Phytoplankton & Primary Production Workshop Summary

Last Updated: January 9, 2023

Overview

On December 6, 2022, the University of Washington Puget Sound Institute hosted a workshop on Phytoplankton & Primary Production. This was a focused technical discussion about opportunities for coupled monitoring and modeling to address gaps in the science of primary production. This included some of the questions regarding inter-annual changes in seasonality and community structure in phytoplankton productivity, including the role of salinity and density gradient changes with climate change drivers. The discussion explored one of the driving scientific questions around this topic:

> Considering future climate change, how do changes in density structure in response to the relative timing of coastal upwelling and earlier river discharge alter growth conditions for phytoplankton productivity?

Dr. Sophia Johannesen, with **Fisheries and Oceans Canada (DFO)** Institute of Ocean Sciences, explored insights from her research, including:

- Based on developing a nitrogen budget and analyzing sediment cores for stable isotopes, total primary productivity in the Salish Sea is unchanged since the 1970s (and for ≤ 100 years)
- The type of productivity might have changed from diatom-dominated to smaller phytoplankton-dominated, but if so the change is not the same everywhere. For example, there are different trends in the Strait of Georgia and Puget Sound, as well as within the Sound between the Hood Canal and Main Basin
- Changes in primary production have yet to be linked to climate stressors, which is an important gap
- To further explore this topic, Sophia plans to collaborate with Maycira Costa to combine existing satellite and sediment trap data. Furthermore, she plans to work with Akash Sastri and Christopher Krembs to combine nutrient, sediment core geochemistry, and taxonomy to analyze changes in the type of productivity relevant to Puget Sound

Dr. Maycira Costa, with the University of Victoria, shared how she is using remote sensing technology and models to analyze phytoplankton trends, including the exploration of functional taxa, and differences between bioregions. Some highlights include:

- Satellite-derived data complement *in situ* monitoring and modeling and can even feed into biogeochemical modeling. Satellite data can be particularly useful to understand large-scale temporal and spatial dynamics
- Algae Explorer is a web map service providing analysis of satellite data from Sentinel 3 to visualize daily changes in surface chlorophyll, for the British Columbia coast and parts of Puget Sound. Hakai Institute, BC, is operationalizing this workflow, and upgrading and integrating the platform into the Canadian Integrated Ocean Observing System (Justin Belluz, justin.belluz@hakai.org)
- Maycira calibrated, developed models, and validated Sentinel 3A and 3B satellite data for chlorophyll, turbidity, and dissolved inorganic matter products based on reflectance data (Giannini et al., 2021) and phytoplankton functional taxa (Vishnu et al., 2022)

- These tools can help explore any changes and potential mismatch in timing between phytoplankton and zooplankton, and is relevant to studying the impacts of food availability on foraging fish, salmon, and other higher trophic level organisms
- Specific to Puget Sound, Maycira recommended validating the satellite products and models for bioregions within it and undertaking the necessary work to adapt these tools further as needed

Dr. Brian Hunt at the University of British Columbia highlighted research on the bottom-up drivers of zooplankton food web structure and function

- Phytoplankton and particulate matter variation relevant to zooplankton nutrition (McLaskey et al., 2022), using fatty acid and stable isotopes to trace the food quality and composition into the food web (Costalago et al., 2020), and organic matter sources in the nearshore and coastal ocean (St. Pierre et al., 2022)
- Brian's upcoming research will expand on these themes and include fine-scale characterization of nearshore zooplankton communities using eDNA to identify community response to resource gradients

Then Dr. Stefano Mazzilli and Ben Parker, with the University of Washington, turned to numerical modeling and highlighted:

- There is an opportunity to better quantify the physical controls and nutrients available to phytoplankton and other biota using existing nutrient reduction scenarios undertaken using the Salish Sea Model. In particular in embayments that have low dissolved oxygen impacts
- Nutrient budgets can help us understand how changes to physical controls such as density gradients and exchange flow influence the availability of nutrients to the euphotic zone.
    - Analyzing the exchange flow is an important step to develop the nutrient budget and one of the most challenging. Khangaonkar et al. (2017) applied a direct tidally averaged mass flux. Ben Roberts presented a proposed approach he may explore for exchange flow calculations that can be applied to the Salish Sea Model using an indirect salinity-based mass flux approach

Materials

Links to the materials for the *Phytoplankton & Primary Production* workshop:

- Slides
- Full video
- Highlight video (coming soon!)
- Chat

Pre-Read Materials

Since attendees had varying levels of familiarity with the following regional models, we shared pre-read materials summarizing how the models represent phytoplankton and primary production specifically.

