The influence of coastal oceans and seas on nutrient limitation in estuaries

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What determines whether N or P more limiting to NPP?

Biogeochemical processes within the estuary:
- Denitrification (vs DNRA)
- Nitrogen fixation
- P adsorption/desorption
- etc.

N:P ratio of watershed inputs

N:P ratio of nutrient inputs from offshore ocean waters
Let’s look at N:P ratio from the landscape to coastal oceans:

- US example, by regions, 1987 to 2012
- N flux estimated by Net Anthropogenic Nitrogen Inputs (NANI) approach
- P flux estimate by Net Anthropogenic Phosphorus Inputs (NAPI) approach
Kg N km$^{-2}$ year$^{-1}$

<table>
<thead>
<tr>
<th>Region</th>
<th>NO$_y$ deposition</th>
<th>Fertilizer</th>
<th>N fixation by crops</th>
<th>Net import (+) or export in foods</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Canada rivers</td>
<td>70</td>
<td>160</td>
<td>30</td>
<td>-50</td>
<td>210</td>
</tr>
<tr>
<td>St. Lawrence basin</td>
<td>610</td>
<td>330</td>
<td>260</td>
<td>-30</td>
<td>1170</td>
</tr>
<tr>
<td>NE coast of US</td>
<td>1200</td>
<td>600</td>
<td>750</td>
<td>1000</td>
<td>3550</td>
</tr>
<tr>
<td>SE coast of US</td>
<td>1020</td>
<td>1170</td>
<td>370</td>
<td>450</td>
<td>3010</td>
</tr>
<tr>
<td>Eastern Gulf of Mexico</td>
<td>760</td>
<td>1260</td>
<td>250</td>
<td>580</td>
<td>2850</td>
</tr>
<tr>
<td>Mississippi River basin</td>
<td>620</td>
<td>1840</td>
<td>1060</td>
<td>-1300</td>
<td>2220</td>
</tr>
<tr>
<td>Baltic Sea drainages</td>
<td>480</td>
<td>1730</td>
<td>30</td>
<td>20</td>
<td>2220</td>
</tr>
<tr>
<td>North Sea drainages</td>
<td>1090</td>
<td>5960</td>
<td>5</td>
<td>-5</td>
<td>7050</td>
</tr>
<tr>
<td>NW European coast</td>
<td>1090</td>
<td>2870</td>
<td>50</td>
<td>-320</td>
<td>3700</td>
</tr>
<tr>
<td>SW European coast</td>
<td>460</td>
<td>3370</td>
<td>15</td>
<td>-65</td>
<td>3780</td>
</tr>
</tbody>
</table>

NANI
(net anthropogenic N inputs)

International SCOPE N Project
(Howarth et al. 1996)
NANI concept developed at first workshop of the International SCOPE Nitrogen Project, Block Island, RI, May 1993
(Hong et al. 2011)
NANI over time for US regions

Unpublished data from NANI / NAPI tool box
~ 25% of NANI exported to coastal oceans on average from 200 watersheds in Europe and the US

(Howarth et al. 2012; Hong et al. 2013)
NAPI over time for US regions

Unpublished data from NANI / NAPI tool box
5.9% of NAPI exported to coastal oceans on average from US watersheds

US: $y=0.059x+2.54$, $R^2=0.55$, N=57, p<0.001
Europe: $y=0.039x+9.76$, $R^2=0.30$, N=78, p<0.001
China: $y=0.029x+11.64$, $R^2=0.44$, N=23, p<0.001
All data: $y=0.034x+10.49$, $R^2=0.54$, N=158, p<0.001
So to estimate N:P ratio of nutrient fluxes to coastal ecosystems by region over time in the US:

25% of NANI divided by 5.9% of NAPI
Estimated N:P ratio (molar) for nutrient fluxes from US regions to the coastal ocean over time

Unpublished data from NANI / NAPI tool box
Estimated N:P ratio (molar) for nutrient fluxes from US regions to the coastal ocean over time

Unpublished data from NANI / NAPI tool box
If inputs of nutrients from watersheds were the only important factor, most estuaries and coastal marine ecosystems in the US (and globally) would be P limited.

Most information does not support a conclusion of widespread P limitation (except at low salinities).

So other controls are clearly important.
Seine and Scheldt Basins and Belgian coast of North Sea

A large scale societal "experiment"
Seine River basin
(Scheldt is very similar)
Molar TN:TP ratio in nutrient flux

Expect N limitation in coastal receiving waters?
Molar TN:TP ratio in nutrient flux

TN:TP, Seine River

Increasing P limitation?
Station 330, Belgian coast, North Sea

max Chla, mg/m³


Phaeocystis

1 µm 1 mm
Chlorophyll in North Sea on Belgian coast

Seine River N load

Scheldt River N load
Coastal waters of North Sea remained N limited, despite very high N:P ratio of inputs from rivers since 1980s.
If inputs of nutrients from watersheds were the only important factor, most estuaries and coastal marine ecosystems in the US (and globally) would be P limited.

