Microbial food-web dynamics in a variable/changing ocean

A. Shifting grazing impacts on picoplankton populations across an ocean productivity gradient

B. Measuring growth and grazing of heterotrophic bacteria using molecular sequences

C. Food web complexities in predicting open-ocean food web responses to increasing temperature and stratification

Michael R. Landry

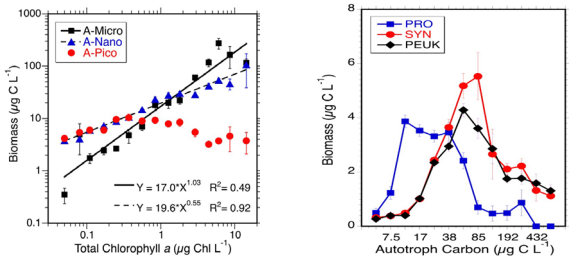
Scripps Institution of Oceanography
University of California, San Diego

Croucher Summer Course, HKUST
Lecture #15, 4 July 2025

1

Shifting grazing impacts on picoplankton populations across an ocean productivity gradient

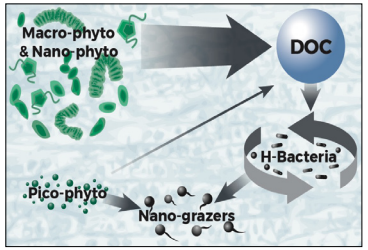
OBSERVATION: Picophytoplankton decline in rich coastal waters of the California Current Ecosystem (CCE). This occurs for all autotrophic picoplankton groups: *Prochlococcus* (PRO), *Synechococcus* (SYN), pico-eukaryotes (PEUK).



Taylor & Landry (2018) MEPS

2

ENHANCED MICROBIAL LOOP (EML) Hypothesis: High phyto biomass indirectly stimulates high grazing on autotrophic picoplankton (PRO, SYN, PEUK).



High Phyto biomass (**Micro** & **Nano**) increases **DOC** production

HBAC growth and production are stimulated

Increasing **grazing turnover** of HBAC

Pico-Phyto contribute little to DOC but suffer the consequences of high grazing on HBAC

Taylor & Landry (2018) MEPS

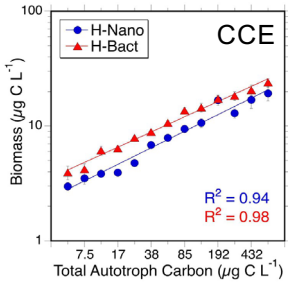
3

SHARED PREDATION CONCEPT: Prey of similar size are vulnerable to the same suite of consumers and suffer grazing mortality losses proportional to the most abundant or targeted prey.

Kuipers & Witte (2000): PRO consumed as secondary prey of H-NANO feeding on more abundant HBAC

Goericke (2011): Proposed that PRO decline in the CCE is driven by grazing on HBAC

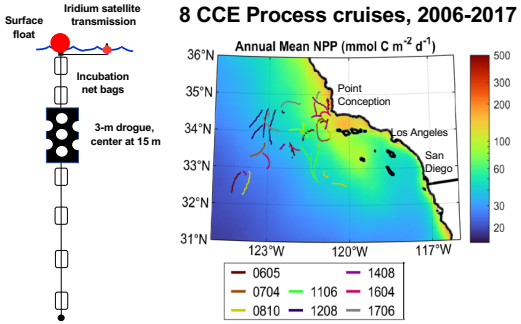
Follett et al. (2022): Proposed that shared predation on HBAC explained poleward collapse of PRO in N Pacific



Taylor & Landry (2018) MEPS

4

METHODS: 2 treatment dilution experiments + ^{14}C-PP; incubated *in situ* at multiple depths on satellite-tracked drift array; >400 mixed-layer experiments, averaged upper 4 experiments (± SEM) for each of 103 array deployments.