1. **Atlantis** video overview (+ slides)
    - *Paper describing the parameters in detail*
    - *Contact: Hem Nalini Morzaria Luna hemnalini.morzarialuna@noaa.gov*

2. **LiveOcean** paper describing the phytoplankton model development and testing
    - *Contact: Parker MacCready p.maccready@gmail.com*
3. **SalishSeaCast** video overview (starting @ 42:43) + *Slides 32 - 52*
    - *Contact: Elise Olson eolson@eoas.ubc.ca and Susan Allen sallen@eoas.ubc.ca*
4. **Salish Sea Model** video overview (+ slides)
    - *Contact: Stefano Mazzilli mazzilli@uw.edu and Tarang Khangaonkar Tarang.Khangaonkar@pnnl.gov*

Highlights

Note: for the full presentation slides and resulting discussion please see the links above. Below are some highlights from the presentations, followed by questions and key discussion points.

Phytoplankton & Primary Production Vital Sign

Dr. Cheryl Greengrove, University of Washington

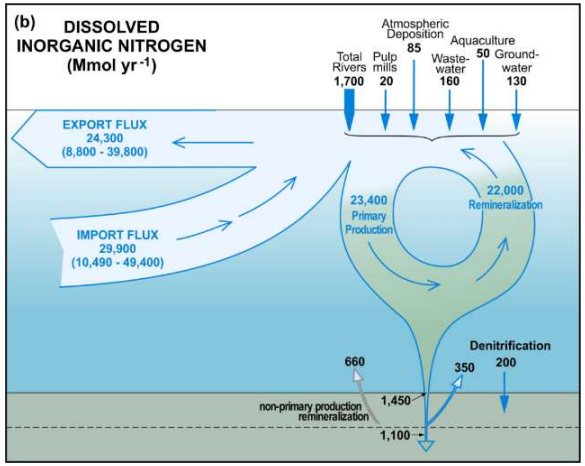
- Cheryl began the series of presentations with a summary of prior Vital Signs workshops on monitoring phytoplankton and the importance of these parallel efforts to coupled monitoring and modeling to address gaps in the science of primary production
- The Phytoplankton & Primary Production Vital Sign Development workshops bring together a community of experts and stakeholders to gather information on phytoplankton and primary production in Puget Sound and lay the foundational framework needed to integrate these critical ecosystem components into the Puget Sound Partnership's Vital Sign Indicators
- Workshop #1 inventoried existing monitoring in the region, Workshop #2 discussed opportunities to connect to other indicators, recovery goals, and ecosystem assessments, and Workshop #3 highlighted insights from other west coast estuary experts

Changing primary productivity in the Salish Sea. A geochemical perspective

Dr. Sophia Johannessen, Fisheries and Oceans Canada (DFO) Institute of Ocean Sciences

Total primary productivity in the Salish Sea is unchanged since 1970s (and for ≤ 100 years)

- Harrison et al. (1983), expanded on prior monitoring data to resolve the patchiness, estimating that the total productivity in the Strait of Georgia was 280 g C m^{-2} yr^{-1}
- Sutton et al. (2013) developed a nitrogen budget for the Strait of Georgia to explore the major levers
    - The unusually rich observational data set allowed the budget to be fairly tightly constrained. The alignment with Harrison et al. (1983) suggests primary productivity has neither increased nor decreased since the 1970s
    - Land-based nitrogen loading is dwarfed by the import and export from the ocean (see adjacent figure)
    - Most of the nitrogen is incorporated into phytoplankton and remineralized; only a small portion is exported into the sediments



