The role of vertically migrating zooplankton in biogeochemical flux

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Outline

• Different roles of zooplankton in the biological pump

• Diel vertical Migration - DVM
  Active N:P transport by zooplankton

• Ontogenic vertical Migration - OVM
  The Lipid Pump – now with N & P
  The Lipid Shunt
Biological pump

Passive flux of POM

Role of zooplankton in flux

Grazing 0-50 m
Packaging - Compacting small into large faster sinking particles

Sloppy feeding – releasing nutrients

Scavengers – mid waters
Breaking up marine snow to smaller slower sinking particles releasing DOM and slowing down POM flux.

Diel Vertical Migration DVM - up-to 400 m depth
Fast track for faecal pellet flux + Excretion of nutrients @ depth

Ontogenic Vertical Migration OVM 500-3000 m
Lipid pump CO₂ sequestration, Lipid shunt

Mortality: lipid rich carcasses
Active flux by zooplankton

Diel Vertical Migration - DVM

- Trade-off: risk, feeding & cost
- Varies between latitudes
- Varies seasonally

Hansen & Visser (2016) L&O 61
Depth of DVM

Bianchi et al. (2013) Nature Geoscience 6
DVM - estimated C flux

Trade-off based model
Fitness =>
Feeding opportunity v.s predation risk

Based on
• Productivity
• Seasonality

Carbon export by vertically migrating zooplankton: an optimal behavior model

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L&O 2016

Active Flux CO$_2$ + pellets produced at depth

Variation due to 95% fitness interval

Ca 25% of total C export flux
How about Excretion of nutrients?
How about Excretion of nutrients?
Steinberg et al. 2002, DSR I 49

Martin et al. 1993  DSR II 40
C:N:P  Hannides et al 2009

Passive N flux

Active DVM driven N flux

Particle

$C_{187}N_{22}P_1$

1.6 mmol N/m$^2$/day

$C_{294}N_{21}P_1$

0.8

$C_{376}N_{22}P_1$

0.45

Zooplankton

$C_{58}N_{14}P_1$

0.11

DVM

Sequestration depth

0.22

DIN + DON

Euphotic zone

Mid-water depths

C:N:P  Hannides et al 2009
Passive N&P flux

Active DVM driven N&P flux

Particle

$C_{187}N_{22}P_1$

1.6 mmol N $/m^2$/day

0.011 mmol P $/m^2$/day

$C_{294}N_{21}P_1$

0.8

0.004

$C_{376}N_{22}P_1$

0.45

0.002

$C_{58}N_{14}P_1$

0.11

0.006

DVM

0.22

Sequestration depth

Zooplankton

Martin et al. 1993, DSR II 40
C:N:P Hannides et al 2009

Hannides et al. 2009, DSR I 56:73-88

Steinberg et al. 2002, DSR I 49

DIN + DON
DIP + DOP

0 m
150 m
300 m
500 m
1000 m

Active Flux

DVM
Conclusions of Steinberg et al and Hannides et al:

Active **Nitrogen** flux by DVM zooplankton is

- 8-45% of the passive PN flux
- Increases the N flux below the mixed layer

Active **Phosphorus** flux by DVM zooplankton

- up to 85% of the PP flux
- can be a driver for surface P limitation
Ontogenic Vertical Migration - OVM

**Diapause:**
- Arrested development
- Lowered metabolism
- No feeding
- Torpid
- Low predation

Lasts Up to 9 months
Overwintering strategies

Overwintering depths >600m

Income breeders
e.g. *Calanus finmarchicus*, *Calanoides acuspes*

Capital breeders
e.g. *Calanus hyperboreus*, *Neocalanus flemingeri*, *N. plumchrus*

Lipid accumulation

Oil sac: 100% WE
WE: 70% DW

Wax Ester ca 80% Carbon
Winter densities and distribution of *Calanus finmarchicus*

Heath et al 2004
ICES J. Mar. Sci
Annual Carbon transport

ca 0.5-10 gC m$^{-2}$ yr$^{-1}$

Total: 5 MT C transported year$^{-1}$ in this area by *Calanus finmarchicus* only.

