Nutrients and Biological Productivity

12.097 Lecture

January 17, 2006

What is a “nutrient”?

- An element or compound that is beneficial or required for biological growth
- “Essential” nutrients are those that are required for growth – i.e., everything dies if the concentration drops below a threshold
- Major: nitrogen (N), phosphorus (P)
  - *silica (Si), sulfur (S) [not for all organisms]*
- Minor: trace metals (e.g., Fe, Co, Mn, Zn), vitamins (e.g., B_{12})

What concentrations are required?

- Stoichiometry of life: Redfield ratio
  - Empirical ratio of phytoplankton collected from various ocean and lake environments
  - C:N:P = 106:16:1
  - The “limiting” nutrient is the one which is in lowest concentration relative to the other two
  - In freshwater systems, P is limiting nutrient
  - In marine systems, N is limiting nutrient *(though this varies widely in coastal vs. open-ocean systems)*

How do organisms acquire nutrients?

Uptake rate of nutrients is described by *Michaelis-Menten kinetics*.

V = velocity of uptake rate

V_{max} = maximum velocity

S = substrate concentration

K_S = substrate concentration at V = ½ V_{max}

Nearly linear at small [S]

Nearly flat at high [S]

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Please see: http://www.steve.gb.com/science/enzymes.html

$$V = V_{\max} \frac{S}{K_S + S}$$

N and P

- Different “sizes”: dissolved and particulate
  - Dissolved = in aqueous solution
  - Particulate = associated with particles (surface-adsorbed, imbedded within, etc.)
- Different “forms”: inorganic and organic
  - N: NH_4^+, NO_2^-, NO_3^-, urea, proteins, nucleic acids
  - P: PO_4^{-3} (+ HPO_4^{-2}, $H_2PO_4^-$, H_3PO_4), phospholipids, nucleic acids
- Oxidation states
  - N: N(V) in NO_3^-, N(0) in N_2, N(-3) in NH_4^+
  - P: P(V) in PO_4^{-3}, other redox states insignificant

The Marine P Cycle: Depth Profile

- Depleted at surface (biological uptake)
- Remineralized during heterotrophic activity (~1000m and sediments)
- Remineralization is Temp-dependent (max in spring in coastal areas)