- Sophia analyzed sediment cores from the Puget Sound and Strait of Georgia
    - Incorporated four sediment cores in Puget Sound from Brandenberger (2011) that were collected in 2005. Additionally, collected and analyzed cores in the Strait of Georgia as recently as 2020
    - Analyzing sediment cores for stable isotopes for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), respectively, can provide insights into whether the source organic matter is marine or terrigenous, the rate of primary productivity, and the length of the food chain
        - Phytoplankton preferentially use up $\delta^{12}C$, leaving behind $\delta^{13}C$, so over the course of a bloom the sinking material becomes heavier in carbon isotopes
        - Analyzing $\delta^{13}C$ and nitrogen $\delta^{15}N$ together makes it possible to define a terrigenous and two marine endmembers
        - The flux of marine derived organic carbon has not increased or declined over the last 100 years in the Strait of Georgia or Puget Sound. Initially it seemed like there might be an increase toward the surface of the sediments, however this is likely attributed to burndown in the sediments

The type of productivity may have changed from diatom-dominated to smaller phytoplankton-dominated, but if so the change observed from sediment cores is not the same everywhere. For example, there are different trends in the Strait of Georgia and Puget Sound, as well as within the Sound including between the Hood Canal and Main Basin.

- Sophia provided a brief overview of the Washington State Department of Ecology's monitoring work showing a potential change in primary production and causes that she is currently investigating for the wider Salish Sea region
- Based on Ecology's network of 37 monitoring stations and parallel meteorological and hydrological, Christopher Krembs (Ecology) has hypothesized a potential change in the type of productivity in the Sound over the last 20 years and potential drivers to investigate[1]

[1] *Further information on the associated hypothesis were presented by Christopher Krembs and others at several regional forums, including the PSEMP phytoplankton group on May 18, 2022 and the Oregon-Washington Water Year 2022 Recap & 2023 Outlook Meeting on October 26, 2022.*

    - **Hypothesis:** Climate change and associated hydrodynamic influences, and/or local human activities change the surface concentration and ratios of nutrients, and that these might subsequently be supporting the change from diatom to smaller phytoplankton dominance, such as dinoflagellates. Furthermore, that this would also result in more rapid recycling within the water column and a more bacterial dominated food chain
    - Annual average nitrate anomaly in the top 30 m of Puget Sound appeared to be increasingly rapidly from 1998 to 2008, but then decreased in the following decade with a potential increase again in recent years. However, this recent trend requires more years of data to confirm
    - During the same time period the silicate to nitrate ratio declined in Puget Sound, indicative of a potential change from diatom to smaller dinoflagellate dominance in phytoplankton blooms
    - Climate drivers on hydrodynamics in Puget Sound have correspondingly changed over the same time period, shown by:
        - River flow from the freshet is earlier in the winter/spring, less during summer, and again more through fall/winter. Accordingly, there is a shift from a snow-dominated flow to a more rain-dominated flow
        - This has resulted in an increase in observed stratification (based on density calculations from temperature and salinity measurements) in Puget Sound, particularly in the late winter
- Sophia showed in her research that during the same time period in the Strait of Georgia, there was not a similar trend in nitrate or the nitrate to silicate ratios, etc. Therefore, different areas of the Salish Sea may be changing differently
    - This anomaly analysis also suggests there is some kind of multi-annual trend for the Strait of Georgia, and that larger scale drivers for these trends needs to be investigated further
- On examination of Organic C sediment flux data in at two locations in Puget Sound, Sophia shared some preliminary results (which may evolve) showing that:
    - Hood Canal may be presenting a trend over the last 100 years and beyond towards an increase in smaller phytoplankton such as dinoflagellates. However, this is not the case for the Main Basin which appeared to have less change in this group over the period, and a potential increase vs. the decrease in the indicator of change for diatoms

Changes in primary production have yet to be linked to climate stressors, which is an important gap. Sophia's proposals and future work include the following to address this:

- Combine existing satellite and sediment trap data in the Strait of Georgia to address the question: how does surface ocean color relate to exported organic matter? (with Maycira Costa (University of Victoria))
- Combine nutrient, sediment core geochemistry, and water column taxonomy data, addressing: has the type of productivity changed over time in the Salish Sea? If so, does the change relate to changes in climate change stressors? (with Akash Sastri (Fisheries and Oceans Canada) and Christopher Krembs (Washington Department of Ecology))
- Collect new cores and deploy sediment traps specifically in Puget Sound (speculative)

