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Proceedings of the Pacific regional peer review on Modeling and monitoring approaches to evaluate the ecological carrying capacity for shellfish aquaculture

March 8-12, 2021
Virtual Meeting

Chairperson: Cher LaCoste
Editor: Jill Campbell

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Foreword

The purpose of these Proceedings is to document the activities and key discussions of the meeting. The Proceedings may include research recommendations, uncertainties, and the rationale for decisions made during the meeting. Proceedings may also document when data, analyses or interpretations were reviewed and rejected on scientific grounds, including the reason(s) for rejection. As such, interpretations and opinions presented in this report individually may be factually incorrect or misleading, but are included to record as faithfully as possible what was considered at the meeting. No statements are to be taken as reflecting the conclusions of the meeting unless they are clearly identified as such. Moreover, further review may result in a change of conclusions where additional information was identified as relevant to the topics being considered, but not available in the timeframe of the meeting. In the rare case when there are formal dissenting views, these are also archived as Annexes to the Proceedings.

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SUMMARY

These Proceedings summarize the relevant discussions and key conclusions that resulted from a Fisheries and Oceans Canada (DFO), Canadian Science Advisory Secretariat (CSAS) Regional Peer Review meeting of March 8-12, 2021 via the online meeting platform Zoom. Two working papers were presented for peer review focusing on: i) an ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound, and ii) monitoring methodologies to support area-based bivalve aquaculture management in the Pacific region.

Due to the COVID-19 pandemic, in person gatherings have been restricted and a virtual format for this meeting was adopted. Web-based participation included DFO Science and Fisheries Management Sectors staff, and external representatives from commercial aquaculture sectors, environmental non-governmental organizations, and academia.

The conclusions and advice resulting from this review will be provided in the form of a Science Advisory Report providing advice to DFO Aquaculture Management to inform monitoring and modeling methodologies required to determine the potential influence of new shellfish aquaculture lease applications and/or the modification of existing leases on the ecological carrying capacity of a specific area (e.g. Baynes Sound).

The Science Advisory Report and two supporting Research Documents will be made publicly available on the Canadian Science Advisory Secretariat (CSAS) website.

INTRODUCTION

A Fisheries and Oceans Canada (DFO) Canadian Science Advisory Secretariat (CSAS), Regional Peer Review (RPR) meeting was held on March 8-12, 2021 via the online meeting platform Zoom. Two working papers were presented for peer review focusing on: i) an ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound, and ii) monitoring methodologies to support area-based bivalve aquaculture management in the Pacific region.

The Terms of Reference (TOR) for the science review (Appendix A) were developed in response to a request for advice from DFO Aquaculture Management. Notifications of the science review and conditions for participation were sent to DFO Science and Fisheries Management staff as well as representatives with relevant expertise from local First Nations, commercial aquaculture sectors, environmental non-governmental organizations, and academia.

The following working papers (WP) were prepared and made available to meeting participants prior to the meeting (working paper abstracts provided in Appendix B):

T. Guyondet, M.V. Krassovski, T.F. Sutherland, M.G.G. Foreman, and R. Filgueira. An ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound. CSAP Working Paper1 2013AQU06 (TOR Objectives 1-3)

T.F. Sutherland, T. Guyondet, R. Filgueira, M.V. Krassovski, and M.G.G. Foreman. Monitoring methods to support area-based bivalve aquaculture management in the Pacific region. CSAP Working Paper2 2013AQUO6 (TOR Objective 4)

The meeting Chair, Cher LaCoste, welcomed participants, reviewed the role of CSAS in the provision of peer-reviewed advice, and gave a general overview of the CSAS process. The Chair discussed the role of participants, the purpose of the various RPR publications (Science Advisory Report, Proceedings, and Research Document), and the definition and process around achieving consensus decisions and advice. Everyone was invited to participate fully in the discussion and to contribute knowledge to the process, with the goal of delivering scientifically defensible conclusions and advice. It was confirmed with participants that all had received copies of the Terms of Reference, working papers, and draft SAR.

The Chair reviewed the Agenda (Appendix C) and the Terms of Reference for the meeting, highlighting the objectives and identifying Jill Campbell as the Rapporteur for the review. The Chair then reviewed the ground rules and process for exchange, reminding participants that the meeting was a science review and not a consultation. The meeting was held virtually on the meeting platform Zoom where audio and text conversations were conducted. Video was only used by presenters during formal presentations or by participants during question period. Members were reminded that everyone at the meeting had equal standing as participants and that they were expected to contribute to the review process if they had information or questions relevant to the paper being discussed. In total, 23 people participated in the RPR (Appendix D).

Participants were informed that Laura Bianucci and Elise Olson had been asked, before the meeting, to provide detailed written reviews for the first working paper, while Chris Pearce and Jennifer Ruesink had been asked before the meeting to provide detailed written reviews for the second working paper. Participants were provided with copies of the written reviews prior to the meeting.

The conclusions and advice resulting from this review will be provided in the form of a Science Advisory Report to DFO Aquaculture Management to inform an ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound and monitoring methodologies to support area-based bivalve aquaculture management in the Pacific region. The Science Advisory Report and two supporting Research Documents will be made publicly available on the Canadian Science Advisory Secretariat (CSAS) website.

REVIEW

Working Papers:	T. Guyondet, M.V. Krassovski, T.F. Sutherland, M.G.G. Foreman, and R. Filgueira. An ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound. CSAP Working Paper1 2013AQU06 (TOR Objectives 1-3)
	T.F. Sutherland, T. Guyondet, R. Filgueira, M.V. Krassovski, and M.G.G. Foreman. Monitoring methods to support area-based bivalve aquaculture management in the Pacific region. CSAP Working Paper2 2013AQUO6 (TOR Objective 4)
Rapporteur:	Jill Campbell
Presenters:	Michael Foreman, Ramón Filgueira, Thomas Guyondet, and Terri Sutherland

PRESENTATION OF WORKING PAPERS AND REVIEWS

Working paper #1 Appendices A, B, and C were presented by the authors first, as the appendices explain how the models were used to inform the ecological carrying capacity assessment in working paper #1. Following author presentations, the two reviewers, Laura Bianucci and Elise Olson, shared their comments and questions, while the authors were given time to respond to them, followed by discussions from all participants. When no further questions were raised by meeting participants on the appendices, the meeting moved on to the main body of working paper #1, following the same format as the discussion on the appendices. When no further questions were raised on working paper #1, working paper #2 was presented by the authors. The two reviewers, Chris Pearce and Jennifer Ruesink, shared their comments and questions and the authors were given time to respond to them, followed by discussion from all meeting participants.

