Towards a better understanding of fish contribution to carbon flux

Working Group Participants (committed thus far):
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Scientific Summary:

The ‘biological pump’, the vertical transport of biologically generated dissolved or particulate organic matter from the surface to the ocean’s interior, plays a key role in ocean biogeochemistry and food webs. Active transport of carbon via diel vertically migrating (DVM) organisms as well as passive transport via their rapidly sinking fecal pellets are major contributors to the ‘biological pump’. There is a wealth of knowledge of zooplankton active and passive transport and their contributions to carbon flux, including recent review articles (Turner 2015, Steinberg & Landry 2017). Respired carbon dioxide (CO_2) and excreted dissolved organic carbon (DOC) of vertically migrating zooplankton can contribute up to 70% of sinking carbon flux. Sinking rates of small or low mass fecal pellets of some zooplankton (i.e., copepods, euphausiids, doliolids, appendicularians, heteropods), as well as phytodetritus and marine snow, range from <10 to hundreds of meters per day, while very large or high mass fecal pellets of other zooplankton (i.e., salps, pteropods, chaetognaths) tend to sink faster (tens to thousands of meters per day). Even with more than 500 studies measuring zooplankton flux, there are still many unknowns with respect to the factors that drive variability of zooplankton flux in time and space.

Fish are even more understudied. To our knowledge, less than ten studies have estimated active transport in DVM fish and only five studies focused on direct measurements of fish passive flux. Mesopelagic DVM fishes from these few studies can contribute ~30-40% of total carbon flux through respired and excreted carbon byproducts. Furthermore, all reports on fish fecal pellets thus far have demonstrated the formation of cohesive, durable, rapidly sinking fecal pellets (Fig. 1). Measured sinking rates of fish fecal pellets reach well over thousands of meters per day. The feces produced by fish are long cylinders that vary in diameter depending on the producing species. The cohesive nature of these fecal pellets renders them less susceptible to bacterial decomposition during rapid decent to the benthos. Due to the combination of rapid sinking rates and low decomposition in the water column, the fecal material produced near the surface likely reaches the benthos in <1 day in most coastal systems. Fecal matter of anchovies in the Peru upwelling system contain high amounts of organic carbon and nitrogen, and represented up to 17% of total carbon flux in sediment traps. Furthermore, estimated

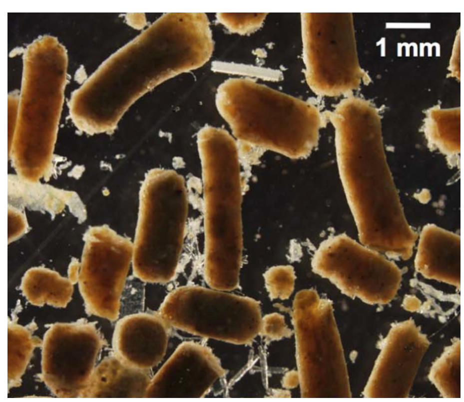

Figure 1. Northern anchovy fecal pellets collected in Santa Barbara Channel sink up to 1370 m d^{-1} (from Saba & Steinberg 2012).

fecal pellet particulate organic carbon (POC) flux from Northern anchovy was comparable to those previously measured from euphausiids and salps and was equal to, and sometimes exceeded, total POC flux measured previously by bottom-moored sediment traps deployed in the Santa Barbara Channel. Additionally, two studies revealed that fish contribute up to 15% of total oceanic carbonate production (inorganic C) via the formation and excretion of various forms of precipitated (non-skeletal) calcium carbonate from their guts. Along with active flux and passive fecal flux, fish mortality, either through the predation of DVM fishes at depth or falls of dead fish/fish parts, can contribute an as yet unquantified amount to the biological pump.

Thus, the passive, downward transport of particulate matter produced by fish and active transport of dissolved and particulate carbon from DVM species is likely a significant component of both organic and inorganic carbon flux in coastal environments. However, fish contribution to the biological pump is a complete unknown. This information is essential to not only determine its potential for a food source for benthic organisms, but also to improve parameterization of key processes affecting the biological pump and to develop more accurate regional and global carbon models. Only then can we begin to understand interannual and seasonal/spatial variability and long-term changes of fish fecal flux, food web regulation of carbon flux, and evaluate the potential role of environmental factors and climate change on fish carbon flux.

This working group is aimed at synthesizing existing knowledge of fish carbon flux, investigating the challenges associated with estimating fish contribution to the biological pump, and paving a path forward to develop approaches to begin filling some of the gaps in this much needed research.

Outcomes and Products:

Through this proposed scoping working group, we will begin to tackle the issue of the carbon flux contribution from upper trophic levels. This contribution is completely ignored in present-day carbon budgets and is likely significant due to high abundances of fish in certain regions (i.e., coastal zones, mesopelagic) and previous documentation of high fish contribution to total carbon flux. Products of the working group meeting will include: 1) a review paper on fish carbon flux with a concluding section on research priorities identified during the meeting; and 2) a science plan for submission of collaborative proposals to funding agencies to expand our knowledge of fish contribution to carbon flux, ranging from single-species laboratory experiments to incorporating fish carbon estimates into regional and global biogeochemical models.