8 CCE Process cruises, 2006-2017

Trophic conditions:

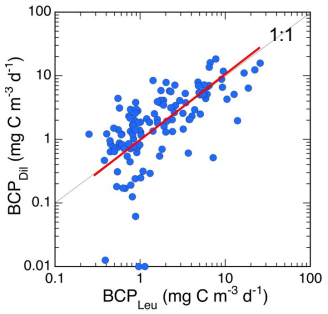
Oligotrophic offshore, Strong coastal upwelling

Spatial variability
Fronts studies 2008-2012
2017 filament study

Interannual variability
2014 heatwave
2015-16 ENSO

5

METHOD VALIDATION



Compared dilution vs ^{3}H-leucine estimates of Bacterial Carbon Production (BCP) for 3 CCE cruises (2014, 2016, 2017).

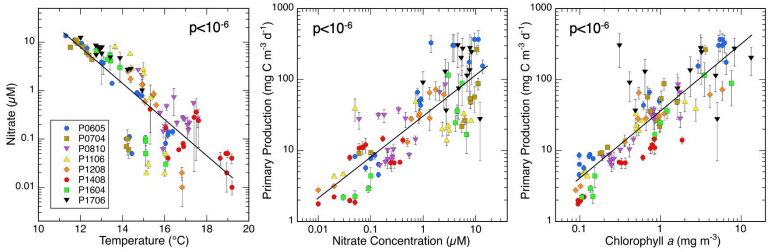
No bias between oligotrophic offshore and upwelling conditions

1:1 relationship for cell C estimates informed by flow cytometry estimates of size variability

Landry et al. (2023) L&O Meth.

6

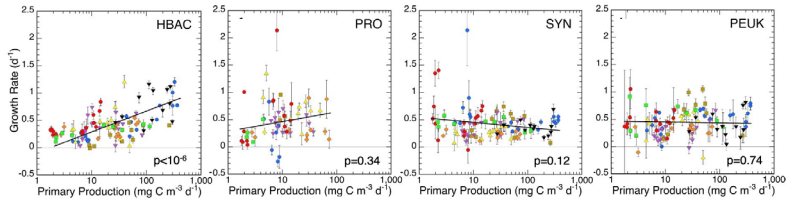
ENVIRONMENTAL RELATIONSHIPS: Two order-of-magnitude variability in mixed-layer nitrate, primary production (PP), chlorophyll a (Chla). Relationships reflect expected dynamics of an upwelling system. Nitrate comes from upwelling of cooler deep water. Primary production (PP) increases with nitrate availability. Strong relationships between PP and Chla.



Landry et al. (2023. PNAS)

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GROWTH RATES: HBAC growth increases with increasing PP (as expected by EML hypothesis). PP effects on growth of PRO, SYN and PEUK are not significant. Rate regressions are Model 2 (Reduced Major Axis).

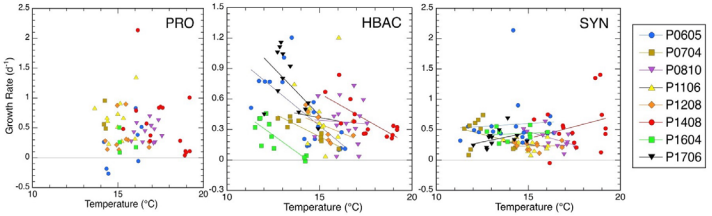


	HBAC	PRO	SYN	PEUK
PP<10	0.23 ± 0.02	0.46 ± 0.08	0.48 ± 0.07	0.42 ± 0.08
10-100	0.42 ± 0.03	0.48 ± 0.05	0.38 ± 0.02	0.44 ± 0.04
PP>100	0.79 ± 0.07	nd	0.38 ± 0.04	0.45 ± 0.06

Landry et al. (2023. PNAS)

8

TEMPERATURE EFFECTS help explain growth rate trends



PRO: No presence below ~14°C. Decline in productive/upwelled water is better explained by low temperature (rather than grazing).

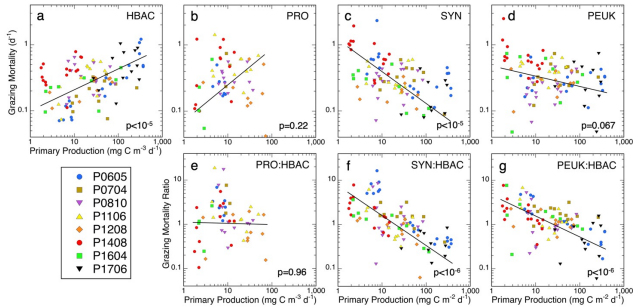
HBAC: Growth increases significantly at low temp overall and for most cruises. Organic resource availability overrides temp effect on growth.