This proceeding document outlines the discussions that took place according to section and topic, where questions and comments raised by the reviewers are captured within the appropriate topics.

GENERAL DISCUSSION OF WORKING PAPER #1 APPENDICES

APPENDIX A – FINITE VOLUME COMMUNITY OCEANOGRAPHIC MODEL (FVCOM)

Freshwater inputs

- A reviewer indicated the Englishman and Little and Big Qualicum Rivers were not included in the model but represent a portion of the influx coming in from the southern entrance. While the overall sensitivity to river loading seems small in BiCEM (Table C5), these extra sources of freshwater may improve the representation of salinity inside Baynes Sound (BS), thereby, potentially affecting stratification and phytoplankton production. Although these three rivers would have a low impact to FVCOM-BiCEM modelling, the authors indicated that the inclusion of the rivers would likely improve the comparison of the modelled vs measured salinity values within Baynes Sound. However, to include these rivers in the FVCOM would require adjusting the triangle grid size to accurately simulate this freshwater flow; a significant undertaking. It was recommended that an additional line of uncertainty or comment be made about what role these rivers might have in impacting parameters such as salinity, temperature, or vertical or horizontal mixing.

- In response to a question from a participant, the authors indicated that the marine phytoplankton and ammonium are being diluted by the freshwater influx near river mouths.

Overmixing

- A reviewer wanted to know if the mixing parameterization in the model sensitivity assessment was based on model physics or if downstream effects were accounted for. The authors indicated that they looked at using many mixing parameters and coefficients but struggled with vertical overmixing that arises inherently from the numerical approximations within FVCOM. Overall, adjusting mixing coefficients appeared to have little effect on stratification. There was limited data on the tidal amplitudes and phases near the northern boundary so the authors had to interpolate and infer values from a larger domain model and available nearby observations. Increasing spatial resolution of the model grid would be beneficial to reduce spurious currents at steep bathymetric slopes, but a lack of computing power limited that option (it takes one week to run the one-year simulation).
- A participant wanted to know how the vertical and horizontal mixing were modeled. The authors indicated they used standard model parameterizations based on literature from the mixing community. The renewal time as a function of depth was modeled using tracer paths, and they obtained similar results to other studies, despite concerns about overmixing in the model. The authors will add text explaining the choices made about the model inputs. Many parameters in the FVCOM and BiCEM are standard and only known within the modelling community. The authors can consider adding a short table describing parameter values.
- A participant wanted to know if the 20 vertical water-column layers were enough and if they considered having a higher resolution near the bottom. The authors indicated that having more layers made the models very expensive to run and that 20 layers appeared adequate. High-resolution bathymetry was available from CHS and incorporated in the model at the early stages of FVCOM development. However, the model performed poorly as the additional layers near the bottom produced spurious currents, especially along slopes. Near the southern entrance to Baynes Sound, the bathymetry is highly variable and had to be smoothed to reduce the formation of spurious currents. The authors will add text to discuss vertical resolution layer choice, especially with respect to the bottom layers and bathymetry. The authors can discuss in the uncertainties section the impact of bathymetry on the formation of spurious vertical currents, which may contribute to the overmixing issue. A participant commented that the modeled bathymetry is up to 20m shallower in certain spots relative to the actual depth (Figure A8). This difference could affect mixing by concentrating the energy over a smaller cross section than in the real world.
- Many participants were concerned with the overmixing which may bring nutrients into the upper levels of the water column resulting in over productivity of phytoplankton. While this may be an issue, the light limitation in the model may reduce production at depth. It would be difficult to run sensitivity analyses of this as the data are limited. Instead, the authors can look at the diffusivity of the model and determine if the model values are reasonable. The authors can also plot the mixing parameter values to see if these values are influencing the overmixing. The authors indicated there might not be an overall overestimation of

phytoplankton but rather that it is an issue of phytoplankton distribution over the vertical water column. A reviewer suggested considering where overmixing and also model misfit were occurring both horizontally (entrances vs inner Sound) and vertically relative to the depth of suspension aquaculture rafts. It was not recommended that the models be re-run but that information be added to the uncertainty section to address these concerns. As well, the authors should attempt to separate the physics from the biology that might be linked to phytoplankton overproduction and tie the uncertainties of both together to gain a better understanding on how they might be influencing the carrying capacity assessment.

- It was unclear what was driving the sensitivity of the vertical structure of the phytoplankton and nutrients in the model, whether it was light dependence, water column mixing, or zooplankton grazing. It might not be possible for the model to get into this level of detail on the vertical structure. The authors can add text describing how the model does capture nutrient transport and how that influences photosynthesis and zooplankton grazing.

Other comments

- The five tidal constituencies that were chosen account for 76% of the variability in the system. The model can accommodate more but increasing the number up to eight would only increase the variability to 80-85%. Rather than trying to improve this via re-running the models, the authors will add text in the uncertainties section to discuss the difference in using five versus the commonly used eight tidal constituencies. Another participant pointed out that increasing the number of tidal constituencies would increase the tidal energy which could further increase the potential overmixing. A participant suggested that using the variability percentage rather than the five or eight constituencies might be more relevant.

APPENDIX B & C – DYNAMIC ENERGY BUDGET AND BIVALVE CULTURE ECOSYSTEM MODEL

Nutrients

- A reviewer indicated that due to the importance of the deep nutrient supply through the southern entrance, a detailed nutrient budget including, for example, sections of nitrate transports across the northern and southern entrances similar to those shown for velocity, could be of interest. The magnitude and extent of the deep intrusion in both salinity and nitrate fields do show differences. Future research could include assessment of the sensitivity of model outcomes to this feature and in particular to mixing, which the authors identify as a potential source for differences in vertical structure between the model and observations.
- The settling rates for bivalve feces and organic detritus in the model were different. It was indicated that the model does not explicitly simulate the dynamics of the settling material once on the bottom, and the exchange rate for ammonium between the sediments and the water column was forced from empirical measurements. However, the authors indicated that more detailed representations of these processes have been included in other models to inform how those settling materials are used and mineralized. This could be potential future work.