Remote Sensing technology to monitor ocean conditions

Dr. Maycira Costa, University of Victoria

Maycira's research and collaborations on remote sensing technology in the Salish Sea:

- Developed Algae Explorer, an online mapping product that uses satellite data from Sentinel 3 to visualize daily change in surface chlorophyll for the British Columbia coast and parts of Puget Sound
    - Hakai Institute, BC, is operationalizing this workflow, and upgrading and integrating Algae Explorer into the Canadian Integrated Ocean Observing System. This will allow wider access and continued improvements through their ongoing provision of services
- Started by defining the quality of the radiometry of the satellite
    - Installed autonomous sensors onboard the BC ferries that captured radiance from the sky and water to produce reflectance, which was used to calibrate and validate the Sentinel 3A and 3B satellite data (Wang, & Costa, 2022)
- Adapted and validated the atmospheric corrections
- Then developed/adapted models for:
    - Chlorophyll, turbidity, and dissolved inorganic matter products based on reflectance data from Sentinel 3A and 3B (Giannini et al., 2021)
    - Phytoplankton groups/phytoplankton functional taxa (Vishnu et al., 2022)
        - The model uses the High-Performance Liquid Chromatography (HPLC) pigments, which are ingested in a CHEMTAX library to define phytoplankton groups. Maycira and her team then associated the phytoplankton groups with the reflectance measured by Sentinel 3. After that, they derived an empiric orthogonal function approach that better describes each of the phytoplankton group that are of interest
            - CHEMTAX library is not comprehensive so, while some groups are represented quite well (e.g., diatoms), others are not. The database will hopefully be expanded in the future
        - Applied the model spatially and temporally to produce phytoplankton bloom maps (e.g., diatom, cryptophyte, green algae, and raphidophyte) that were validated against not only *in situ* data, but also by Hakai's independent analysis
- Defined bioregions to understand how they change over time (Marchese et al., 2022)
    - Used neural network and self-organized mapping methods to define the bioregions
    - Analyzed phytoplankton phenology within the climatology of the bioregions throughout the year on a weekly basis from 2016 – 2021 to understand what is changing and the importance of those changes
- Merged Ocean Color data into a long time series analysis from 1997 – present (Pramlall et al., under review)
    - Validated against observations in British Columbia and found it retrieves chlorophyll very well. However, the spatial resolution is 4 km
- Defined phytoplankton functional types, bioregions, and phenology for the entire North Pacific (Konick, Costa et al., in prep)
- Considered the potential mismatch in timing between phytoplankton blooms and zooplankton that impacts the quality of food available to juvenile salmon (Suchy et al., 2019, Suchy et al., 2022)

Reflections

- Specific to Puget Sound, Maycira recommended validating the satellite products and models for bioregions within it and undertaking the necessary work to adapt these tools further as needed
- Satellite derived data is just one piece of the puzzle that complements *in situ* monitoring and modeling. It can be particularly useful to understand large scale temporal and spatial dynamics
    - There is an opportunity for satellite-derived data to be better used to feed into and validate the existing biogeochemical models for the region
- The upcoming PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) mission in 2024, with full hyperspectral payload, will be able to provide information on many more biogeochemical parameters, based on very narrow bands
    - Ferry-based hyperspectral data is the same type of data that PACE will be able to collect, so anticipate being able to apply models to calibrate, validate, and analyze phytoplankton functional taxa data from these two sources

Compile and analyze historical primary production data

Dr. Jan Newton, NANOOS

- Jan highlighted an opportunity to compile and analyze historical C-14 primary production data from several projects between 1999 – 2014 that has been unused till now. Not only are C-14 uptake measurements rare, but these observations have accompanying chlorophyll and phytoplankton counts so are also valuable for assessing the comparability of these more commonly available measures of phytoplankton change
- Jan is looking for resources to support an oceanography (or similar) senior or master student for a summer, or ideally a year to get a manuscript together and make these data available to the modeling and monitoring community

Bottom up drivers of zooplankton food web structure and function

Dr. Brian Hunt, University of British Columbia

Brian shared a teaser on research and considerations related to the connections between phytoplankton, zooplankton, and upper trophic levels, including:

