Primary production approach 5: Estimate Net community production based on *in situ* variations in oxygen, nutrients, carbon, or biomass (often chlorophyll)

- Examine annual or seasonal scale changes in $O_2$, $NO_3^-$, $CO_2$, Chl $a$ concentrations in the upper ocean.
- As long as exchange, diffusive losses, and grazing (for Chl $a$) can be accounted for this approach should provide an estimate of NCP.
Mixed layer $O_2$ is in equilibrium with the atmosphere.

Rate of subsurface $O_2$ accumulation provides information on NCP.

Riser and Johnson (2008)
Late summer primary production event.
Direct Measurements will Never Provide Synoptic Estimates of Productivity
Satellites to the rescue...but we don’t measure production from space

Satellites can provide measurements of temperature, sea surface irradiance, and chlorophyll. Need models that relate these to primary production.
Deriving Photosynthesis-Irradiance Relationships

• A photosyntheron can be used to quantify photosynthesis as a function of irradiance.

• $^{14}$C-bicarbonate is added to whole seawater samples, samples are placed in temperature and light controlled incubation.

• After short incubations (<2 hrs) rates of photosynthesis are derived.
Photosynthetic responses to irradiance

\[ \alpha = \Delta P/\Delta I = \text{initial slope of the } P \text{ vs. } I \text{ relationship} \]

\( \alpha \) varies based on physiological changes to the cellular photosynthetic machinery

\( P_{\text{max}} \) varies depending on environmental conditions such as nutrients and temperature
Satellites “measure” chlorophyll, temperature, and light

• ~1 km resolution

• Need models that relate photosynthesis to these remotely sensed variables.

• Nontrivial challenges with remote sensing: stability and accuracy of sensors, correction for atmospheric interferences, and conversion from ocean color to chlorophyll.

• Depth-dependent descriptions of phytoplankton productivity generally include the following terms: vertical light attenuation, biomass normalized productivity, photoperiod length, and incident light flux.
Seasonal variations in mixing and temperature in the Sargasso Sea note winter time deepening of the mixed layer coincides with seasonal cooling.
North Atlantic Spring Bloom

- Chlorophyll a (μg L⁻¹)
- Silicate (μM)
- Nitrate (μM)

47°N

20 April 30 April 10 May 20 May 30 May

Julian Days 1989
Trapezoidal integration

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Production ($\mu$g C L$^{-1}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>25</td>
<td>6.4</td>
</tr>
<tr>
<td>45</td>
<td>5.0</td>
</tr>
<tr>
<td>75</td>
<td>3.0</td>
</tr>
<tr>
<td>5-75 m Int.</td>
<td>363 mg C m$^{-2}$ d$^{-1}$</td>
</tr>
</tbody>
</table>

Area of trapezoid = Height * avg. base

\[
[(25 \text{ m} - 5 \text{ m}) \times (6.5 \text{ mg C m}^{-3} \text{ d}^{-1} + 6.4 \text{ mg C m}^{-3} \text{ d}^{-1})/2] = 129 \text{ mg C m}^{-2} \text{ d}^{-1}
\]
\[
[(45 \text{ m} - 25 \text{ m}) \times (6.4 \text{ mg C m}^{-3} \text{ d}^{-1} + 5.0 \text{ mg C m}^{-3} \text{ d}^{-1})/2] = 114 \text{ mg C m}^{-2} \text{ d}^{-1}
\]
\[
[(75 \text{ m} - 45 \text{ m}) \times (5.0 \text{ mg C m}^{-3} \text{ d}^{-1} + 3.0 \text{ mg C m}^{-3} \text{ d}^{-1})/2] = 120 \text{ mg C m}^{-2} \text{ d}^{-1}
\]
\[
\text{Sum 5-75 m} = 363 \text{ mg C m}^{-2} \text{ d}^{-1}
\]
Conditions for net primary productivity

\[ \int_0^z \frac{1}{p} \frac{dP}{dt} > 0 \]

\[ \int_0^z \frac{1}{p} \frac{dP}{dt} < 0 \]