SYN: Temp tends insignificant. Growth relatively high in warm low-nutrient waters. Effects of lower temp balance increased nutrients inshore.

Landry et al. (2023. PNAS)

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GRAZING MORTALITY: HBAC increases with PP. SYN declines with PP; PRO and PEUK trends not significant. Contrary to EML, relative grazing ratios on SYN and PEUK decrease at higher PP.



Landry et al. (2023. PNAS)

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GRAZING MORTALITY SHIFT: Relative grazing impacts on picoplankton (compared to HBAC) are not constant but vary with system productivity.

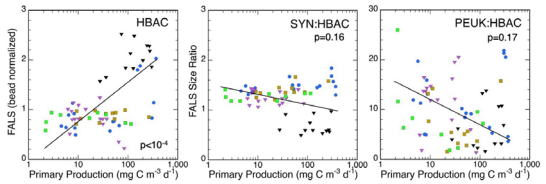
Mortality rate scaling calculation:

Grazing of HBAC at high PP	0.61 d^{-1}
SYN:HBAC mortality ratio at low PP	x 3.9
Projected SYN mortality at high PP	2.38 d^{-1}
SYN growth at high PP	0.38 d^{-1}
Net rate of SYN	-2.00 d^{-1} (86% loss d^{-1})

Persistence of SYN and PEUK populations despite greatly intensified grazing for HBAC highlights the importance of shifting mortality in maintaining a stable niche for picophytoplankton in high PP waters.

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EXPLANATIONS?



Using FALS cell size index, HBAC size increases with PP, but relative size variability of SYN and PEUK cannot account for grazing mortality trend.

Potential mechanisms consistent with results:

1) Compositional or behavioral variability of grazer assemblages that alter prey selectivity (e.g., switching based on relative abundances of H- and A-Picos);
2) Environmental selection of HBAC prey populations with different tradeoffs in growth rate maximization versus predation defenses.

Landry et al. (2023. PNAS)

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SUMMARY POINTS

1. Mortality variability is poorly considered in models of microbial interactions (self-assembly, niche partitioning) that typically highlight physiological capabilities of competing ecotypes as the main determinant of distributional outcomes. Dynamic several-fold variability in microbial mortality that scales with primary productivity provides new insights into distributional patterns of PICO-plankton in coastal regions.
2. High PP increases HBAC abundance, cell growth and grazing. EML hypothesis breaks down in translating high HBAC mortality to A-PICO via shared predation.
3. Order-of-magnitude variability in mortality ratios suggests highly selective predators or selection for microbes with tightly coupled tradeoffs in growth and grazing.
4. Large shifts in relative grazing mortalities of co-occurring microbes challenge long-held view that protistan grazing mainly determines overall biomass while viruses uniquely regulate diversity by "killing the winners". Fast-growing HBAC are punished by high grazing impacts not experienced by phototrophs, allowing SYN & PEUK to persist despite growing slower than average HBAC.

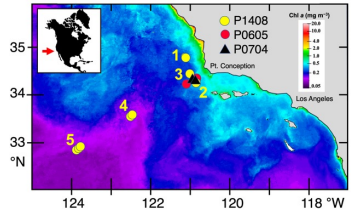
13

Estimating taxon-specific growth and grazing of heterotrophic bacteria using molecular sequences

Dilution experiments with16S-sequenced initial and final populations

Approach: use parallel estimates of PRO from flow cytometry and sequences to normalize relative sequence to cell abundance estimates.