- Phytoplankton and particulate matter variation relevant to zooplankton nutrition (McLaskey et al., 2022)
    - Phytoplankton composition and size structure matter to zooplankton
    - The fatty acid ratio DHA: EPA (Docosahexaenoic Acid:Eicosapentaenoic Acid) is an important metric; the higher the ratio, the better quality the food is for zooplankton
        - Microzooplankton can convert the 18-carbon polyunsaturated fatty acids (PUFAS) that are abundant in pico-phytoplankton to DHA and EPA, so pico-phytoplankton can support a varied and nutritious prey field
- Used fatty acid and stable isotopes to trace the food quality and composition into the food web (Costalago et al., 2020)
    - Supports the seasonal shift in trophic pathways to diatom dominated in the spring and flagellate dominated in summer. However, fatty acid can also be sourced through microzooplankton which may confound this observed change

- Organic matter sources in the nearshore and coastal ocean (St. Pierre et al., 2022)
    - The input of terrestrial materials scale with the proximity to watersheds
    - Macrophytes can contribute up to ~20% of POM biomass
- Future work
    - Characterization of additional organic matter sources to coastal ocean (e.g., urban environments)
    - Understanding food web pathways - application of multiple trophic markers (fatty acids and isotopes), in addition to zooplankton stomach DNA to further resolve our understanding of zooplankton diets
    - Understanding the role of resources as drivers of zooplankton food web structure (e.g., organic matter contributions to the system) - fine scale characterization of nearshore zooplankton communities using eDNA to identify community response to resource gradients

Tools for sub-basin and inlet nutrient budgets

Dr. Stefano Mazzilli, University of Washington Puget Sound

- There is an opportunity to better quantify the physical controls and nutrients available to phytoplankton and other biota using existing nutrient reduction strategy scenario runs of the Salish Sea Model. In particular, in embayments that have been identified as having low dissolved oxygen, and have expected eutrophication impacts.
- Using the model applied in the Puget Sound Nutrient Reduction Project we extracted some initial results to first see if the representation of phytoplankton is as expected in three embayments identified by the State as having low dissolved oxygen and non-compliance. Second, to get feedback on how to refine further analysis of primary production. This included total net primary production, dissolved oxygen, nitrogen, salinity, temperature, and two parameters that are representative of diatoms and dinoflagellate biomass, respectively
- Khangaonkar et al. (2021b) analyzed the heatwave years from 2014 – 2017 and demonstrated that the model is responsive to interannual changes in hydrology and meteorology, and changes over that time had cascading impacts on phytoplankton and zooplankton
    - The modeling results showed there was a clear correlation between increased river flow and exchange flow, which led to increased nutrients in the system that increased primary productivity. This subsequently led to increased zooplankton biomass and grazing. In the paper, the authors postulate that this ultimately resulted in an increase in the herring population during that period.
- Nutrient budgets can help us understand how changes to physical controls such as density gradients and exchange flow influence the availability of nutrients to the euphotic zone.
    - Analyzing the exchange flow is an important step to develop the nutrient budget and one of the most challenging. Khangaonkar et al. (2017) applied a direct tidally averaged mass flux. Ben Roberts presented a proposed approach he may explore for exchange flow calculations that can be applied to the Salish Sea Model using an indirect salinity-based mass flux approach

Quantifying Estuarine Advective Exchange with the Salish Sea Model

Ben Roberts, University of Washington

- Quantifying advective fluxes in and out of any control volume using salinity can help us understand why changes to other parameters of interest like dissolved oxygen are happening. For example, the availability of nutrients because of physical advection from the ocean vs. a change in the internal biogeochemical processes
- Ben presented a plan to use a method from MacCready (2011) to extract the Total Exchange Flow from the Salish Sea Model existing runs
    - A benefit to this approach is that it does not require rerunning the model, so the data can be extracted from the existing results and scenarios
    - *Processing code is public*