The group will work to address the following goals:

1. ***Synthesize the existing research on fish carbon flux***: In summarizing knowledge from existing fish flux, the working group will focus on both active and passive flux measurements. We will identify species, major taxon groups, and habitats (i.e., reef, mesopelagic) targeted in previous studies in order to pinpoint future research priorities. Additionally, we will compare those fish flux measurements to those reported for zooplankton. Finally, we will put forth an attempt to estimate fish fluxes on larger scales (different ecosystems, regions, etc.) using two potential approaches: a) Combining fisheries stock assessment data with existing fish flux data; and 2) Incorporating a fish component into biogeochemical models. This information will be compiled and reported in the review paper mentioned above.

2. ***Recognize challenges in measuring fish carbon flux and discuss approaches to resolve them***: Measurements of *in situ* abundance of fish fecal pellets or their flux are lacking, reflecting the difficulty of adequately sampling these particles via traditional methods (i.e., sediment traps) due to the high mobility and schooling of fish leading to spatial heterogeneity or "patchiness" in fecal pellet production in surface waters. Sediment traps also do not sample active transport, and approaches to measure active flux must make several assumptions of energy budget components including size, metabolic rate, swimming speed, and growth rate which will all vary between individuals, species, and environmental conditions. Furthermore, the species composition, abundance, and spatial/vertical distributions of fish are required in order to extrapolate laboratory- or field-based carbon flux measurements or estimates to regional and global scales. This is, in itself, a big challenge in fisheries science, particularly for mesopelagic fish whose abundance is thought to be significantly underestimated. Through group discussion, we will recognize these and other challenges in these measurements and discuss possible solutions to overcome them. For instance, can we combine fecal pellet production and sinking rates measured in the laboratory or through Individual Based Models (IBMs) and extrapolate those rates to fish abundance (through stock assessment approaches that use both fisheries-independent and fisheries-dependent sources) *in situ*? Are passive and active flux rates species-specific or is there a relationship with biomass that can be applied for extrapolation?
3. ***Develop research priorities to fill the large gaps in understanding fish carbon flux***. Specifically:
    - Define key laboratory and/or field studies for directly measuring fish flux (dissolved and particulate organic and inorganic carbon)
    - Develop individual-based models for dominant fish species in order to estimate fecal pellet production rate
    - Determine best approaches to upscale existing models or developing new models for estimating fish contribution to carbon flux on regional and global scales.

    In order to determine contribution of fish to the biological pump on regional and global scales, we need to better understand several processes including species- or biomass-specific fish fecal pellet production rate (how many pellets produced per fish or per biomass per time) and respiration and excretion rates of CO_2 and DOC, respectively, sinking rates and carbon biomass of the fecal material, the biomass and species composition of fishes, the relative contribution of DVM fishes to the total fish population, and an idea of the temporal variability of these processes.
4. ***Identify opportunities to obtain resources needed to move this research forward***. Ultimately, convergence of these four goals will enable us to develop a science plan that will foster prepared action for rapid response to funding opportunities by participants of the working group, and other interested researchers, in order to expand our knowledge of fish contribution to carbon flux.

The working group participants include several early career researchers and range in expertise from zooplankton and fish ecologists and physiologists, biogeochemists, fisheries economists, and modelers that span in scale from IBMs to regional and global biogeochemical modeling, and all participants use diverse approaches to examine these processes. We are also in the process of inviting a few individuals whose research focuses on sedimentation processes (physical and geological), but they have not committed prior to this proposal submission. This diverse working group ensures productive and thoughtful discussion and output on such an interdisciplinary research problem. Including motivated international participants allows for international scientific coordination including the implementation of similar approaches to multiple regions for better parameterization of carbon flux in global models. It also opens up international funding opportunities to implement the working group science plan.

Relevance to OCB:

Our proposed workshop addresses two broad OCB research themes including *Biological Pump* and *Ocean Carbon Uptake and Storage*. Specifically, we would be addressing OCB's current research priority on *Water column and seafloor ecological and biogeochemical processes and associated effects on carbon export and the biological pump*.

Furthermore, our working group will directly address research areas prioritized at the Biological Pump Workshop in February 2016 supported by NSF and coordinated by OCB (Burd et al. 2016). By synthesizing carbon flux of a higher trophic level, we will provide a fish-focused component to the three research themes they present including food web regulation of export, the dissolved-particulate continuum, and variability in space and time. Additionally, by developing a step-wise approach for combining observational data from laboratory- and field-based fish flux measurements with regional and global modeling studies, we answer the call encouraged by Honjo et al. (2014).

Finally, our proposed goals will benefit and potentially leverage the EXport Processes in the Ocean from Remote Sensing (EXPORTS) Science Plan (Seigel et al. 2016). EXPORTS was formed and vetted by the research community with the ultimate goal of developing "a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth's carbon cycle in present and future climates." Our outcomes will address specific EXPORTS science plan questions including the amount and efficiency of vertical transfer of organic matter from the surface to depth, and via the inclusion of fish carbon, will assist in the goal to reduce uncertainties in current and future estimates of carbon export.