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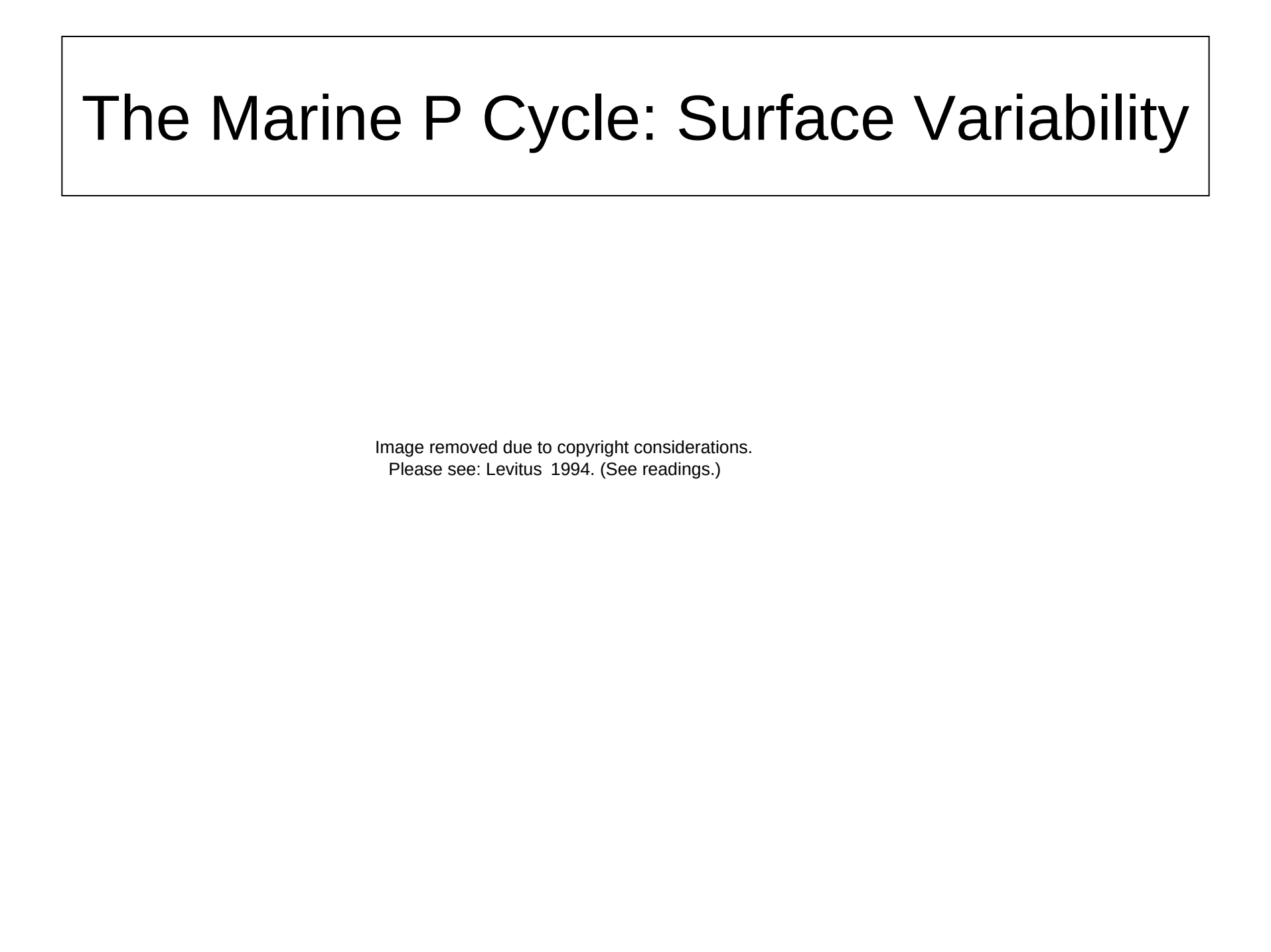
The Marine P Cycle: Surface Variability



The Marine P Cycle

- Abiotic reactions:
  - Adsorption to positive-charged minerals (e.g., clays)
  - Complexation with metals (e.g., Fe^{+3}, Al^{+3}, Ca^{+2})
- Biotic reactions:
  - Uptake by phytoplankton & bacteria
- Sources:
  - Continental weathering of P-containing minerals
  - Anthropogenic activity (soap)
  - ➔ River runoff (~90%)
- Sinks:
  - Burial of particulate material (cells, minerals) in sediments
  - Sea bird guano
- τ_{res} of diss. PO_4^{-3}: 1-2 min

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Please see: Valiela, 1995 (*Marine Ecological Processes*) (See readings.)

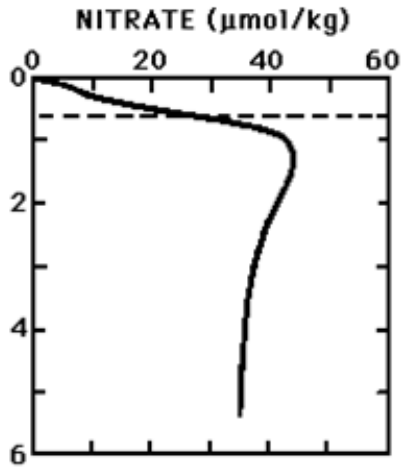
The Marine N Cycle: Depth Profile

Very similar behavior to PO_4^{-3}
Depleted at surface; remineralized at depth

Deep water is a source of NO_3^- to surface ocean (via upwelling)

NH_4^+ and NO_2^- follow similar depth profiles (though much lower conc's)

[DON] >> [DIN]



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The Marine N Cycle: Surface Variability

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Please see: Levitus 1994. (See readings.)