Discussion

- Jan Newton, noted it is interesting to see the Silicate: Nitrate ratio decrease in Puget Sound and the San Juan Archipelago, but increase in the Strait of Georgia. She mentioned she looks forward to sharing and discussing the data further offline
- Joel Baker asked Sophia if you had the opportunity to collect and analyze 10 long cores in the Salish Sea to follow up on this work, where would you would put the sampling sites to give the most information? Sophia said she would:
    - Prioritize the Puget Sound since there is fewer samples overall and they are generally older. Sophia would repeat the same stations that were previously sampled to see if the trends have continued
    - Ideally sample at a location where the ratio of the surface mix depth to the sedimentation rate is low for better temporal resolution (e.g., 2-3 years)
    - Recommend sampling cores sequentially to inform subsequent sampling locations
    - Seth Book added that he would recommend the same Hood Canal sites (HC-3, HC-5) as well as Dabob Bay and the southeast arm of Hood Canal
- Parker MacCready asked Sophia if her flux analysis can be compared to the 280 g C m-2 yr-2 that Harrison et al. (1983) identified?
    - Sophia responded that in the Strait of Georgia about 96% of the fresh organic matter that is marine derived at the surface is remineralized before it reaches the bottom. Over a 350 m water column, only about 4% of that organic matter reaches the bottom, so if we start with what is happening in the bottom and extrapolate we would be using the tail to wag the dog too much. She suggested it is better to use the segment core trends over time relative to themselves and may even be able to quantify the percentage increase/decrease
- Michael Connor asked how crucial and expensive is the ferry correction of the data?
    - Maycira reflected that the ferry data is an extremely rich data set that will be very important for the PACE mission and atmospheric correction model for this region. Unfortunately, ferry sensors are quite expensive, require a lot of maintenance (e.g., bi-weekly in the springtime), and generate a lot of data to process. The BC Ferries stopped supporting this program in mid-2020 due to COVID restrictions
    - Maycira emphasized that she would start by validating whether her products are accurate enough for Puget Sound though. That we do not need to go back to the reflectance, but start by comparing the products themselves to the literature, *in situ* data,

and/or compile a database of observations. Then later on, we can consider whether it would be valuable for the Puget Sound region to invest in infrastructure to engage with the PACE mission in a consistent way
    - Brandon Sackmann shared that the State is actively in the process of resurrecting monitoring on the Victoria clipper. The new system will include a thermosalinograph, and also make it easier for other researchers in the region to install additional sensors
    - Seth Book mentioned it be helpful to have continuous reflectance data from Hood Canal during Coccolithophore blooms coupled with primary productivity results and suggested adding spectral sensors to vessels in the South (e.g., UW research vessel)
- Bart Christiaen asked if there is an understanding of the contribution of macrophytes in nearshore environments to total the biomass of primary producers / total primary production in Puget Sound?
    - Michael Connor suggested a hypsographic chart approach could be used in a quick first-order estimate. In general, though, it sounded like this is an area for further exploration
- Seth Book noted that he is looking forward to researchers developing tools with greater spatial resolution that can be used to analyze site specific issues in places like the Hood Canal
    - Maycira suggested looking at the European satellite data when analyzing embayments because it has a 300 m spatial resolution. She noted that the data may need to be tuned to the region though
    - Brandon Sackmann also highlighted that some of the terrestrial platforms like Landsat and Sentinel 2 have a 10 – 30 m spatial resolution, although would require additional work to calibrate and validate for the region
- Sophia reflected that the nutritional value of picoplankton and the contribution of terrigenous material are both fascinating and is planning to connect with Brian to discuss what could potentially be traced in the sediments
- Lincoln Loehr asked if the sediment core data can pick up a signal of changes associated with reductions in particulate organic matter discharged from pulp and paper mills and municipalities since 1972?
    - Sophia shared that yes, the sediment cores recorded a pulp mill signal in contaminants - mainly dioxins and furans. C/N ratios and the terrigenous flux (from stable isotopes) also reflect changes in pulp mills as well as land-clearing in general
- Michael Connor noted that it is what is striking about model data comparison is the model misses daily maxes. It could be that these daily maxes and mins are more important markers to the health of the system and should be captured in the sensitivity analyses