Workshop Logistics:

We propose a 2-year project with a tentative start date of May 1, 2018. A two-day working group meeting will occur in Year 1, and the participants will work collaboratively to complete the outcomes during the remainder of Year 1 and Year 2. The working group meeting is proposed for late Summer or Fall of 2018, which provides sufficient time to align schedules of all working group participants. This will be held in New Jersey, likely at the Rutgers University Inn and Conference Center for logistical ease of planning for lead Dr. Saba. Participants will arrive by personal vehicle or plane to the designated location the afternoon/evening prior to the start of the workshop.

The format of the workshop will seek to build avenues for collaboration and fill important gaps outlined above. There will be short presentations focused on each goal designed to stimulate discussion. The meeting will begin by outlining what we know about fish carbon flux, and then will proceed into paving a path forward to build upon existing knowledge and identify solutions in methodological approaches. The working group meeting is designed to maximize interactions from a diverse research group that will work to establish a step-wise interdisciplinary approach to better understand fish contribution to the biological pump.

Anticipated Budget and Justification:

We are requesting $26,964 for venue, audio/visual equipment, meals and rooms for attendees, local, domestic, and international travel for participants, and supplies. These estimates are based on similar workshops hosted at Rutgers on a variety of topics.

The venue is estimated to include a meeting room for 15-20 people. Audio/visual equipment will be used for presentations in order to promote discussion toward meeting working group goals. Attendees will be provided food and beverages throughout each day to ensure a productive workshop. Some office supplies will be needed to facilitate discussion during the working group meeting. Publication costs requested will be used to publish the review paper on fish carbon flux co-authored by working group participants.

Budget Item	Amount	Justification
Venue + AV	$1,300	1 venue in large enough to host 12 attendees; Projector screen, laptop with presentation capabilities, 1 podium microphone, 2 handheld microphones, webinar hookup access for remote participants
Food & Beverage	$860	Coffee and light breakfast ($150), lunch ($250), coffee/tea/snack in the afternoon ($60), per diem for dinner in the evening for 2 nights ($864)
Vehicle Travel	$972	Estimated at 3 people traveling by car in the Mid-Atlantic region up to 300 miles each way at a rate of $0.54/mile
Air travel	$7,000	Estimated at 5 people traveling via domestic flights ($3000) and 4 by international flights ($4000).
Hotel rooms at conference center	$3,300	Estimated at $150/room/night (2 nights) for 11 people (Saba is local and will not need hotel)
Supplies	$500	Supplies will include printing costs for various meeting materials, flip charts for facilitation note taking, markers for facilitation notes, etc.
Publication costs	$3,000	Anticipated costs associated with publication of workshop proceedings
Total Direct Costs	**$17, 396**	
F&A	**$9,568**	Rutgers overhead rate for this project is 55%.
Total	***$26,964***	

References cited:

Burd, A.B., Buchan, A, Church, M., Landry, M., McDonnell, A., Passow, U., Steinberg, D., Benway, H. 2016. Towards a transformative understanding of the biology of the ocean's biological pump: Priorities for future research. Report of the NSF Biology of the Biological Pump Workshop, February 19–20, 2016 (Hyatt Place New Orleans, New Orleans, LA), 67 pp., doi:10.1575/1912/8263.

Honjo, S., Eglinton, T.I., Taylor, C.D., Ulmer, K.M., Sievert, S.M., Bracher, A., German, C.R., Edgcomb, V., Francois, R., Iglesias-Rodriguez, M.D., van Mooy, B., Repeta, D.J. 2014. Understanding the role of the biological pump in the global carbon cycle: An imperative for ocean science. Oceanography 27(3):10-16, http://dx.doi.org/10.5670/oceanog.2014.78.

Saba, G.K., Steinberg, D.K. 2012. Abundance, composition, and sinking rates of fish fecal pellets in the Santa Barbara Channel. Scientific Reports 2: doi:10.1038/srep00716.

Siegel, D.A., Buesseler, K.O., Behrenfeld, M.J., Benitez-Nelson, C.R., Boss, E., Brzezinski, M.A., Burd, A., Carlson, C.A., D'Asaro, E.A., Doney, S.C., Perry, M.J., Stanley, R.H.R., Steinberg, D.K. 2016. Prediction of the Export and Fate of Global Ocean Net Primary Production: The EXPORTS Science Plan. Frontiers in Marine Science 3:22, doi: 10.3389/fmars.2016.00022.

Steinberg, D.K., Landry, M.R. 2017. Zooplankton and the Ocean Carbon Cycle. Annual Review of Marine Science 9: 413-444, doi: 10.1146/annurev-marine-010814-015924.

Turner, J.T. 2015. Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump. Aquatic Microbial Ecology 27: 57-102, doi:10.3354/ame027057.