Zooplankton role in biogeochemical cycles: Progress and prospects for the future
Carbon sequestration

$\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2$

Euphotic zone

Deep ocean floor sediments

Photosynthesis

Organic carbon in particles (sequestered decades)

Deep Sea

100 m

Organic carbon in particles (centuries)

1000 m

C burial (millennia)

Monthly Carbon Dioxide Concentration

AIR

Respiration

$\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2$

Deep Sea

D O C

Total CO$_2$ in surface ocean (parts per million)

1950
1960
1970
1980
1990
2000
2010

2000
2005
2010
2015
2020
2025
2030
Feeding the deep sea

Fecal pellet from gut of Myctophid

Copepod (*Scopalatum*) and marine snow

DOM

Sea cucumber - deposit feeder
Outline

• Ecosystem comparison of fecal pellet flux & active transport
• Long-term changes in zooplankton-mediated export
• Lesser known - DOM cycling, deep sea, gelatinous zooplankton
• Prospects & considerations for the future
• Conclusions
Ecosystem comparison of fecal pellet flux & active transport
Study sites

K2 47° N, 160° E
ALOHA 22° 45’N, 158° W
BATS 32° 10’N, 64° 30’W
Pal LTER 64-68° S, 62-75° W

SeaWIFs
Zooplankton community comparison

Neocalanus copepods

ALOHA and BATS

Pal LTER

krill

copepod

salps

pteropods

S.E. Wilson
Zooplankton scatology

Shape, size – taxa
Color – diet

salp

C,N content:
Directly measured & Volume - C conversion
Changes in fecal pellet classes with depth

ALOHA

150m

300m

500m

K2

Wilson et al. (2008)

Scale bar = 500 µm
BATS fecal pellet flux time series (June ‘07-June ‘08)
Pal LTER Fecal Pellet Flux (Jan-Dec. 2008)

Fecal Pellet Flux (mg C/m²/d)

Start Date

01/15 01/22 01/29 02/12 03/01 03/15 04/01 05/01 06/01 07/01 09/01 10/01 11/01 11/15 11/22 11/29 12/06 12/14 12/20 12/27 01/03

Shape
- Amorphous
- Cylindrical
- Ellipsoid
- Tabular

422
## Overall fecal pellet comparison between sites

<table>
<thead>
<tr>
<th>Site- Summer (annual)</th>
<th>Median POC/pellet (ugC/ pellet)</th>
<th>Pellet Flux across 150 m (mg C/m²/d)</th>
<th>Total POC flux (mg C/m²/d)</th>
<th>Pellets/total POC flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATS (annual)</td>
<td>0.009 (0.01)</td>
<td>3 (6.5)</td>
<td>13 (29 for BATS)</td>
<td>24 % (56 %)</td>
</tr>
<tr>
<td>ALOHA</td>
<td>0.04</td>
<td>2.5</td>
<td>18 (29 for HOT)</td>
<td>14 %</td>
</tr>
<tr>
<td>K2</td>
<td>0.17</td>
<td>6.5 - 7.4</td>
<td>23 - 62</td>
<td>12-28 %</td>
</tr>
<tr>
<td>PAL LTER (annual)</td>
<td>1.3 (0.79)</td>
<td>42 (31)</td>
<td>73 (6)</td>
<td>57% (&gt;100 %)</td>
</tr>
</tbody>
</table>
Vertical Migration and active transport

- Grazing
- Respiration: \( \text{CO}_2, \text{DOC} \)
- Excretion: \( \text{NH}_4, \text{DON} \)
- Defecation (POC, PON)
- Microbial loop
- Respiration: \( \text{CO}_2, \text{DOC} \)
- Excretion: \( \text{NH}_4, \text{DON} \)
- Defecation (POC, PON)
- (Molts, mucus, death)

Base of mixed layer

Vertical migrators
Mesozooplankton vertical biomass profiles

ALOHA deployment 1

Day

Night

BATS/ Sargasso Sea deployment 1

Day

Night

Steinberg et al. (2008), Goldthwait & Steinberg (2008)
### Overall active transport comparison between sites

<table>
<thead>
<tr>
<th>Site- Summer (annual)</th>
<th>Mean active CO2 +DOC+POC flux (mg C/m²/d)</th>
<th>Trap POC flux (mg C/m²/d)</th>
<th>Active transport/Trap POC flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(BATS)</td>
<td>(4)</td>
<td>(29)</td>
<td>(14 %)</td>
</tr>
<tr>
<td>ALOHA (HOT*)</td>
<td>2-8 (5)</td>
<td>18 (29)</td>
<td>11-44 % (19 %)</td>
</tr>
<tr>
<td>K2</td>
<td>16-46</td>
<td>23 - 62</td>
<td>26-200%</td>
</tr>
</tbody>
</table>


* Increasing
Examples of long-term changes in zooplankton-mediated export

- Sargasso Sea (BATS)
- Western Antarctic Peninsula (Pal LTER)
Increase in mesozooplankton biomass (top 150 m) at BATS

Day & night combined

\[ n = 213 \]
\[ r^2 = 0.07 \]
\[ p < 0.0001 \]

Steinberg et al. (in review)

+ 0.01 g/m²/year
50% increase over 16 yrs.
Increased more at night

41% increase over 16 yrs.