Phytoplankton

- A reviewer was concerned that the BiCEM was not representing the fall bloom. The fall bloom typically is comprised of different phytoplankton species than the spring blooms. It is unclear how important the fall bloom is for bivalve energy storage during the winter months.

Some growers indicated that the fall bloom is important for post-reproductive improvements through the winter. The authors responded by saying they were trying to keep the model simple by only including one phytoplankton variable. While they wanted to include additional parameters, they did not have the data to calibrate the model. Future work could include additional phytoplankton groups to capture the fall blooms including collection of field data. Phytoplankton taxa groups (diatoms, flagellates, and others) were added to Working Paper#2 as recommended variables for phytoplankton community analysis.

- A reviewer commented that the FVCOM-BiCEM overestimation of phytoplankton below the upper layers, especially in the lower Sound (see Figs C9 and C10), might obscure the true sensitivity of the bottom bivalve cultures. Considering the bottom oysters were the most sensitive in the scenarios (i.e. maximizing stock and/or expanding farming areas; see Table 7) they might be more heavily impacted if baseline phytoplankton concentrations were actually lower. The authors answered that such a bias is unlikely as model overestimation occurs in the deeper parts of the Sound at depth > 20m while bottom bivalve culture occurs in much shallower waters (up to 5 - 6m) along the edges of the Sound.

Zooplankton

- There were a number of questions about how zooplankton were sampled and incorporated into the model. Authors response: Zooplankton were sampled at up to 40 stations across BS and the northern Strait of Georgia (SOG) during the 2016-2017 sampling period using vertical net hauls from the bottom depth. Since the depths in the northern SOG was sometimes deeper than those in BS, the former net hauls captured larger deeper-dwelling zooplankton. Following the advice of the DFO Pacific Water-Properties plankton group, the authors limited the zooplankton community used in the model based on seasonal depth-preference, which coincided with a size and age spectrum (e.g. Euphausids), to standardize zooplankton between Baynes Sound, northern SOG, and the depth of aquaculture practices. There is a lack of time-series data to determine if zooplankton grazing is underestimated because of this; the potential implication being that since zooplankton are the main grazers in the system, an underestimation of zooplankton could influence the carrying capacity. The authors will include more information on how zooplankton were sampled and included in the model (size, community composition, predator-prey relationships, zooplankton size relative to water column habitat).
- Many participants were concerned about the zooplankton reductions in the maximum production model scenario. It was suggested that the authors should add text to indicate that discussing the effect of zooplankton reduction on higher trophic levels (particularly salmon and herring) is out of the scope of the TOR. However, this work could be done in the future regarding ecosystem level management in lieu of a shellfish ecological carrying capacity, which relies on a control point consisting of a nutrient-phytoplankton-zooplankton-shellfish loop. The authors responded how zooplankton’s role in the model is not intended to represent higher trophic levels and operates only in terms of being a carbon sink. It was recommended that the authors highlight the caveats of the zooplankton data, in terms of how zooplankton are handled in the model, how realistic the reductions are, and the limitations of the results.
- Some participants requested the authors indicate the proportion of zooplankton reduction that is due to a reduction in food availability vs from predation from bivalves. On the same note, participants requested more information (i.e., coefficient values) on how bivalve grazing rates/preference for zooplankton are incorporated into the BiCEM model.

Bivalves

- A participant was uncertain how the oyster growth rate from the DEB was incorporated in the BiCEM over the tray depths. The authors indicated that in the BiCEM, each grid triangle has associated biomass and depth gradient information which inform the model. The average growth rate over a rack of trays depth was used since the model resolution is not sufficient to isolate individual trays within a rack. This approach worked well for both wild and farmed oysters as they are the same species. The clam model used growth rates found in the literature which varied based on intertidal submergence, but there was very limited data for this topic.
- In response to a question about bivalve mortality, the authors stated that while population density does not change in the models, mortality was accounted for by adjusting the density to a mean over the production cycle. Seeding strategy, density, and mortality information were obtained from two industry partners located in the upper and lower regions of Baynes Sound. The oysters growouts were consistent with commercial growing practices.
- A participant wanted to know if biofouling organisms exert significant phytoplankton grazing pressure. The authors noted that biofouling was very limited during their oyster cultivation experiments. This observation could be due in part to industrial standard practice of changing trays as the bivalves grow over the seasons, thereby removing any biofouled trays from the system. However, the overall pressure of biofouling organisms on phytoplankton is an uncertainty, given different aquaculture equipment and other types of industry practices. The authors will add short text to this effect.
- A participant noted that bivalve sampling was only done between 0-1m in the intertidal zone, however bivalves exist outside this narrow range and are not included in the model. The authors responded with a description of the intertidal bivalve data set that was collected from many sources that covered over a significant coverage of Baynes Sound: DFO-PBS Shellfish Data Unit; Industry; University (published and unpublished); AMD management reports, and the general literature. These data were collated and assessed for use in BiCEM early on in the process. Given the varying study objectives, variety of bivalve taxa, and their preference in tidal height, the data sets spanned from the low to high tidal heights, They also included cultured and wild, densities, length/weight, and growth rings of bivalves depending on the end-user. The bottom bivalve distribution used in the model covers all the intertidal zone down to 6m below mean sea level and even deeper in some places. The majority of intertidal bivalves do not extend far into the subtidal area.
- A participant requested clarification on how the model handles intertidal bivalves when they are out of the water. The authors said the model assumes that feeding and other physiological processes stop when the tides indicate an area is “dry”. Text will be added indicating no filtering or activity is occurring during this period. Another participant questioned the resolution of the intertidal area and wondered if the model is accurately representing the extensive tidal flats, The authors indicated the triangle grid has a 40m resolution over the intertidal areas. In addition, the extension of FVCOM into the intertidal resulted in a successful coupling and wetting/drying process that did not feedback negatively on the subtidal circulation predictions. The authors could prepare a plot showing how much area is dry during the cycle.
- Wild oyster beds were not included as a culture type due to the lack of data and limited habitat space available for them. However, wild oysters do exert pressure on the system. The authors should add text in the uncertainties section indicating this data limitation and its potential consequences.