The Marine N Cycle

- Many more reactions in N cycle than in P cycle
  - Due to possible changes in redox state, presence of gaseous component (N_2)
- No abiotic reactions
- Biotic reactions:
  - NO_3^- reduction:
    - Assimilatory (N used in biosynthesis)
    - Dissimilatory (N not used in biosynthesis) = **Denitrification**
  - NH_4^+ oxidation
- Sources:
  - N_2 fixation (anthro & natural)
  - River runoff
  - Sewage
- Sinks:
  - Biological uptake by cells
  - Burial in sediments

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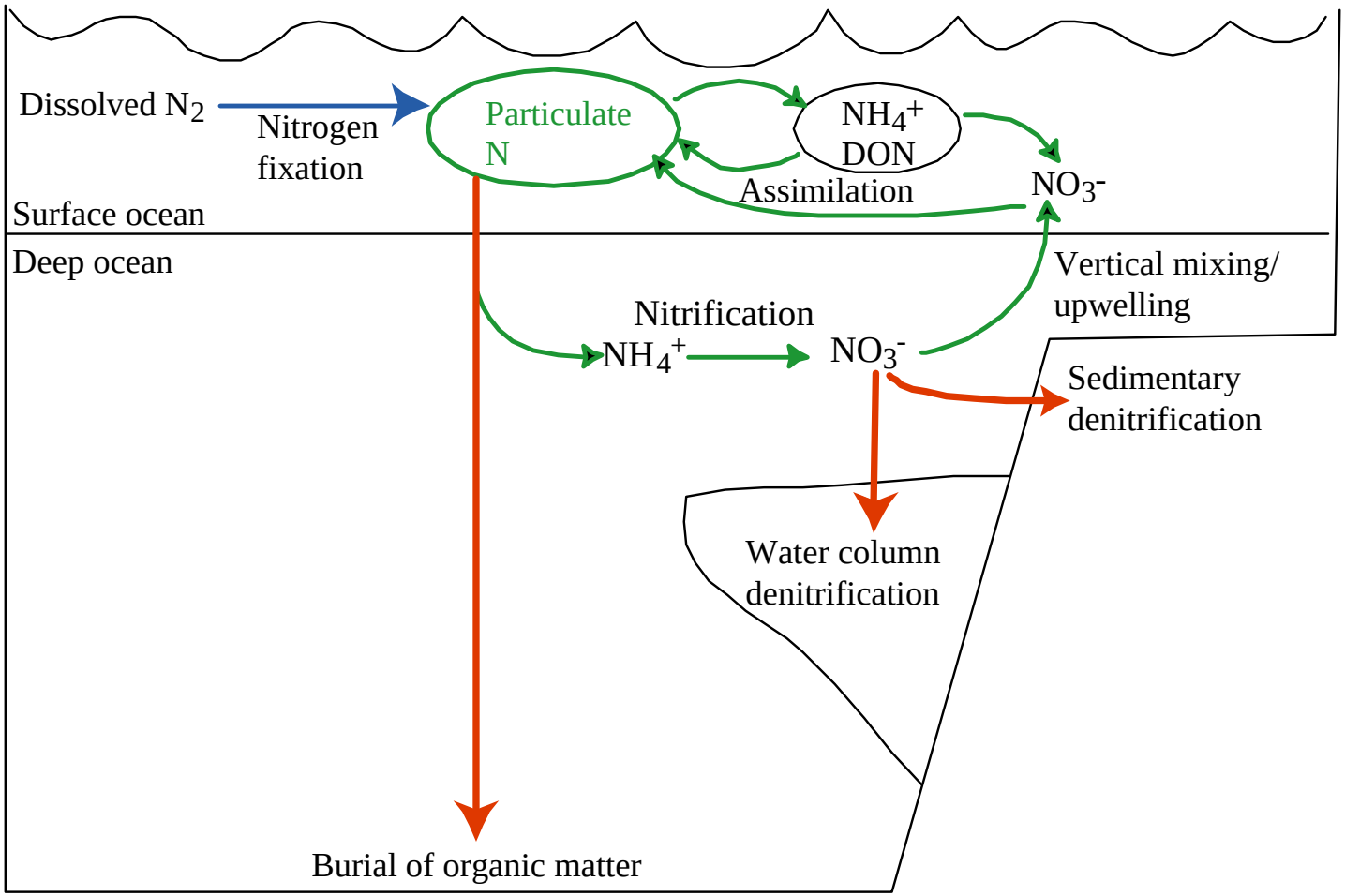
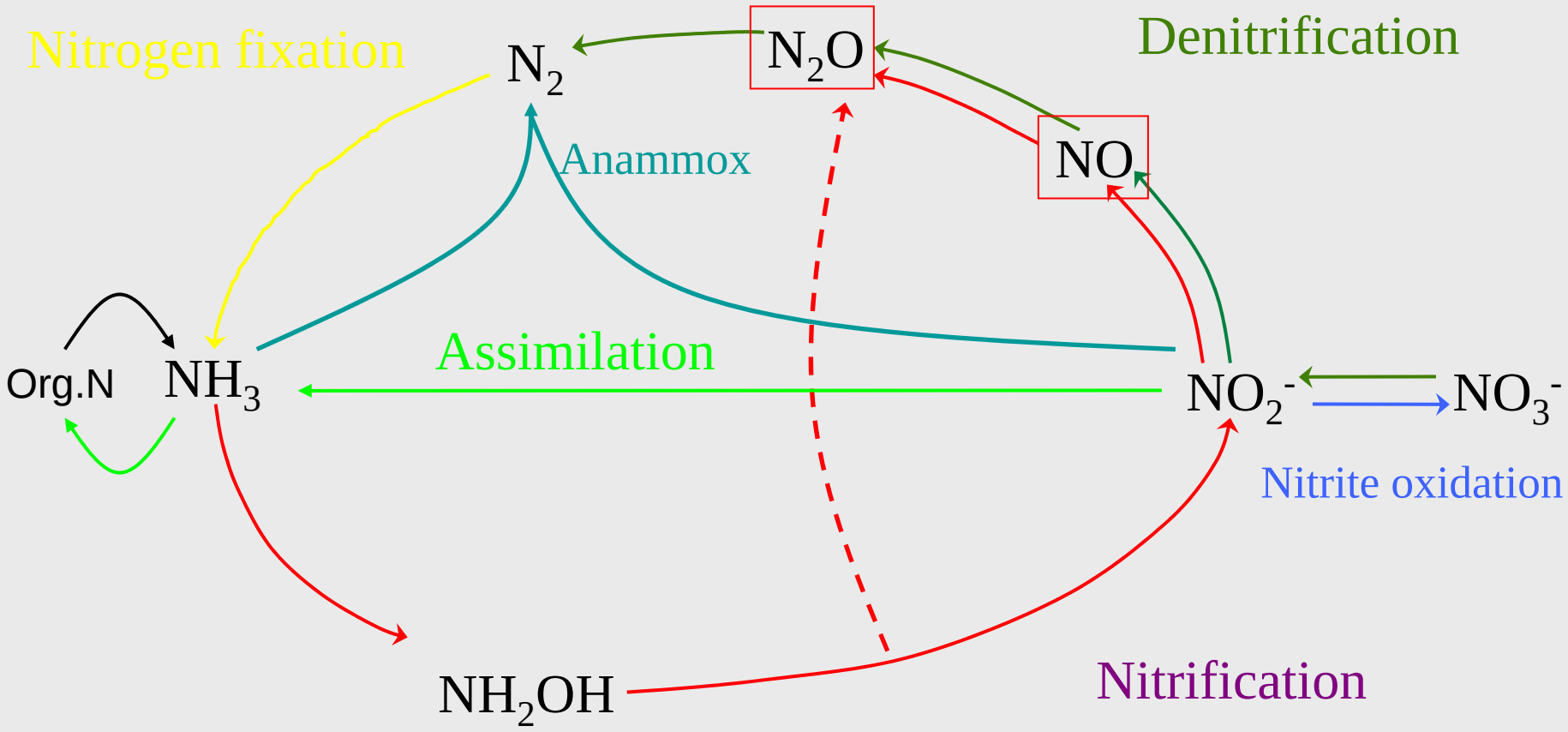
Please see: Valiela, 1995 (*Marine Ecological Processes*) (See readings.)