Goal: Test approach, initial results, areas for improvement

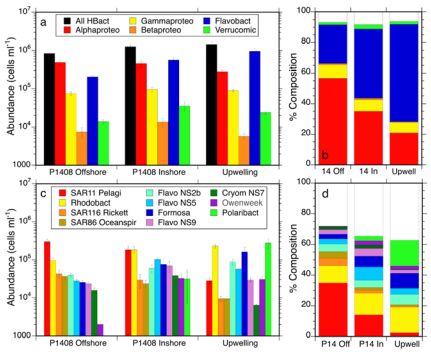


Cruise 2014 occurred during a major heatwave in eastern Pacific, with unusually low nutrients, high T inshore

Exp groups: 2014 offshore
2014 inshore
2006-07 normal upwelling

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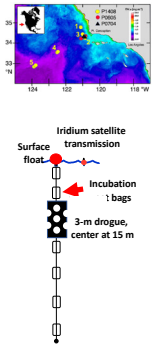
Abundance estimates from 16S sequences



P1408 Offshore
0.04 μM NO_3
0.1 mg Chla m^{-3}
65 mg C m^{-3} d^{-1}

P1408 Inshore
0.04 μM NO_3
0.6 mg Chla m^{-3}
283 mg C m^{-3} d^{-1}

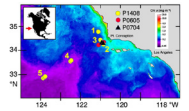
Upwelling
11.2 μM NO_3
1.7 mg Chla m^{-3}
2160 mg C m^{-3} d^{-1}

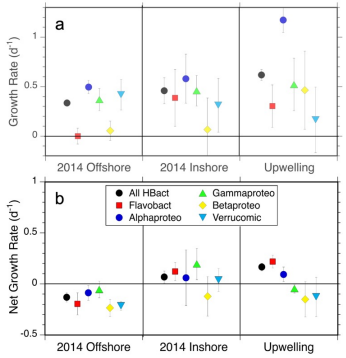


Landry et al. 2024. AME

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Taxon-specific intrinsic growth rates and net growth rates



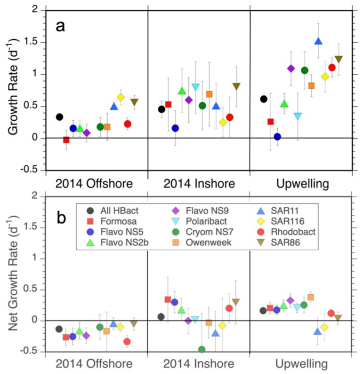


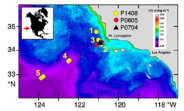
Major Groups
Measurable rates, substantial uncertainties
NO_3 effect on growth ?
Net growth overall ± 0.2 d^{-1}

Landry et al. 2024. AME

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Taxon-specific intrinsic growth rates and net growth rates





Major Taxa

Larger rate differences

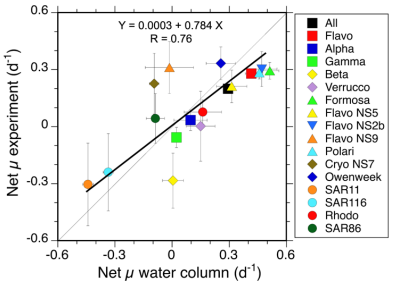
Clearer enrichment effects

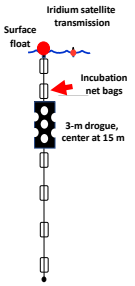
Still muted net growth ± 0.2 d^{-1}

Landry et al. 2024. AME

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Taxon-specific response to upwelling conditions
A Lagragian field test of net rates





"Net experimental rates (d^{-1})" = Y axis are rate estimates from in situ bottles incubations

"Net water column rates (d^{-1})" = X axis are rate estimates determined from initial and final samples of the water column with no incubation

Landry et al. 2024. AME

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Some lessons learned:

"Bottle effects" – there is a widely held view that microbial communities change dramatically when you put them in bottles. We observed that the bottle changes were about the same as in the natural community sampled over days following a satellite tracked drifter. Differences: careful bottle filling, *in situ* bottle incubations (experience natural light and temperature).

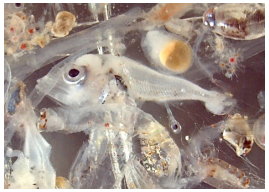
Growth rates are relatively modest, responsive to environ. richness (0.1-1.5 d^{-1}) – nothing of the magnitudes of 3-5 d^{-1} that have been reported from grow-out "dilution cultures" analyzed by Card-FISH or 16S sequences.

Concerning issue: high growth SAR11; low growth Flavobact – PCR bias: differences in the amplification efficiencies of different 16S sequences in repeated PCR cycles. Calibration standard (Silverman et al. 2021) using replicate samples run through different numbers of PCR cycles to correct reads with a log-ratio linear model.