+ 71%

+ 86%

p < 0.01
Increase in active transport and fecal pellet production at BATS

Annual migratory CO$_2$ + DOC + POC flux across 150 m

Annual fecal pellet production (egestion) in top 150 m

Steinberg et al. (in review)
Active transport especially important mechanism for phosphorus (P) removal from the euphotic zone

Enhanced P-limitation of biological production in the N. Pacific subtropical gyre

(Hannides, Landry, et al. 2009)
Warming in the Western Antarctic Peninsula

Average winter (June-Aug.) temperature
+1.1°C per decade: 6°C since 1950: 5x global ave.

Sea ice is declining

Increase in Heat Content of Water Over Shelf

Sensitive to ENSO, Southern annual mode (SAM)
Long-term changes in zooplankton in the Antarctic Peninsula

Decreasing and shifting closer inshore?

Increasing over time (and expanding over shelf)?

(A. McDonnell)

(L. Madin)

(Grid line 600 - North)
Zooplankton composition change effects on particle export

Mean sinking rate = 200 m/ d

Salp fecal pellet

Mean sinking rate = 700 m/ d

Steinberg et al., in prep

(Phillips et al. 2009)
Changes in krill, salps, & fecal pellet flux
North (600 line, all stations averaged)

<table>
<thead>
<tr>
<th>Year</th>
<th># krill m⁻²</th>
<th># salps m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>1.9</td>
<td>0.25</td>
</tr>
<tr>
<td>2010</td>
<td>0.05</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Potential increase in overall flux

$r^2=0.18$
$p=0.08$

$r^2=0.16$
$p=0.1$
Lesser known -

• role in DOM cycling
• processes/rates in meso- & bathypelagic
• role of gelatinous zooplankton
• top-down control & cascading effects *
Links between zooplankton-DOM and microbial community

Using FISH

Condon et al. (in review)

DOC Uptake ($\mu$mol l$^{-1}$ h$^{-1}$)

% used within 6 hr.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>NWC</th>
<th>+Glu</th>
<th>Mnem</th>
<th>Chry</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>&lt;1%</td>
<td>13-19%</td>
<td>53-57%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

% Change in bacterial phylotypes after 12 hours

Using FISH

- $\alpha$-proteobacteria
- $\beta$-proteobacteria
- $\gamma$-proteobacteria
- Bacteroidetes
- Planctomycetes
- Archaea

Condon et al. (in review)
**Metabolic C requirements vs. sinking POC attenuation**

Integrated 150-1000 m

<table>
<thead>
<tr>
<th></th>
<th>ALOHA dep. 1</th>
<th>ALOHA dep. 2</th>
<th>K2 dep. 1</th>
<th>K2 dep. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria</td>
<td>3x</td>
<td>4x</td>
<td>4x</td>
<td>11x</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>2x</td>
<td>2x</td>
<td>2x</td>
<td>9x</td>
</tr>
<tr>
<td>Delta POC</td>
<td></td>
<td></td>
<td>1x</td>
<td>0.9x</td>
</tr>
</tbody>
</table>

Steinberg et al. (2008, Limnol. Oceanogr.)
Mesopelagic zooplankton distribution- North Atlantic- importance of particle feeders, gelatinous zooplankton

UVP-underwater video profiler

Stemmann et al. (2008, DSRII)
Jelly falls

*Pyrosoma* off W. Africa, >350 m

Arabian Sea, 1400 m

*Nemopilema*, Sea of Japan, ~200 m

Lebrato & Jones (2009)

Billett et al. (2006)

Yamamoto et al. (2008)
A few considerations & prospects for the future
Modeling the biogeochemical impact of diel vertical migration

DVM fluxes are significant above the daytime resting depth

Bianchi, Galbraith, Kearney, Stock, & Sarmiento (in prep)
Microelectrode

Biogeochemical implications:
- Methanogenesis in gut
- Facilitate Fe dissolution and remineralization

Courtesy of K. Tang
Biogeochemical tracers

Stable N isotopes

$\delta^{15}N$ of Zooplankton (%)

Diaz-N Contribution to Zoops (%)

N$_2$ fixers (diazotrophs) determined to be food for mesozooplankton via $\delta^{15}N$ measurements.

A mechanism by which new N is cycled in the food web.

Montoya et al. (2002)

Landrum et al. (in press, DSR I)
Ocean observing systems

Courtesy of V. Tunnicliffe & C. Barnes

 Courtesy of Bob Collier
Summary & Conclusions

• Fecal pellet flux & active transport increased with increasingly productive environments (caution-dependent upon season).

• Changes in zooplankton community structure over time, or in space, differentially alters organic matter export & C sequestration. Implications for feeding the deep sea too.

• The role of some major groups (e.g., gelatinous zooplankton) and process rates in major habitats (the meso- and bathypelagic zones) are still insufficiently known, & are needed to incorporate the role of zooplankton into predictive biogeochemical models.

• New technologies, more sensitive measurement techniques, novel biogeochemical tracers, & our input as a community into design of ocean observatories will be key to continued progress.
Muchas gracias!

• Zooplankton symposium organizers & local hosts
• VERTIGO, BATS, HOT, Pal LTER coauthors & collaborators
• Kam Tang, Daniele Bianchi, Bob Collier

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