Resources

Referenced in the presentations

Dr. Sophia Johannesen

- Johannessen, S. C., Macdonald, R. W., & Strivens, J. E. (2021). Has primary production declined in the Salish Sea? *Canadian Journal of Fisheries and Aquatic Sciences*, *78*(3), 312–321. Available at: https://doi.org/10.1139/cjfas-2020-0115
- Sutton, J. N., Johannessen, S. C., & Macdonald, R. W. (2013). A nitrogen budget for the Strait of Georgia, British Columbia, with emphasis on particulate nitrogen and dissolved inorganic nitrogen. *Biogeosciences*, *10*(11), 7179–7194. https://doi.org/10.5194/bg-10-7179-2013

- Brandenberger, J. M., Louchouarn, P., & Crecelius, E. A. (2011). Natural and Post-Urbanization Signatures of Hypoxia in Two Basins of Puget Sound: Historical Reconstruction of Redox Sensitive Metals and Organic Matter Inputs. *Aquatic Geochemistry*, *17*(4–5), 645–670. Available at: https://doi.org/10.1007/s10498-011-9129-0
- Harrison, P. J., Fulton, J. D., Taylor, F. J. R., & Parsons, T. R. (1983). Review of the Biological Oceanography of the Strait of Georgia: Pelagic Environment. *Canadian Journal of Fisheries and Aquatic Sciences*, *40*(7), 1064–1094. Available at: https://doi.org/10.1139/f83-129

Dr. Maycria Costa

- Marchese, C., Hunt, B. P. V., Giannini, F., Ehrler, M., & Costa, M. (2022). Bioregionalization of the coastal and open oceans of British Columbia and Southeast Alaska based on Sentinel-3A satellite-derived phytoplankton seasonality. *Frontiers in Marine Science*, *9*, 968470. Available at: https://doi.org/10.3389/fmars.2022.968470
- Nasiha, H. J., Wang, Z., Giannini, F., & Costa, M. (2022). Spatial Variability of In Situ Above-Water Reflectance in Coastal Dynamic Waters: Implications for Satellite Match-Up Analysis. *Frontiers in Remote Sensing*, *3*, 876748. Available at: https://doi.org/10.3389/frsen.2022.876748
- Suchy, K. D., Young, K., Galbraith, M., Perry, R. I., & Costa, M. (2022). Match/Mismatch Between Phytoplankton and Crustacean Zooplankton Phenology in the Strait of Georgia, Canada. *Frontiers in Marine Science*, *9*. Available at: https://doi.org/10.3389/fmars.2022.832684
- Wang, Z., & Costa, M. (2022). Autonomous Shipborne In Situ Reflectance Data in Optically Complex Coastal Waters: A Case Study of the Salish Sea, Canada. *Frontiers in Remote Sensing*, *3*, 867570. Available at: https://doi.org/10.3389/frsen.2022.867570
- Giannini, F., Hunt, B. P. V., Jacoby, D., & Costa, M. (2021). Performance of OLCI Sentinel-3A satellite in the Northeast Pacific coastal waters. *Remote Sensing of Environment*, *256*, 112317. Available at: https://doi.org/10.1016/j.rse.2021.112317
- Suchy, K. D., Le Baron, N., Hilborn, A., Perry, R. I., & Costa, M. (2019). Influence of environmental drivers on spatio-temporal dynamics of satellite-derived chlorophyll a in the Strait of Georgia. *Progress in Oceanography*, *176*, 102134. Available at: https://doi.org/10.1016/j.pocean.2019.102134

Dr. Brian Hunt

- McLaskey, A. K., Forster, I., Del Bel Belluz, J., & Hunt, B. P. V. (2022). A high-resolution time series of particulate matter fatty acids reveals temporal dynamics of the composition and quality available to zooplankton in a temperate coastal ocean. *Progress in Oceanography*, *206*, 102843. Available at: https://doi.org/10.1016/j.pocean.2022.102843
- St. Pierre, K. A., Hunt, B. P. V., Giesbrecht, I. J. W., Tank, S. E., Lertzman, K. P., Del Bel Belluz, J., Hessing-Lewis, M. L., Olson, A., & Froese, T. (2022). Seasonally and Spatially Variable Organic Matter Contributions From Watershed, Marine Macrophyte, and Pelagic Sources to the Northeast Pacific Coastal Ocean Margin. *Frontiers in Marine Science*, *9*, 863209. Available at: https://doi.org/10.3389/fmars.2022.863209