The Marine N Cycle



Microbial N Cycle



N redox State:	(-III)	(-I)	(0)	(I)	(II)	(III)	(V)

N transformations in presence of O_2

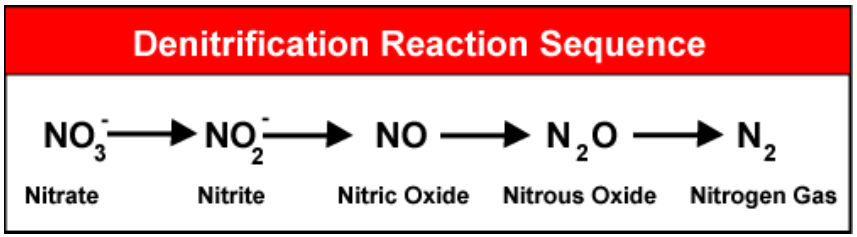
- Assimilatory NO_3^- reduction:

  $NO_3^- \rightarrow NH_4^+$
- NH_4^+ is most bioavailable form due to biosynthesis needs (e.g., proteins & nucleic acids)
- Organisms prefer NH_4^+ uptake rather than NO_3^- due to E requirement of NO_3^- reduction
- NH_4^+ is primary remineralization product of zooplankton and other heterotrophs → this can be largest source of N for phytoplankton and bacteria in open ocean (low nutrient environments)

- Nitrification (oxidation of N):
  - $NH_3 + 3/2\ O_2 \rightarrow NO_2^- + H_2O + 2H^+$
  - $NO_2^- + ½\ O_2 \rightarrow NO_3^-$
  - Steps 1 and 2 performed by different organisms (e.g., *Nitrosomonas* and *Nitrospira*)
  - Require conservative enzymes such as ammonia monooxygenase (AMO)
  - Requires O_2 but can occur at low $[O_2]$
  - Reduces CO_2 to organic C
  - Maximum rate at ~150m in open ocean

Anoxic N transformations

- Denitrification (reduction of N):



- Organic C is oxidized to CO_2
- Requires 0 or low [O_2]
- Important organisms: heterotrophic bacteria
- Enzymes are highly conserved and membrane-bound (e.g., nitrate reductase)
- Largest sink of N in estuaries (15-71%) = 4-5X N_2-fixation

- Anammox (oxidation *and* reduction of N):
  - $NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O$
- Newly discovered process occurring in bacterial order *Planctomycetales*
- Potential cellular system: Anammoxosome
- Seen in anoxic zones of Black Sea, wastewater treatment plants
- Rates and prevalence unknown

Nitrogen fixation

- N_2-fixation (reduction of N):
  - $N_2 \rightarrow NH_4^+$
- Requires high [Fe^{+2}] and 0 or low [O_2] – cells often have anoxic microzones to reduce local [O_2]
- Inhibited by high [NH_4^+]
- Important organisms: *Trichodesmium*, *Oscillatoria*

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Please see: http://www.imagequest3d.com/catalogue/freshwater/pages/u013_jpg.htm