GENERAL DISCUSSION OF WORKING PAPER #1

SPATIAL RESOLUTION

- A participant was unsure if the disproportionate nearshore effects of phytoplankton reduction are due to the density of the farms or to the shallow water. They wanted to know if the fraction of phytoplankton uptake by cultured shellfish is a function of culture biomass or the spatially-restricted culture. The authors responded by saying there was some text in the working paper to this effect. The higher sensitivity in the shallow areas is because there is less water to filter and not due to the higher densities on the farms. The authors also indicated that suspension racks give bivalves more access to phytoplankton and they can therefore grow faster. Farms over the deeper water will tend to have less of an impact on nearby farms due to increased water column mixing.
- A participant noted that there may be local areas where the carrying capacity may be a problem which would be of concern for management and permitting. An author noted that FVCOM does not take the additional drag associated with suspension structures into account, which may result in less precise results. However, it appears as though the spatial resolution is fine enough since the model was validated with observations to help inform management decisions (i.e., Fig 12-14).
- It was discussed that the models have been validated as far as the data allow since the model outputs align well with observations, so there is confidence in the model outputs and they can be reliable for management use at small spatial scales (i.e., Fig 12-14). The client indicated they are most interested in the cumulative impact of the variables and how the addition of new farms will compound those impacts.
- This model could be utilized by AMD at other locations with carrying capacity questions.

GROUND TRUTH BIVALVE DENSITIES AND PHYTOPLANKTON

- A participant thought the aquaculture stocking densities seemed low. They explained that often bivalves are not cultured over the entire tenure area, which may affect the density values. In terms of suspension oyster culture, the authors received their information on stocking (seeding) densities and culture practices from industry partners, particularly those they partnered with for the culture experiments. In terms of intertidal bivalves (wild and cultured), the authors received significant and comprehensive data sets from the archived PBS Shellfish Data Unit (fisheries stock assessment surveys), Annual Aquaculture Statistical Reports, Industrial in-house monitoring surveys (netted, not-netted, diversity, intertidal heights spanning tidal range, shell lengths, tissue weights, growth rings), Industrial consultations, University theses, and general literature. However, information was lacking on bottom oyster cultivation densities. As well, the growth cycle for suspension is longer than one year, but since the model was only run for one year, the densities had to be altered to factor in this additional feeding time. The authors noted it was difficult for them to know if they were under or overestimating the stock and more data would be preferred. The participant also mentioned that in some areas, the local densities are very high and there seems to be little impact on the ability to successfully culture, indicating the model may be underestimating the ability of BS to grow shellfish. They recommended more data be collected to verify bivalve densities and phytoplankton abundances. The clients also recommended these data be obtained to further validate the models, especially on an ongoing basis to ensure the model is up to date.

CLIMATE CHANGE

- Participants noted that summer oyster mortality events are becoming more common, as are various pathogens and diseases. However, there have also been large spawning events observed in warm years. The authors noted that manila clams and Pacific oysters, the two most common wild and cultured species, grow well in temperatures warmer than what is typical for BS. In the future, the models will need to take changes in bivalve feeding and growth rates into account. As well, increased temperatures and precipitation will result in increased stratification and reduced mixing, and species compositions of phytoplankton and zooplankton may also change. The authors should include a short discussion or uncertainty regarding the impacts of climate change. Regional climate models could be looked at to inform future model parameters.

OTHER COMMENTS

- Explain more of the literature where harmful effects of aquaculture were found in Section 4.2.1. This will help put the results obtained in this work into context.
- Add a table indicating types of existing and expansion aquaculture structures, their proportions, densities, surface areas, etc, (based on data availability/security). If this information is provided by management, ensure the same values were used in the models.
- A reviewer was concerned the DEB and BiCEM are calibrated and validated using the same data. It is not certain if the model parameters will be able to accurately produce conditions for other years. The authors will mention in the uncertainties section that these two are linked and that this will be valuable future work.

GENERAL DISCUSSION OF WORKING PAPER #2

TOR OBJECTIVE 4 WORDING

- A reviewer was unsure about the wording in the last sentence of TOR objective #4: "Recommend indicators and identify/describe known associated changes ***to*** shellfish" (emphasis added to highlight the concern). There was discussion as to whether the methodology looks at the impacts of shellfish aquaculture on the ecosystem rather than the changes in the shellfish due to the impacts of aquaculture. The authors responded by saying this was discussed at length with the client and while the sentence might be confusing, they wanted it to be as all-encompassing as possible. The author directed participants to section 2.3.10 (page 18) of the working paper#2, where three shellfish monitoring metrics were recommended for the detection of potential changes to shellfish populations: 1) Diversity and abundance; 2) Recruitment of juveniles; and 3) Condition index (shell length vs ashed tissue weight). This section also included a literature review to provide context on how these metrics can be applied as well as their relevance. It was not recommended that the wording of the TOR be changed or that any changes need to be made to the working paper.

SAMPLING DESIGN

- It was acknowledged that sampling design was out of the scope of the TOR because it cannot be applied to all locations/conditions equally and it requires a management objective However, general guidelines for developing sampling designs to monitor benthic and suspension culture might be considered. Mention of the spatial and temporal changes (seasonal, tidal, daily, for example) that need to be considered when developing sampling design would be helpful. The authors can provide literature to point readers towards study design considerations but were concerned with providing design elements in the absence of an identified bay and management objective. A participant was concerned about providing guidance leading to 1) too little information that may be applied generically and inappropriately; and 2) a disservice to the integrity of the current CSAS product. Authors suggested to identify study design as a future consideration and the next step to support area-based monitoring programs.

- Guidelines on how to determine optimal number of replicates was requested. The authors indicated that replication requirements for monitoring variables falls into study design, which is outside the scope of TOR#4. However, the authors will include the following sentence in the working document regarding study design themes that readers could consider when developing a future monitoring program: 1) temporal and spatial frequency, 2) reconnaissance surveys to identify reference sites using chosen indicators/variables; 3) reconnaissance surveys to determine replication requirements for each monitoring variable (power analysis); and 4) cost-effective, practical methods (e.g. substitute carbon and nitrogen with organic content).
- Information on how to choose a reference site was requested. Although this request is beyond the scope of the TOR#4, the authors suggested that reference sites should be located within the same bathymetric contour and substrate type of that of the site of concern. A reconnaissance study could confirm reference areas using appropriate indicator variables and comparing with literature values. Providing more information on this topic would be out of the scope of the TOR.
- The reviewers requested the variables be ranked in some way to aid in study design, perhaps using a ‘stoplight’ method or by indicating the costs of sampling. Authors cautioned against ranking the variables between ‘best and worst-suited’ variables, as these rankings will vary according to site-specific conditions, study objective, etc. Alternately, generic study designs or indicator/variable rankings may mislead end users. Participants acknowledged monitoring variable significance and application will vary by location, condition, purpose or question being asked and culture type. Authors will add text identifying site-specific study design, appropriate monitoring variables, and associated management thresholds as a potential for future work.