Depth (m)

Gross Photosynthesis

Compensation depth \((P_{\text{cell}} = R_{\text{cell}})\)

Critical depth \((P_{\text{water}} = R_{\text{water}})\)
Winter mixing introduces nutrients to the upper ocean; seasonal increases in irradiance results in deepening of the critical depth and shoaling of the mixed layer. The result: net accumulation of biomass.
• Where does primary production go?
  – Export
  – Bacteria
  – Grazing
  – Dissolved organic matter
The Microbial Loop

Classic Food web

Phytoplankton

Herbivores

Higher trophic levels (zooplankton, fish, etc.)

A simplified depiction of the microbial loop

Inorganic Nutrients

Dissolved organic matter

Heterotrophic bacteria

Protozoa
What other components of the biological pump are important?

• The majority of organic material in the ocean is in the dissolved phase (operationally defined as <0.7 μm or 0.2 μm)
Why dissolved organics matter

- Dissolved organic matter constitutes the largest global reservoir of fixed carbon \(~700 \times 10^{15} \text{ g C}\).
- Oxidation of even 1% of the seawater DOC pool in a 1 year period would exceed annual anthropogenic CO$_2$ emissions.
- DOC can also serve as an important component of new production.
Seasonal variations in mixing and temperature in the Sargasso Sea—note winter time deepening of the mixed layer coincides with seasonal cooling.
Upper ocean total organic carbon at BATS
Remember DOC = \sim 98\% of the TOC.

Note the build up in DOC through the spring and summer, with subsequent export the following winter.
TOC Profiles at BATS

Figure courtesy of Craig Carlson, UCSB
Typical DOC profile:
elevated in near surface water, decreasing through the thermocline, stable at depth.

- Labile pools cycle over time scales of hours to days.
- Semi-labile pools persist for weeks to months.
- Refractory material cycles over on time scales ranging from decadal to multi-decadal...perhaps longer...

Figure 5 Conceptual cartoon of the various pools of refractory, semilabile, and labile DOC in the open ocean. This figure is based on the mean profile for all DOC data collected at the Bermuda Atlantic Time-series Study (BATS) site in the Northwestern Sargasso Sea. The magnitude and distribution of the various pools of lability will vary depending on the location of the study site and the degree of thermal stratification of the water column (see Hansell, Chapter 15). The refractory pool is divided into two broad pools based on the deep ocean gradient observed by Hansell and Carlson (1990a). They observed the lowest concentration of DOC (3.4 \mu M C) in the North Pacific and used this concentration to represent refractory DOC which turns over on time scales of greater than ocean mixing (A, white box). The deep DOC concentrations in excess of the 3.4 \mu M C represents the fraction of the biologically refractory pool that turns over on time scales of ocean mixing (i.e., centuries; B, light gray box).
Sources of DOM to ocean ecosystems

1. Direct algal excretion
2. Zooplankton (sloppy feeding, excretion)
3. Viral lysis
4. Bacterial release
5. Solubilization of POM

Exudation % ¹⁴C primary production, zooplankton % carbon ingested, solubilization % C released from aggregates, bacterial % release from ¹⁴C labeled organic substrate. Sources: Nagata (2001), Carlson (2002).

Figure 1 Three major pools of dissolved organic matter (DOM) and the processes contributing to them.
Amino acids

Nucleotides and nucleic acids

Lipids

Vitamins

Monosaccharides

Polysaccharides

Glucose
Fructose

Starch
Cellulose
Glycogen

Identified DOM compound classes
The vast majority of organic matter in the sea remains chemically uncharacterized.