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Food web complexities in predicting open-ocean food web responses to increasing temperature and stratification

Expand your definition of microbial food web to include this guy



Plankton net tow with larva of Southern Bluefin Tuna (SBT) collected in the oligotrophic eastern Indian Ocean in Feb. 2022

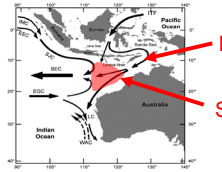
Marine ecosystem models tell us almost uniformly that warming and stratification of the open ocean will impact higher trophic levels in two ways:

1. direct reduction in nitrogen availability and primary production
2. "trophic amplification" – altered/reduced energy transfer because of longer food chains (primary producers get smaller)

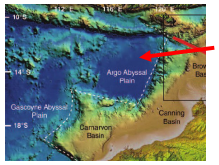
Fisheries modelers have sought to predict future changes by utilizing current knowledge of the physical parameters of critical fish habitats and projecting where they will occur in the Future Ocean.

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Habitat of larval SBT



Currents: Murgese & De Deckker (2005)
Spawning area: Matsuura et al. (1997)



Keep & Harrowfield (2008)

Only global spawning area for Southern Bluefin tuna (SBT)

- feeds in rich high-latitude waters
- spawns in oligotrophic tropical waters

Indonesian ThroughFlow (ITF)
only low-latitude connection between major oceans

- path of excess heat flow from western Pacific warm pool to Indian Ocean
- poorly known biogeochemistry, productivity and food webs

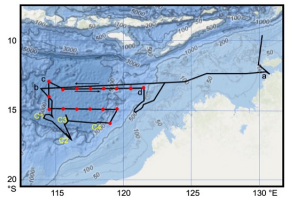
21

BLOOFINZ – Bluefin Larvae in Oligotrophic Ocean Foodwebs, Investigations of Nutrients to Zooplankton

Goal: to understand determinates of habitat quality for larval SBT and potential vulnerabilities to climate change



R/V Roger Revelle
RR2201, Jan-Feb 2022



Cruise track in Argo Basin

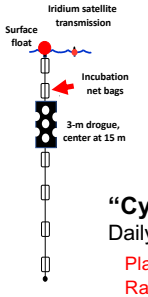
End-to-end: nutrients to larval fish

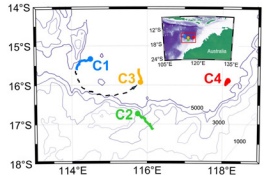
Traditional fisheries approaches
Larval feeding, growth and survival

Oceanography, plankton ecology
Biogeochemistry – C, N and Fe
Biomass, productivity, grazing, export
Food web fluxes, isotopes

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Lagrangian process experiments





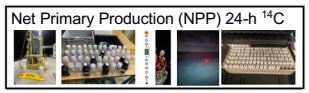


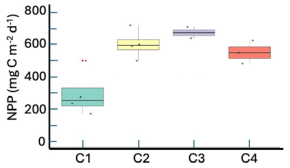
"Cycle" experiments following marked water parcels
Daily (3-5 days) integrated sampling/incubations over full EZ

Plankton structure – flow cytometry, pigments, microscopy, genetics, nets
Rates – ^{14}C-primary production, $^{15}NO_3$, $^{15}NH_4$ uptake, $^{15}N_2$ fixation,
phyto growth and microzoo grazing, mesozoo grazing, export
Tuna larvae – abundance, feeding selectivity, daily growth

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Primary Productivity: EZ-integr (80 m)



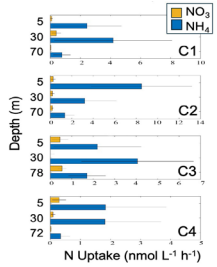


NPP = 450 ± 40 mg C m^{-2} d^{-1}
~ 2X Gulf of Mexico, Atlantic Bluefin spawning
< Stn. ALOHA, subtropical Pacific

S. Kranz

^{15}N-NO_3, NH_4 uptake rates

Diel 4-h incubations over 24 h



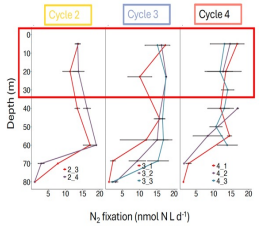
Mean uptake ratio:
NH_4 = 15X NO_3 uptake
"recycling system"