EXISTING THRESHOLDS

- A participant wanted to know how the existing threshold values were obtained. The authors indicated that they included management thresholds for different monitoring variables based on regulatory research projects, DFO Aquaculture Activities Regulation (AAR, 2021), and the general literature. The participant wanted to know if the existing thresholds can be used as early indicators, such as with sediment porewater sulfides. The authors responded that a sediment pore-water sulfide classification system associated with a benthic organic enrichment gradient was established in both the Maritime and Pacific regions. The author’s presentation provided a nomogram relating benthic organic enrichment categories, sediment pore-water sulfide classifications, and taxa responses derived from both national and international studies (Hargrave et al. 2008). The classification system has categories that span from oxic, hypoxic, and anoxic thresholds, allowing one to see a trend at the early stages of organic enrichment.

WET VS DRY SIEVE OF SEDIMENTS

- There was discussion regarding methods of sieving sediments. The authors presented the use of wet sieve methods to properly capture fine clay sediments, which is an important parameter to detect when looking at the impacts of shellfish aquaculture on the ecosystem. The reviewer questioned whether dry sieving techniques could be added, however due to the importance of properly capturing the proportion of clay, wet sieving is the recommended methodology.

MEASURES OF SHELLFISH GROWTH

- Both shell length and body condition index are used to determine shellfish growth, depending on the study objective. A reviewer noted that the wording in the working paper is unclear as to whether shell length, tissue weight, or condition index should be used and what information it can provide. As well, there are multiple body condition indices that should be discussed. The authors responded that some confusion regarding this topic may be due to a scenario-building outcome of Working paper#1, where oyster tissue weight provided a less consistent measure of growth change relative to that of shell length for the ecological carrying capacity assessment. Both measures were included in working paper#1 to increase the success of a robust outcome. Working Document#2 cites Filgueira et al. (2015), who 1) recommends that condition index (relationship between shell length and tissue weight) is a simple and reliable indicator for ecological shellfish carrying capacity assessment; and 2) notes that recent modelling efforts show that shell length and tissue weight can be used as independent indicators for these assessments. In addition, these metrics are simple for monitoring and support shellfish Dynamic Energetic Budget models and other Canadian ecological shellfish carrying capacity studies. The authors can provide clarifying text highlighting that these shellfish variables (shell length, tissue weight, condition index) should not be ranked a priori and can be used in any combination based on the end-user application and/or context.

EELGRASS MONITORING

- Leaf Area Index (LAI): A reviewer indicated that the equation suggested to calculate leaf area index might result in overestimations of eelgrass. In particular, shoots/cm^2 could be changed to shoots/m^2, and individual blade length is not measured which, if only the longest blade is being measured, would result in overestimations of leaf area. The reviewer and author will work together to ensure the leaf area index calculations and methodologies are applied properly.
- The authors clarified reviewer’s feedback summarizing preferences for certain methods in working paper#2. The authors presented an advantage regarding the use of the Leaf Area Index (LAI) method, where it does not include sample collection that could be destructive to an emerging or dispersed eelgrass bed over time. Although this advantage shouldn’t be taken as a preference over other methods, LAI is commonly used for monitoring programs in the Pacific region. The authors also highlighted the advantages of sample collection for both eelgrass shoots and root systems, where the latter provides a significant over-wintering role that supports the seasonal emergence of eelgrass. A discussion ensued regarding eelgrass sampling. Authors will add a sentence in the eelgrass section where the root system biomass can be sampled using a core barrel to provide 1) a bulk root measure or 2) single root biomass estimates following dissection from the core sample. These estimates can be related to corresponding bulk or individual shoots values, depending on the required resolution of a program.
- It was suggested that various eelgrass monitoring options be provided with varying levels of detail. The authors responded by saying they refrained from recommending complex methodology here, and providing monitoring options or levels of intensity could be too

prescriptive as the methodology would vary depending on the research objective and time of year (monitoring design out of scope of TOR#4).

- The authors highlighted that eelgrass is designated as both a sensitive (nursery ground) and critical habitat for general ecosystem considerations. Authors are familiar with concerns regarding eelgrass habitats as they are considered for the siting criteria developed for the Pacific region finfish aquaculture regulation. Authors would be interested to hear the clients view from the shellfish perspective. The clients indicated that eelgrass monitoring is important in their assessments as many tenures include eelgrass beds and aquaculture is allowed to occur over eelgrass as long as the habitat is not impacted. The clients also indicated that the purpose of monitoring eelgrass is that it is highly responsive to ecosystem change and is therefore a good indicator species. If there are other indicator species they should prioritize, that information would be helpful. The authors can recommend prioritizations either in species or monitoring options once local conditions, management/research objectives, have been established as future work (currently out of the scope of this TOR#4)
- Although it has been recognized that emerging and fast-evolving remote techniques are challenging to prescribe in a monitoring program, the Authors suggested that a light review of available remote-sensing techniques can be included in the working paper#2 to monitor eelgrass and other variables over large spatial scales.
- Future work could also consider adding eelgrass as a variable in the BiCEM.

PHYTOPLANKTON COMMUNITY STRUCTURE

- A reviewer wanted to see more information about sampling the phytoplankton community since bivalves can feedback with respect to differential grazing and nutrient dynamics. In particular the reviewer wanted more information on how to sample phytoplankton functional groups (i.e., diatoms vs non-diatoms). The authors agreed with the value of adding functional phytoplankton groups to working paper#2, even though this type of taxonomy analysis can be expensive. Authors suggested the functional groups be expanded to 3 groups: diatoms, flagellates, and other taxa, since diatoms and flagellates are the seasonal indicators of phytoplankton succession. Information on how to sample for phytoplankton functional groups can be added to the paper. Authors solicited a conversation on chlorophyll size fractionation (picoplankton and nanoplankton) where the ratio of picoplankton to total plankton be used as an indicator of the effect of bivalves on phytoplankton community structure. This concept and associated methods are summarized in the literature review and methods of the phytoplankton production section in working paper #2.
- A participant further supported this method that has been groundtruthed in other east coast settings. The authors indicated that this application may be dependent on season, tide, location in the bay, etc.