Most information does not support a conclusion of widespread P limitation (except at low salinities).

N limitation appears to be much more common.

So other controls are clearly important.
What determines whether N or P more limiting to NPP?

Biogeochemical processes within the estuary:
- Denitrification (vs DNRA)
- Nitrogen fixation
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- etc.

N:P ratio of watershed inputs

N:P ratio of nutrient inputs from offshore ocean waters
3-fold increase in nitrogen inputs to West Falmouth Harbor, Cape Cod, MA, 2002 to present, expected to now decline. No change in P inputs.

Inadvertent “experiment,” caused by bad policy decision. But science opportunity nonetheless.
Despite large N inputs, DIN concentrations have tended to remain low.
Outer, better flushed part of harbor

Inner, more N-polluted part of harbor

Low DIN and very low N:P ratios indicate N limitation
West Falmouth Harbor exchanges water tidally with Buzzards Bay through one narrow outlet. Simple physics and high precision water balance allows precise estimation of net N and P fluxes.

Samples collected hourly over 24 hours using automatic sampler, on many different days over several years. Analyzed for TN, TP, etc.

Hayn et al. 2013
Watershed inputs

3,000 mol N d\(^{-1}\)

Net import from Buzzards Bay during summer

500 mol N d\(^{-1}\)
80 mol P d\(^{-1}\)
(N:P = 6:1)

Net P import in summer is sufficient to support the use of 1,280 mol N d\(^{-1}\) by primary producers (or \(~ 40\% \) of the load).

An important mechanism (although not the only one) that helps keep the system N-limited. See Roxanne Marino’s poster!
Whether coastal ocean sources can provide enough P to help maintain N limitation depends in part on N:P ratio of coastal waters (low off of East Coast of US, and North Sea)......
Molar N:P ratio for inorganic nutrients near bottom

Courtesy of Francis Chan, based on NOAA’s World Ocean Atlas
Molar N:P ratio for inorganic nutrients in surface waters on the continental shelves of North America plotted as a function of the width of the shelf.

Courtesy of Francis Chan, based on GLODAPv2 and ETOP01 databases.
Nitrate and SRP in surface waters on the continental shelves of North America plotted as a function of the width of the shelf.

Both nitrate & SRP are less on wider shelves, reflecting losses, but nitrate losses are greater, driving N:P ratio pattern.

Courtesy of Francis Chan, based on GLODAPv2 and ETOP01 databases
Whether coastal ocean sources can provide enough P to help maintain N limitation depends in part on N:P ratio of coastal waters (low off of East Coast of US, and North Sea)......

.... And is scale dependent: Depends upon advection of coastal ocean water into the system (exchange of tidal water into the Harbor in case of West Falmouth).
Ocean influence on estuaries that have significant advection of ocean waters into them:

- Naturally high production
- Tendency toward N limitation along US East Coast, Gulf of Mexico, etc.
- Tendency toward co-limitation by N & P along US West Coast.
Predictions for French Mediterranean lagoons:

- Micro-tidal & little freshwater input, so little estuarine circulation or import of ocean water – therefore, oligotrophic if watershed nutrient inputs are low.

- Adjacent Mediterranean waters have high N:P ratio, so to the extent estuaries receive import of ocean water, tendency toward P limitation (when watershed nutrient inputs are low).
Relationship between SRP and DIN in lagoons along French Mediterranean coast:
French Mediterranean lagoons

Oligotrophic and P-limited

Eutrophic and N-limited

Souchu et al. 2014
Conclusions/predictions:

• Nutrient inputs from land tend to have high N:P ratios and therefore drive estuaries towards P-limitation

• (a variety of internal biogeochemical processes mediate the influence of nutrient inputs from land on nutrient limitation)

• Nutrient inputs to estuaries from coastal oceans can be important when import of ocean water is significant; these inputs lead to high productivity even for estuaries with pristine, low nutrient watersheds.

• Corollary: low production, oligotrophic estuaries can occur only when advective import of ocean water is low, and watershed nutrients are low

• Ocean nutrient inputs will tend to lead to N-limitation when adjacent continental shelves are wide (with associated low N:P ratios)

• When adjacent continental shelves are narrow, ocean nutrient inputs favor co-limitation by N & P
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