> 600 km coal train
Lipid pump – what is left behind – respired CO$_2$

Population Abundance in diapause
Life history strategies => Capital or income breeder

If capital breeder – Number of eggs produced

OW temperatures for respiration

Size / Stage structure for estimating lipid content

Assumptions:
Metabolic rate $2.5 \times 10^{-7} \, \mu\text{gC}^{1/4} \, \text{s}^{-1}$
Arousal of diapause when 85% lipid$_{\text{max}}$ content is burned
Mortality (non predatory) : 0.001 d$^{-1}$

Model calculations length of diapause
Seasonal copepod lipid pump promotes carbon sequestration in the deep North Atlantic

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Calanus hyperboreus and the lipid pump

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Limn. Oceanogr. 62, May 2017
The Lipid Pump

Respired C during diapause
The Lipid Pump

Sequestration of overwintering *C. finmarchicus* and *C. hyperboreus*

0.5 to 8 gC m\(^{-2}\) yr\(^{-1}\) \(\Rightarrow\) 2 to 8 gC m\(^{-2}\) yr\(^{-1}\) sinking passive C flux @ same depth
Lipid Pump & Lipid shunt

Wax Ester
- ca 80% Carbon
- No Nitrogen
- No phosphorus

Jónasdóttir et al 2015 PNAS
“Actively feeding copepods characteristically excrete copious amounts of ammonia derived from dietary amino acids..... the animal may be channelling dietary amino acids away from growth and instead discarding amino N as ammonia leaving the carbon skeletons of amino acids to form fatty alcohol”

Sargent et al 1977
Including mortality

Structural mass

Lipid mass
gC m⁻² y⁻¹

Kobari et al. 2008
Bradford-Grieve et al. 2001

Neocalanus sp.
C. hyperboreus
C. finmarchicus
C. fin & C. hyp
Adveective loss of overwintering *Calanus finmarchicus* from the Faroe–Shetland Channel

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Faroe Bank Channel

Iceland Basin

Faroe Shetland Channel

4.2°C

-0.5°C

ca 80 kT C/yr
Calanus finmarchicus and C. hyperboreus
Mortality flux

Active N&P flux

Particle
\(C_{187}N_{22}P_1\)
1.6 mmol N/m\(^2\)/day
0.011 mmol P/m\(^2\)/day

\(C_{294}N_{21}P_1\)
0.8
0.004

\(C_{376}N_{22}P_1\)
0.45
0.002

Sequestration depth

Passive N&P flux

Active N&P flux - LP

Zooplankton
\(C_{58}N_{14}P_1\)
0.11
0.006

\(C_{57}N_{20}P_1\)

0.22

DVM

0.11
0.006

0.11
0.006

Aubert et al 2013

Mid-water depths

Calanus
\(C_{57}N_{20}P_1\)
Calanus finmarchicus
hyperboreus
 glacialis
 pacificus
 helgolandicus
carinatus
 acutus
 australis
 sincus
 marshalle
 chilensis
Neocalanus tonsus
 plumchrus
cristatus
 flemingeri
Calanoides carinatus
 acutus
Rhincalanus gigas
Eucalanus bungii
californicus
SUMMARY

Biological pump: particle flux and microbial mineralization

Where the carbon (DOC+DIC) ends up
Biological pump: particle flux and microbial mineralization

Where the dissolved nutrients (DIN, DON, DIP and DOP) end up
Biological pump: particle flux and microbial mineralization + zooplankton migration, both DVM and OVM

Where the carbon (DOC+DIC) ends up
Biological pump: particle flux and microbial mineralization + zooplankton migration, both DVM and OVM

Where the dissolved nutrients (DIN, DON, DIP and DOP) end up
Conclusion

- Zooplankton play a significant role in transporting nutrients and carbon to intermediate and deep ocean.

- There is a decoupling between carbon and nutrient flux through microbial processes and the “lipid shunt”

- OVM is particularly effective in transporting carbon, with only a small removal of surface nutrients.