OTHER VARIABLES NOT INCLUDED

- Water current sampling methodologies, micro/macro plastic detection, LIDAR, satellite imagery, drones, aerial/remote sensing methodologies were considered but not included. The authors indicated use of these methodologies will depend heavily on local conditions, require expensive, specialized equipment to sample, and expert knowledge to interpret results. Some of these methodologies are also rapidly evolving and the authors are wary of providing information that may quickly become out of date. Sampling for micro-plastics is particularly challenging due to contamination and the difficulty of pin-pointing the source.

The authors will add information about sampling for plastics along with caveats. Arial and remote sensing can be added as a literature review, but specific methodologies will not be added. Some of the emerging technologies can be added in the future work section.

- While bivalve filtration rates and feces production rates are important to ecosystem modeling, the authors determined these variables to be research methodology rather than monitoring methodology. As well, sampling these variables is sophisticated and not suitable for application by end users of this document. Future research may make these easier to sample.

IMPACTS TO SALMON

- A participant mentioned that the impacts of bivalve aquaculture on salmon have not been discussed. The authors noted that the higher trophic levels (herring, salmon, sea lions, etc.) are out of the scope of the TOR. The participant indicated that these species might need to be considered in terms of habitat capacity rather than carrying capacity. The author responded that not all methods could be captured within the scope of the TOR, but that some of the habitat assessment metrics (organic enrichment, copepods, eelgrass) might provide habitat capacity information.

CONCLUSIONS

- The participants agreed the TOR objectives were met and both working papers were accepted with the suggested revisions.
- It was not suggested that any of the models be re-run to provide clarification on any of the concerns/questions raised. Rather, the authors will add text to the appropriate sections of the paper to clarify.
- Summary bullets were drafted with agreement from the participants that they were to be further developed, and that the draft SAR and draft PRO will be circulated to participants in the coming weeks for final review and input.

RECOMMENDATIONS

- Further examine the magnitude and extent of the deep-water intrusion in both salinity and nitrate fields and their influence. Future research could include assessment of the sensitivity of model outcomes to this feature and in particular to mixing that affects potential differences in vertical structure between the model and observations.
- Future work could include more detailed representations of settling/dispersion and mineralization rates for bivalve feces and organic detritus in the model.
- Future work could include the addition of phytoplankton community groups to capture spring, summer, and fall blooms with the collection of field data.(e.g. diatom, flagellate, and other broad taxa groups).
- Regional climate models as well as long-term climate change trends could be looked at to inform future model parameters. For example, increased temperatures and precipitation will result in increased stratification and reduced mixing, and potential shifts in species compositions of phytoplankton and zooplankton, thereby, influencing bivalve feeding and growth rates. Eelgrass could be included in biogeochemical models (e.g. BiCEM).

- The development of a study design for an area-based management monitoring program would augment the existing recommendations regarding monitoring methods.
- In terms of an environmental monitoring program, future research should 1) further validate management regulatory thresholds surrounding mat-forming indicators, such as, sulfide-oxidizing bacteria and Opportunistic Polychaete Complex in a variety of substrates and settings; 2) establish thresholds for key indicator variables; and 3) examine multiple stressors in a cumulative effects environmental setting.
- Consideration of emerging trends in monitoring variables (e.g. plastics, areal and remote sensing applications) will help address the influence of recently acknowledged stressors or provide high-resolution, spatially-explicit assessments of sensitive habitats.

ACKNOWLEDGEMENTS

We appreciate the time contributed to the RPR process by all participants. In particular, we thank the reviewers, Laura Bianucci, Elise Olson, Chris Pearce, and Jennifer Ruesink for their time and expertise. We also thank Cher LaCoste as Chair of the meeting and Jill Campbell as the Rapporteur.

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DFO. 2015. Carrying capacity for shellfish aquaculture with reference to mussel aquaculture in Malpeque Bay, Prince Edward Island. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/003.

Filgueira, R., L.A. Comeau, and T. Guyondet. 2015. Modelling carrying capacity of bivalve aquaculture: a review of definitions and methods. Can. Sci. Advis. Sec. Res. Doc. 2015/002. v + 31 p.

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APPENDIX A: TERMS OF REFERENCE

MODELING AND MONITORING APPROACHES TO EVALUATE THE ECOLOGICAL CARRYING CAPACITY FOR SHELLFISH AQUACULTURE

Regional Peer Review Process – Pacific Region

March 8-12, 2021
Virtual meeting

Chairperson: Cher Lacoste

Context

In British Columbia (B.C.), shellfish culture is located primarily on the west coast of Vancouver Island and the Strait of Georgia, with the most prolific production sites associated with Baynes Sound, Cortez Island, and Okeover Inlet. Although the culture of shellfish was developed over 100 years ago in B.C., little research exists pertaining to the ecological capacity of shellfish production in these prolific, sheltered bays. Shellfish production is influenced by a balance of water quality, hydrodynamics (bay flushing), and food supply (plankton). A carrying capacity assessment is required to assess this balance and identify any bay-wide limitations due to a potential competition for resources or shift in ecosystem functioning.

Ecological carrying capacity (defined as the magnitude of aquaculture activity that can be supported without leading to unacceptable changes in ecological processes, species, populations, communities, and habitats in the aquatic environment) can be investigated using mathematical models that integrate complex interactions between aquaculture activities, bivalve physiology, and the environment. The methodological approaches for assessing carrying capacity range from indices of processes, to farm models, spatial models, and food web models. These models utilize core biogeochemical (nutrient-seston-bivalve interactions) and hydrodynamic (water circulation) equations of varying dimensions and complexity. Most carrying capacity models have focused on the dynamics of phytoplankton or organic seston and their interaction with bivalves, with a focus on the extent to which bivalves utilize these food resources (related to ecological carrying capacity).