Anthropogenic impact on N_2 fixation:
Currently = natural fixation

N contamination in coastal env's

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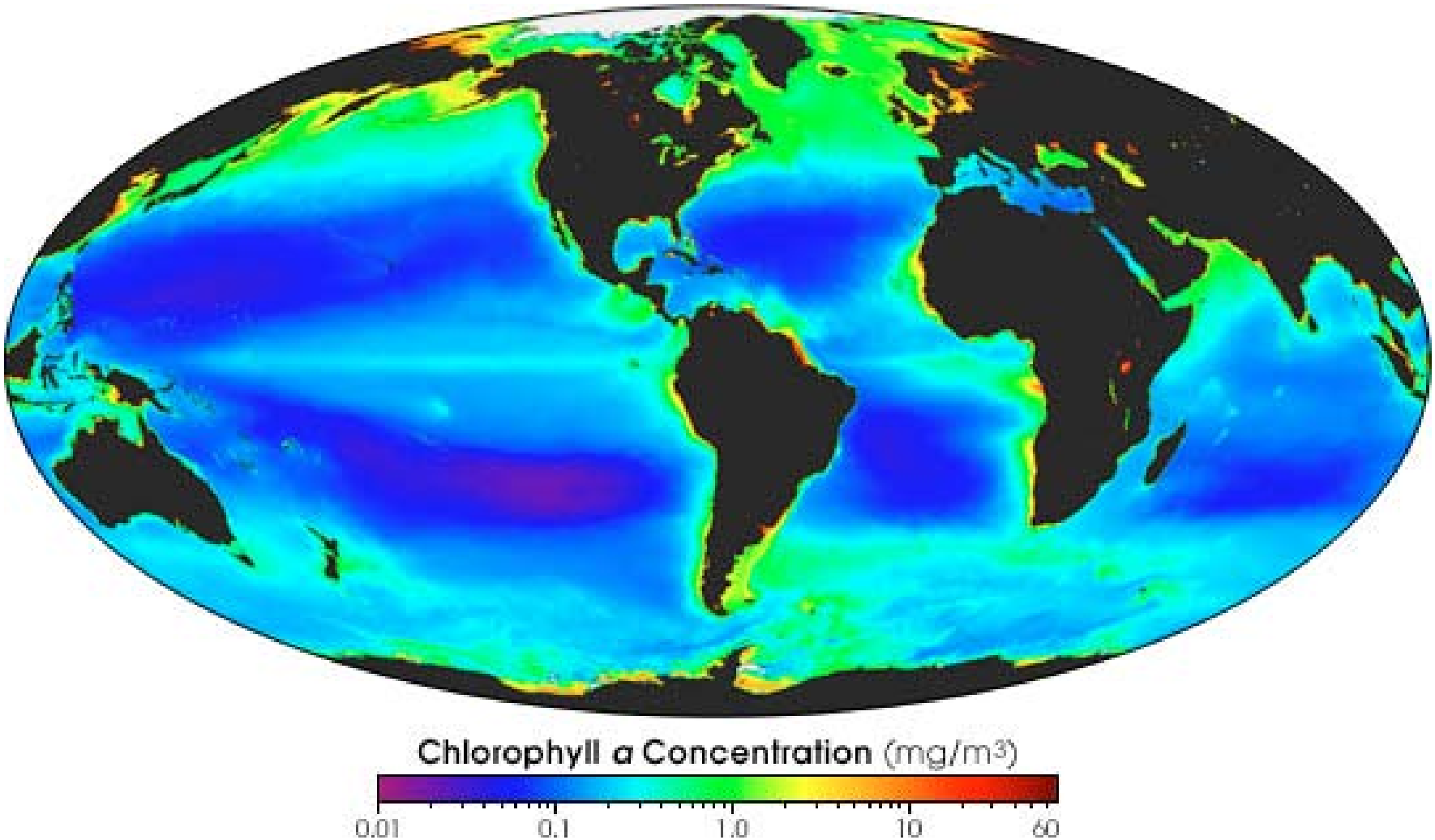
Please see: http://www.msnbc.msn.com/id/4624359/

- Excess N in groundwater and rivers leads to eutrophication of coastal zones
- Destroys existing habitats (promotes anoxia)
- Particularly problematic in regions with septic systems

What does it all mean for the productivity of the ocean?



SEAWIFS data from K. Casciotti

Productivity: Definitions

- Important value because it is major mechanism by which surface ocean and atmospheric [CO_2]'s are maintained at 2X lower than expected.
- Gross primary production (GPP):
  - Input of energy and organic matter into ecosystem
  - Equals all photosynthetic production
- Photoassimilation:
  - GPP – rate of O_2 production associated with photorespiration
- Net primary production (NPP):
  - Rate of photoassimilation – rate of dark respiration (heterotrophs)
- *f* ratio
  - New production / total production

- Depends on light ($h\upsilon$), nutrient concentrations, T (small)

Light

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Please see: http://www-ocean.lbl.gov/seawifs/9712SeaWiFS.html