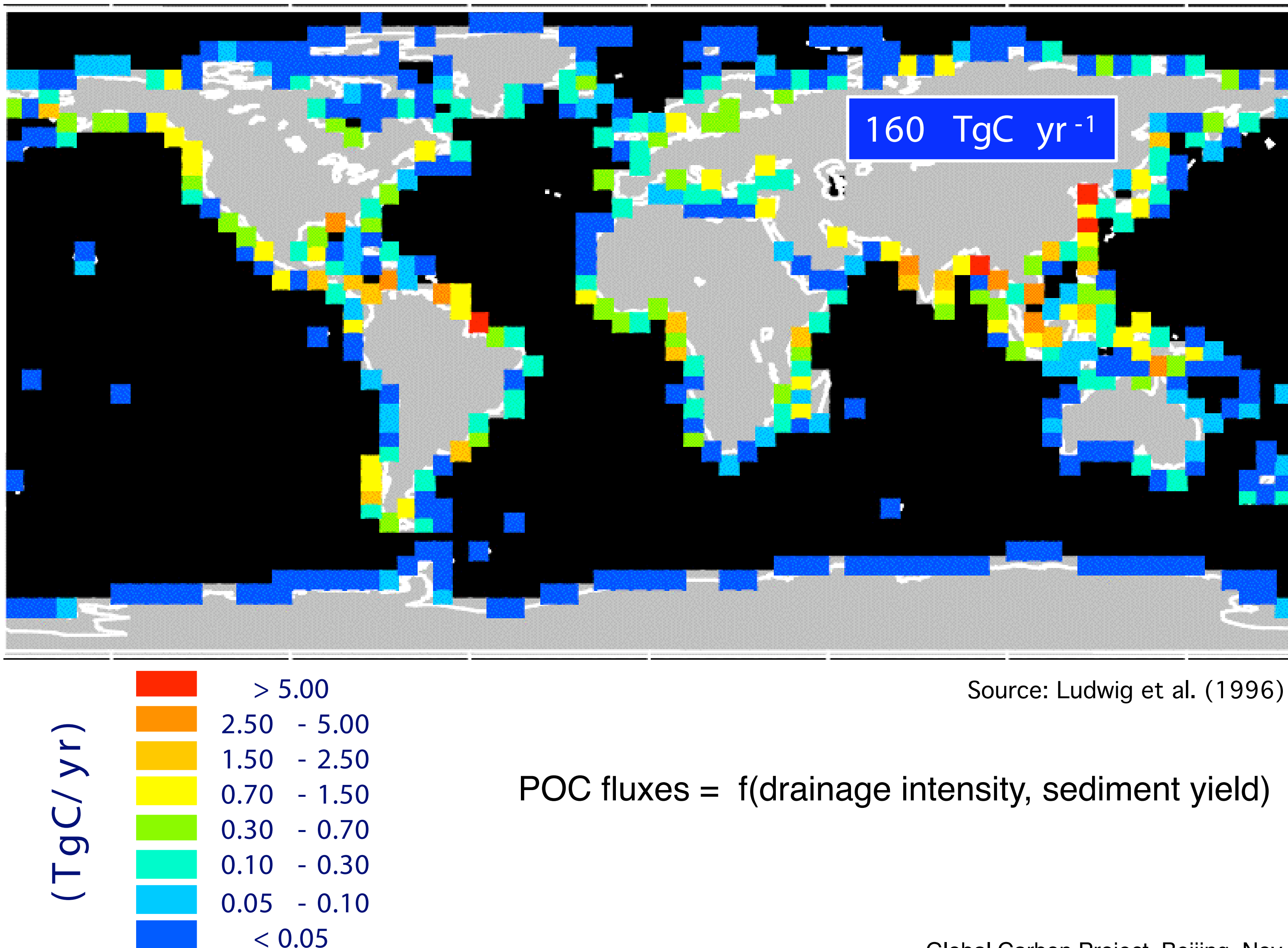
Source: Ludwig et al. (1996)

(TgC/yr)

- > 5.00
- 2.50 - 5.00
- 1.50 - 2.50
- 0.70 - 1.50
- 0.30 - 0.70
- 0.10 - 0.30
- 0.05 - 0.10
- < 0.05

DOC fluxes = f(drainage intensity, soil basin carbon, river basin slope)

Spatially-explicit model: POC



Source: Ludwig et al. (1996)

POC fluxes = f(drainage intensity, sediment yield)

How to estimate the fate of OC regionally?

- It is therefore possible to estimate fluxes of OC regionally
- Additional sources (Smith, comm. pers.):
  - Human wastes: ballpark highest estimate is 2×10^{12} mol/yr is making it to the ocean.
  - Animal agriculture: likely small because most agriculture does not occur in the coastal zone and the material is well reacted by the time it makes it to the ocean (nitrate is the main nutrient delivered by rivers)
- These sources are small globally but could be important locally
- A critical aspect is the reactivity of the material as it largely determines how much of the load is oxidized in the coastal ocean.