Both carrying capacity assessments and potential management thresholds of indicators are bay specific, reflecting the relevance of bay-scale hydrodynamics and characteristics on ecosystem functioning. Indices based on the comparison of key oceanographic and biological processes have been used as proxies for the carrying capacity of bivalve aquaculture sites. These indices compare the energy demand of bivalve populations (based on filtration rates) and the ecosystem's capacity to replenish these resources. Additionally, monitoring methodologies associated with potential carrying capacity indicators can provide a baseline for a future ecosystem monitoring program. Based on the information collected on long-term monitoring programs, regulatory management thresholds for ecological indicators could be established.

These indicators may include shellfish condition index, intertidal sediment quality (redox), and the depletion of suspended food particles (seston, plankton).

Modelling approaches to shellfish carrying capacities were reviewed in a 2015 Gulf Region Canadian Science Advisory Secretariat (CSAS) Regional Peer Review , "Carrying capacity for shellfish aquaculture with reference to mussel aquaculture in Malpeque Bay, PEI" (DFO 2015, Filgueira et al. 2015). The result of the 2015 review was the identification of a high resolution, spatially-explicit model (e.g. FVCOM -Finite Volume Community Ocean Model – Bivalve Culture Ecosystem Model) as the most efficient approach to assess ecological carrying capacity of shellfish aquaculture.

Due to the significant influence of local environmental conditions on ecosystem functioning, carrying capacity studies are ecosystem-specific. In the Pacific Region, FVCOM will be coupled with a Bivalve Culture Ecosystem Model (BiCEM) resorting to the Dynamic Energy Budget (DEB) to simulate bivalve physiology and their interactions with the ecosystem. The coupled model will be first applied to Baynes Sound. Since Fisheries and Oceans Canada (DFO) Aquaculture Management identified Baynes Sound as a priority site in 2009, based on its production status, DFO Science followed up by acquiring relevant research data to support a carrying capacity assessment. Accordingly, this modelling approach focuses on the traditional nutrient-plankton-zooplankton approach with the addition of bivalve sub-models. The inclusion of other commercial, recreational and aboriginal (CRA) fishery components or a benthic assimilatory assessment would require an additional food web and benthic assimilatory approach, which would increase the complexity and uncertainty of the outcomes that are relevant for shellfish.

DFO Aquaculture Management has requested that Science Branch provide advice on monitoring and modeling methodologies required to determine the potential impacts of new or modified existing shellfish aquaculture applications on the ecological carrying capacity of a specific area. The assessment, and advice arising from this CSAS Regional Peer Review (RPR), will be used to develop decision making frameworks to aid management of new and amendment of existing shellfish aquaculture applications.

Objectives

The following working papers will be reviewed and provide the basis for discussion and advice on the specific objectives outlined below.

T. Guyondet, M.V. Krassovski, T.F. Sutherland, M.G.G. Foreman, and R. Filgueira. An ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound. CSAP Working Paper1 2013AQU06 (Objectives 1-3)

T.F. Sutherland, T. Guyondet, R. Filgueira, M.V. Krassovski, and M.G.G. Foreman. Monitoring methods to support area-based bivalve aquaculture management in the Pacific region. CSAP Working Paper2 2013AQUO6 (Objective 4)

The specific objectives of these reviews are to:

1. Evaluate the hydrodynamic accuracy of the FVCOM model component and discuss the biological applicability of the biogeochemical (BiCEM) component in the coupled Baynes Sound model.
    a. Compare modelled and observed water properties.
    b. Identify uncertainties and consequences associated with data availability and modelling parameterizations through sensitivity analyses for this Pacific region application of FVCOM-BiCEM.
2. Assess ecological carrying capacity for shellfish aquaculture in Baynes Sound at a bay wide scale using a high-resolution, spatially-explicit hydrodynamic-biogeochemical coupled model (FVCOM-BiCEM).
3. Include an assessment of the potential influence of new site applications on existing farms across varying spatial scales for use in management decision-making with respect to shellfish aquaculture facilities.

4. Recommend monitoring methodologies including field and laboratory protocols for use by regulatory, industry, and science personnel. Recommend indicators and identify/describe known associated changes to shellfish.

Expected Publications

- 1 Science Advisory Report
- 1 Proceedings
- 2 Research Documents

Expected Participation

- Fisheries and Oceans Canada (DFO) (Ecosystems and Oceans Science, Aquaculture
- Resource Management, Aquaculture Programs, Aquaculture Environmental Operations)
- Province of BC
- Academia
- Indigenous communities/organizations
- Aquaculture industry

References

DFO. 2015. Carrying capacity for shellfish aquaculture with reference to mussel aquaculture in Malpeque Bay, Prince Edward Island. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/003.

Filgueira, R., L.A. Comeau, and T. Guyondet. 2015. Modelling carrying capacity of bivalve aquaculture: a review of definitions and methods. Can. Sci. Advis. Sec. Res. Doc. 2015/002. v + 31 p.

APPENDIX B: WORKING PAPER ABSTRACTS

Working Paper #1: An ecological carrying capacity assessment for shellfish aquaculture in Baynes Sound

Baynes Sound (BS) is considered one of the most prolific production sites for bivalve culture in British Columbia (B.C.). Bivalve production is influenced by a balance of water quality, hydrodynamics (bay flushing), and food supply (plankton). An ecological carrying capacity assessment is required to assess this balance, where mathematical models can integrate these complex interactions using a high-resolution spatially-explicit model. The Finite Volume Community Ocean Model (FVCOM) was coupled with a Bivalve Culture Ecosystem Model (BiCEM) resorting to the Dynamic Energy Budget (DEB) to simulate bivalve physiology and their interactions with the ecosystem. The physical oceanographic conditions are simulated using FVCOM, analogous to previous aquaculture-motivated applications in the Broughton Archipelago and Discovery Islands. Both oceanographic observations and FVCOM outputs show a characteristic two-layered estuarine circulation over BS. This estuarine circulation appears to be strengthened or weakened by river run-off and atmospheric forcing on a seasonal scale and constitutes an overall key feature for the Sound's water inner circulation and exchange with the Strait of Georgia. The biogeochemical processes are simulated using BiCEM, which predicted that wind forcing, tidal mixing, and estuarine residual circulation contribute to the regular nutrient replenishment from the deep waters of the Strait of Georgia, leading to high levels of pelagic primary productivity (phytoplankton). In turn, this phytoplankton productivity supports the potential for secondary production of zooplankton and bivalve culture. In general, the response of zooplankton and wild bivalve populations to the existing shellfish aquaculture activity indicates a system within the Sound's ecological carrying capacity. Although the planned expansion of additional farm coverage and stock, currently under review, would impose an increased demand on the Sound's pelagic resources, the results do not indicate that the additional bivalve production could not be sustained. However, a precautionary approach should be considered with high-stocking scenarios and concentrated areas, such as, Fanny, Mud, and Deep Bays. Gradual aquaculture development in concert with proper monitoring of environmental and cultured shellfish conditions (Working Paper#2) in sensitive areas will provide sustainability of BS.