Carbohydrates, neutral sugars, amino acids, and amino sugars make up ~20% of the bulk DOC pool in the upper ocean.
Isolation of DOM by ultrafiltration

Cross Flow Filtration

Size selective concentration of DOM

Typically solutes > 1nm are concentrated for subsequent analyses

Selects for HMW fraction (about 30-35% TOC)

Some salts collected also
Ultrafiltration high molecular weight DOM (HMWDOM)

>1000 D DOM fraction 30-35% TOC

< 1000 D DOM fraction 65-70% TOC

Photos from Dan Repeta
Final product
30-35% of total DOC
Spectral and chemical analyses of HMWDOC

Carbohydrate 50-70% of HMWDOC

Acid hydrolysis followed by monosaccharide analyses yields 7 major neutral sugars that represent 5-10% of surface water DOM
NMR and carbohydrate analyses of deep sea HMWDOC

Monosaccharide distribution

<table>
<thead>
<tr>
<th>Monosaccharide</th>
<th>Deep</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>F</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>A</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>X</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>GI</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>M</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>G</td>
<td>19</td>
<td>23</td>
</tr>
</tbody>
</table>
Cosmogenic $^{14}$C production

Fossil fuel dilution

Atmosphere

Bomb $^{14}$C

Air-Sea Exchange

Surface Ocean

Deep Ocean

Factors controlling $^{14}$C in atmospheric and oceanic reservoirs

$^{14}$C half-life is 5730 years
DOC cycling via DO$^{14}$C

Williams, Oeschger, and Kinney; Nature v224 (1969)

UV photooxidation

Natural Radioactivity Activity of the Dissolved Organic Carbon in the Northeast Pacific Ocean

The "age" of the dissolved organic matter in the deep sea relative to its origin in the euphotic zone has been a matter of speculation for some time. 1. Photosynthetic fixation of carbon dioxide into plant carbon by phytoplankton and subsequent bioturbated solubilization or stabilization of organic carbon takes place primarily in the upper 200 m of the sea. A small, as yet unknown, fraction of this organic carbon is transferred into the deep water by physical processes such as turbulent mixing and sinking of surface water at high latitudes. In addition, particulate organic carbon which sinks from the surface may be converted into dissolved organic matter as depth. In order to determine how "old" this dissolved organic carbon is, the natural radioactivity activity has been measured for two deep-water samples taken off southern California.

The dissolved organic carbon was converted to carbon dioxide (and subsequently to methane for radioactivity measurements by photooxidation with high energy ultraviolet radiation). Seawater was collected with a 100 L stainless steel sampler and stored in 2001, pre-cleaned steel bottles lined with polythene (no increase in organic carbon was detected during the storage period before analysis). Prefiltration to remove particulate organic matter was not necessary, because the concentration was less than 4 µg/L. The seawater was acidified to pH 3 with hydrochloric acid, sparged free of carbon dioxide (99.99 per cent) with oxygen gas and fumigated to 0.1% initial for 24 h. using a 1,200 W mercury-arc lamp (Balence 150 W chart) (Oeschger, et al. 1969). The carbon dioxide so formed was sparged from the solution with oxygen gas and trapped in a stream of water to convert it into tritium carbonate. Complete oxidation was accomplished by reaction of the carbon dioxide in the irradiated seawater (detected by a Beckman model 18 infrared analyser) with the amount of carbon dioxide resulting from the net conversion of the organic carbon in the seawater before oxidation. The tritium carbonate was collected by filtration, washed with water in a nitrogen atmosphere and dried in vacuo.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Δ14C(‰)</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1880m</td>
<td>-351</td>
<td>-3470±330 ybp</td>
</tr>
<tr>
<td>1920m</td>
<td>-341</td>
<td>-3350±300 ybp</td>
</tr>
</tbody>
</table>
Radiocarbon in the Atlantic and Pacific Oceans

Peter M. Williams and Ellen Druffel; Nature 1987, JGR 1992

DIC $^{14}$C in surface waters of the Atlantic and Pacific has the same isotopic value.

DOC is always older than DIC (by 4 kyrs in surface water)

Deep ocean values of DOC are equal to a radiocarbon age of 4000-5000 yrs

Either there is a source of “old” DOC, or DOC persists for several ocean mixing cycles