N. Yingling

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Nitrogen Fixation

$^{15}N_2$-equilib , 24-h in situ incubation



Upper 30m
6.9 ± 0.3
mg N m^{-2} d^{-1}

Full EZ
15.0 ± 0.7
mg N m^{-2} d^{-1}

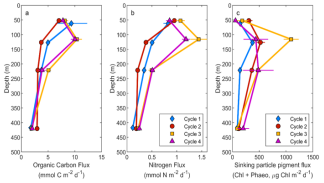
N_2 fixation ≈ 74.4 mg C m^{-2} d^{-1}
16.5% of NPP

No obvious blooms of *Trichodesmium* or DDAs

S. Kranz

Export particle flux





C Export = 87.6 mg C m^{-2} d^{-1}
Export Ratio = 19.5% of NPP
Stn ALOHA e-ratio ≈ 5% of NPP

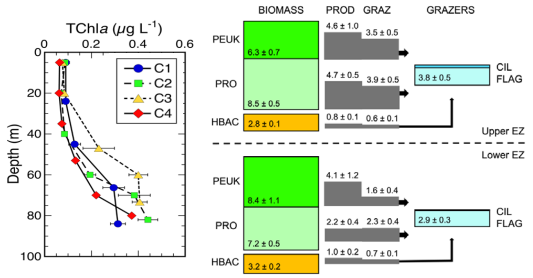
M. Stukel

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Two-layer oligotrophic oceanic food web

Phyto growth and microzoo grazing rates

PEUK = photosynthetic eukaryotes
PRO = *Prochlorococcus*
HBAC = heterotrophic bacteria



Stocks: mg C m^{-3}
Rates: mg C m^{-3} d^{-1}

Picoplankton dominated upper EZ

P-Euks more important in lower EZ

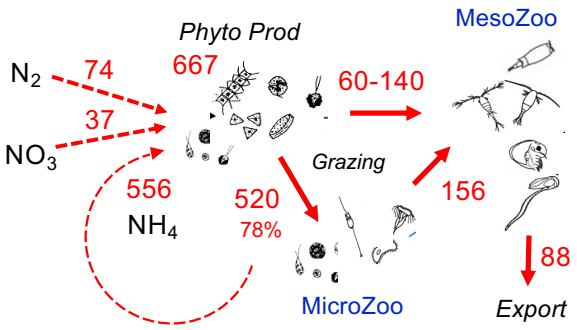
Micro-grazing
91% PRO production
78% Tot Phyto prod

M. Landry

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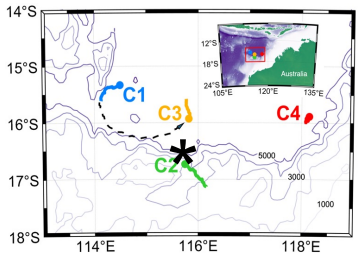
A resolved food-web carbon balance

all nutrient-production-grazing-export rates as mg C-equ m^{-2} d^{-1}

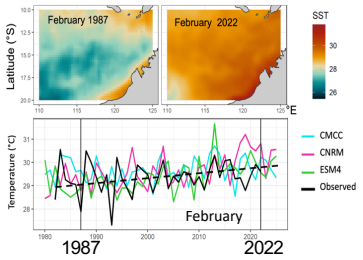


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An inter-decadal comparison of larval tuna feeding & growth



* Site of classic SBT larval study in the Argo Basin, Jan-Feb 1987.
Jenkins, Young, Davis - 5 papers



Upper: Satellite SST, Feb. 1987, 2022.
Lower: Climate model and observed SST in the Argo basin region 1980-2024.