Working Paper #2: Monitoring methods to support area-based bivalve aquaculture management in the Pacific region

The Pacific Shellfish Aquaculture Management Division (AMD) of Fisheries and Oceans Canada (FOC) requested recommendations regarding monitoring methodologies along with associated field and laboratory protocols that can be used by regulatory, industry and science personnel when carrying out environmental assessments (RSIA, 2013). The sampling methods put forward in this report are intended to support a wide variety of approaches ranging from general area-based monitoring programs or local emerging issues associated with a significant knowledge gap. A suite of environmental variables that support bivalve aquaculture assessments was selected based on the following: 1) recommendations arising from government advisory processes and/or the scientific community; and 2) the ability of the indicator to detect potential shifts in ecosystem conditions and processes. The benthic variables selected include sediment texture, geochemical (e.g. organic, redox), macrofaunal, meiofaunal, and epifaunal attributes, while pelagic variables consist of both physical (temperature, salinity, dissolved oxygen, light) and biotic characteristics (phytoplankton, zooplankton). Relevant bivalve attributes include cultured and wild density, diversity, and condition indices. The pelagic and bivalve indicators represent a nutrient-seston-plankton-bivalve loop that can support a high resolution, spatially-explicit, hydrodynamic-biogeochemical coupled model capable of evaluating ecological bivalve carrying capacity.

APPENDIX C: AGENDA

Canadian Science Advisory Secretariat

Centre for Science Advice Pacific

Regional Peer Review Meeting (RPR)

Modeling and monitoring approaches to evaluate the ecological carrying capacity for shellfish aquaculture

March 8-12, 2021 (9 am to noon PST)
Virtual Platform on Zoom
Chair: Cher Lacoste

DAY 1 – Monday, March 8, 2021

Time	Subject	Presenter
0900	Introductions/Overview of virtual platform Review Agenda CSAS Overview and Procedures	Chair
0915	Review Terms of Reference	Chair
0930	Presentation of Working Paper #1: Model Validation (Appendices A (FVCOM), B (DEB),C (BiCEM), 10-15 min each).	Authors
1000	Overview Written Reviews WP#1: Appendices A,B,C	Reviewers & Authors
1030	***Break***	
1045	Presentation of WP#1: Main Document (Carrying capacity and scenario-building, 30-min)	Authors
1115	Overview Written Reviews WP #1: Main Document	Reviewers & Authors
12:00	Adjourn for the Day	

DAY 2 – Tuesday, March 9, 2021

Time	Subject	Presenter
0900	Review Agenda & Housekeeping Review Status of Previous Day (*As Necessary*)	Chair
0915	Discussion & Resolution of Results & Conclusions WP #1	RPR Participants
1030	***Break***	
1045	Discussion & Resolution of Results & Conclusions cont'd	RPR Participants
1130	Develop Consensus on Paper Acceptability & Agreedupon Revisions (TOR objectives) WP #1	RPR Participants
1200	Adjourn for the Day	

DAY 3 – Wednesday, March 10, 2021

Time	Subject	Presenter
0900	Review Agenda & Housekeeping Review Status of Previous Day (As Necessary)	Chair
0915	Review Terms of Reference	Chair
0930	Presentation of Working Paper #2 (20-30 minutes)	Authors
1030	***Break***	
1045	Overview Written Reviews WP #2	Reviewers & Authors
1115	Discussion & Resolution of Results and Conclusions WP #2	RPR Participants
12:00	Adjourn for the Day	

DAY 4 – Thursday, March 11, 2021

Time	Subject	Presenter
0900	Review Agenda & Housekeeping Review Status of Previous Day (*As Necessary*)	Chair
0915	Discussion & Resolution of Results & Conclusions WP #2	RPR Participants
1030	***Break***	
1045	Develop Consensus on Paper Acceptability & Agreedupon Revisions (TOR objectives) WP #2	RPR Participants
1130	*Science Advisory Report (SAR)* – Introduction and Overview in preparation for the next day	RPR Participants
1200	**Adjourn for the Day**	

DAY 5 - Friday, March 12, 2021

Time	Subject	Presenter
0900	Review Agenda & Housekeeping	Chair
0915	*Science Advisory Report (SAR)* Develop consensus on the following for inclusion: • Summary bullets • Sources of Uncertainty • Results & Conclusions • Figures/Tables • Additional advice to Management (as warranted)	RPR Participants
1030	***Break***	
1045	*Science Advisory Report (SAR) cont'd*	RPR Participants
1145	Next Steps – Chair to review • SAR review/approval process and timelines • Research Document & Proceedings timelines • Other follow-up or commitments (*as necessary)*	Chair
1200	**Adjourn meeting**	

APPENDIX D: PARTICIPANTS

Last Name	First Name	Affiliation
Bianucci	Laura	DFO Science
Campbell	Jill	DFO Science, Centre for Science Advice Pacific
Chasse	Joel	DFO Science – Gulf Region
Christensen	Lisa	DFO Science, Centre for Science Advice Pacific
Filgueira	Ramon	Dalhousie University
Foreman	Mike	DFO Science
Grant	Jon	Dalhousie University
Guyondet	Thomas	DFO Science – Gulf Region
Han	Guoqi	DFO Science
Heath	Bill	Project Watershed
Krassovski	Maxim	DFO Science
Lacoste	Cher	DFO Science
Marrie	Chris	DFO Fisheries Management, Aquaculture
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Munro	Alex	Raincoast Sea Farms
Olson	Elise	University of British Columbia
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