- Costalago, D., Forster, I., Nemcek, N., Neville, C., Perry, R. I., Young, K., & Hunt, B. P. V. (2020). Seasonal and spatial dynamics of the planktonic trophic biomarkers in the Strait of Georgia (northeast Pacific) and implications for fish. *Scientific Reports*, *10*(1), 8517. Available at: https://doi.org/10.1038/s41598-020-65557-1

Modeling

- Premathilake, L., & Khangaonkar, T. (2022). Explicit quantification of residence and flushing times in the Salish Sea using a sub-basin scale shoreline resolving model. *Estuarine, Coastal and Shelf Science*, *276*, 108022. Available at: https://doi.org/10.1016/j.ecss.2022.108022
- Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., Mohamedali, T., & Pelletier, G. (2018). Analysis of Hypoxia and Sensitivity to Nutrient Pollution in Salish Sea. *Journal of Geophysical Research: Oceans*, *123*(7), 4735–4761. Available at: https://doi.org/10.1029/2017JC013650
- Khangaonkar, T., Nugraha, A., Yun, S. K., Premathilake, L., Keister, J. E., & Bos, J. (2021b). Propagation of the 2014–2016 Northeast Pacific Marine Heatwave Through the Salish Sea. *Frontiers in Marine Science*, *8*, 787604. Available at: https://doi.org/10.3389/fmars.2021.787604
- Khangaonkar, T., Nugraha, A., Premathilake, L., Keister, J., & Borde, A. (2021a). Projections of algae, eelgrass, and zooplankton ecological interactions in the inner Salish Sea – for future climate, and altered oceanic states. *Ecological Modelling*, *441*, 109420. Available at: https://doi.org/10.1016/j.ecolmodel.2020.109420
- MacCready, P., McCabe, R. M., Siedlecki, S. A., Lorenz, M., Giddings, S. N., Bos, J., Albertson, S., Banas, N. S., & Garnier, S. (2021). Estuarine Circulation, Mixing, and Residence Times in the Salish Sea. *Journal of Geophysical Research: Oceans*, *126*(2). Available at: https://doi.org/10.1029/2020JC016738
- Ahmed, A., Figueroa-Kaminsky, C., Gala, J., Mohamedali, T., Pelletier, G., & Sheelagh, M. (2019). *Puget Sound Nutrient Source Reduction Project. Volume 1: Model Updates and Bounding Scenarios* (No. 19-03–001; p. 102). Department of Ecology. Available at: https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html
- Khangaonkar, T., Long, W., & Xu, W. (2017). Assessment of circulation and inter-basin transport in the Salish Sea including Johnstone Strait and Discovery Islands pathways. *Ocean Modelling*, *109*, 11–32. https://doi.org/10.1016/j.ocemod.2016.11.004
- Newton, J., & van Voorhis, K. (n.d.). *Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound* (No. 02-03–059). Washington State Department of Ecology. Available at: https://apps.ecology.wa.gov/publications/documents/0203059.pdf
- MacCready, P. (2011). Calculating Estuarine Exchange Flow Using Isohaline Coordinates*. *Journal of Physical Oceanography*, *41*(6), 1116–1124. Available at: https://doi.org/10.1175/2011JPO4517.1

Engaging in the workshop series

Our region is navigating complex and challenging decisions on how best to manage nitrogen, dissolved oxygen, and the potential impacts on the key habitats and species of the Salish Sea. The University of Washington Puget Sound Institute is supporting a series of scientific workshops to help

address technical uncertainties, advance modeling, and refine monitoring to improve our understanding of nutrients and broader water quality in the Salish Sea. Learn more about upcoming workshops or review the recordings and presentation materials from previous workshops.

Continue the discussion

- If you have not already, please join the listserv to receive periodic updates about Puget Sound Institute's program to foster regional water quality science, including information about upcoming workshops
- Join us for the follow up workshops to dig into these technical uncertainties
- Reach out to Stefano Mazzilli (mazzilli@uw.edu) and Marielle Larson (marlars@uw.edu) if you:
    - Are interested in contributing or helping with one of the upcoming workshops or modeling and monitoring analyses
    - Want to recommend another expert, program, or study for us to connect with to help advance the research
    - Have additional ideas or questions