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An inter-decadal comparison

Variable	1987	2022
Surface Temp (°C)	**27.46 ± 0.03**	**29.45 ± 0.06**
Surface Salinity (psu)	34.81 ± 0.01	34.58 ± 0.01
Mixed layer (m)	**16 - 22**	**14.1 ± 1.1**
SBT larvae 1000 m^{-3}	156 ± 37	33 ± 4
median	12.1	14.0
SBT % tuna larvae	82.1	89.5
SBT size (mm SL)	2.7 - 9.8	2.4 - 13.4
SBT feeding (%)	52.7	94.0
SBT prey per gut	0.85 ± 0.5	3.9 ± 0.18
SBT growth (mm d^{-1})	0.32 ± 0.01	0.39 ± 0.01
Copepods		
% environment	87.1 ± 2.6	79.4 ± 1.3
% diet	92.7	26.8 ± 4.4
Appendicularians		
% environment	12.9 ± 2.6	10.6 ± 1.2
% diet	0.66	58.9 ± 6.8

2°C warmer

more stratified

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An inter-decadal comparison

Variable	1987	2022
Surface Temp (°C)	27.46 ± 0.03	29.45 ± 0.06
Surface Salinity (psu)	34.81 ± 0.01	34.58 ± 0.01
Mixed layer (m)	16 - 22	14.1 ± 1.1
SBT larvae 1000 m^{-3}	**156 ± 37**	**33 ± 4**
median	**12.1**	**14.0**
SBT % tuna larvae	**82.1**	**89.5**
SBT size (mm SL)	**2.7 - 9.8**	**2.4 - 13.4**
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similar SBT median density
SBT dominance
SBT size range

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higher feeding incidence
4X more prey per larvae
faster growth rate

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An inter-decadal comparison

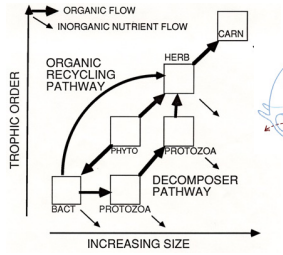
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3X lower feeding on copepods

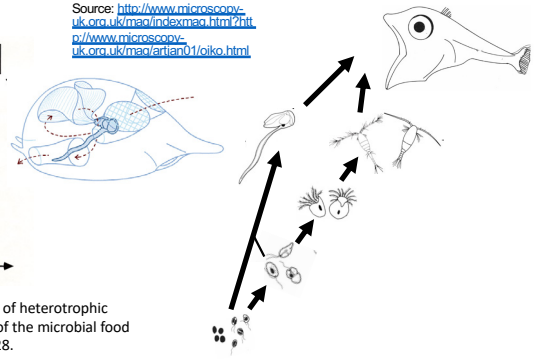
90X higher feeding on apps

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Short-circuiting the microbial loop



Source: http://www.microscopy-uk.org.uk/mag/indexmag.html?http://www.microscopy-uk.org.uk/mag/artjan01/oiko.html



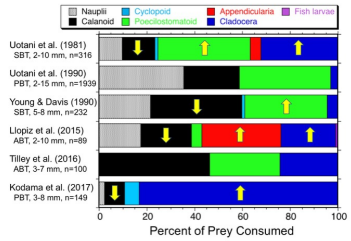
Williams, P. J. leB. 1981. Incorporation of heterotrophic processes into the classical paradigm of the microbial food web. Kieler Meersforsch. Suppl. 5: 1–28.

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Implications of the dietary shift

Increased transfer efficiency to larval tuna – apps short-circuit the microbial food web.

Bluefin larvae selective feeding on appendicularians is very rare. Whereas co-occurring Skipjack, *Auxis*, bullet tuna are app specialists (often 90% of diet).



Landry et al. (2018) ICES JMS

What has changed over 35 years:

- Temperature (activity) effect?
- Larval behavioral selection?
- Depth (fine-scale) distribution?
- Different app species?

Baseline knowledge of lower-level food web not known for 1987.

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35 years after the last major study of SBT larval habitat in the eastern Indian Ocean, we expected to see some indication of climate-driven habitat decline.

Instead, SBT larvae fed and grew at higher rates. Prey selectivity shifted from cyclopoid/poecilostomatoid copepods to appendicularians – a more direct, efficient transfer from the microbe-dominated food web base, but rarely seen in larval prey selection by bluefin species.

1. Flexibility in food-web relationships can contribute to recruitment resiliency in the future ocean. Cannot assume historical relationships will apply or that future larval habitat quality will depend only on projections from current physical environment (e.g., temperature range).
2. Importance of system-level field studies of oligotrophic-ocean nursery areas to understand food-web relationships and to document change.

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Thank you for your attention!

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