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2024 **NSARB-2024-001**

Nova Scotia Aquaculture Review Board

IN THE MATTER OF: Applications made by C & G AQUACULTURE for NEW MARINE SHELLFISH LICENCE/LEASE in MERIGOMISH HARBOUR, PICTOU COUNTY for the SUSPENDED, BOTTOM WITH GEAR AND BOTTOM WITHOUT GEAR CULTIVATION OF AMERICAN OYSTER, BAY SCALLOP, QUAHOG, AND RAZOR CLAM.

C&G Aquaculture

APPLICANT

-and-

Minister of Fisheries and Aquaculture

PARTY

Affidavit of Nathaniel Feindel

I, Nathaniel Feindel, of Shelburne, Nova Scotia, affirm and give evidence as follows:

1. I am the Manager of Aquaculture Development and Marine Plant Harvesting in the provincial Department of Fisheries and Aquaculture (the Department). I started with the Department in 2015 as an aquaculture advisor. I have been in my current management role since 2017.

2. I have worked in the aquaculture industry for approximately 14 years.

3. I have personal knowledge of the evidence sworn to in this affidavit except where otherwise stated to be based on information or belief.

4. I state, in this affidavit, the source of any information that is not based on my own personal knowledge, and I state my belief of the source.

Review Team

5. When the Department considers an application for aquaculture licence a licensing coordinator is assigned to coordinate the review. The licensing coordinator assigned to this application was Lynn Winfield.

6. I led the Review Team for this application. The Review Team consisted of Aquaculture Advisor Melinda Watts (Aquaculture Development Unit), Dr. Anthony Snyder, and Dr. Amanda Swim aquatic animal health veterinarians, and Stephanie Hall, Ph.D. from the

Aquatic Animal Health Unit and Danielle St. Louis, David Cook, and Gretchen Wagner from the Operations Unit. Mapping and spatial analysis was provided by Matthew King, a GIS Officer with the Development unit.

7. This Affidavit will address the application before the Nova Scotia Aquaculture Review Board (the "Board") in this adjudicative hearing. A single application was submitted to the Department by the applicant, C&G Aquaculture ("C&G") on September 21, 2021. The application is for proposed lease area: AQ#1448.

8. On July 9, 2024, the Department submitted the following documents to the Board: the application form, Development Plan, and Scoping Report (the "Application Package") and the Report on Outcomes of Consultation.

9. In early 2024, the Department identified that the proposed lease area overlapped with three parcels of registered land (two parcels are crown land) on the adjacent Pig Islands. The applicant decided to revise the lease boundary and remove the approximate 0.48-hectare overlap. A map produced by the Department depicts the original proposed lease boundary and the area of overlap with the three parcels of land. This map can be found on pages 73 and 74 of the Application Package.

10. The resulting "Schedule A", produced by the Department, depicts the official lease space for the site application. This can be found on pages 8 and 9 of the Application Package.

11. The Department wishes to clarify a discrepancy in the Executive Summary on page 2 of the Application Package and in the Application Description on page 2 of the Report on the Outcomes of Consultation submitted to the Board by the Department. In each document, it was noted that the proposed leased area overlapped with two (2) parcels of land and an adjustment was made to the final proposed lease boundary to remove the overlap. The discrepancy is a result of the two parcels of crown land being grouped into one parcel.

History of Application

12. An option to lease was granted to C&G on September 23, 2020, for a period of six months. It was extended for an additional six months, expiring on September 23, 2021.

13. Lynn Winfield received the Application on September 21, 2021.

Network Consultation

14. Under s.14 of the *Aquaculture Lease and Licence Regulations* (the "Regulations"), when the Department receives a completed application, we are required to undertake consultations with relevant federal and provincial departments or agencies (the "Network").

15. The Network consulted in this application included: Fisheries and Oceans Canada (DFO), the Canadian Food Inspection Agencies (CFIA), Transport Canada (TC), Environment and Climate Change Canada – Canadian Shellfish Water Classification Program and

Canadian Wildlife Service (CWS), the Nova Scotia Department of Environment and Climate Change (NSECC), the Nova Scotia Department of Agriculture (DOA), the Nova Scotia Department of Municipal Affairs and Housing (DMAH), the Nova Scotia Department of Communities, Culture, Tourism, and Heritage (CCTH), the Nova Scotia Department of Natural Resources and Renewables (DNRR), and the Nova Scotia Office of L'nu Affairs (OLA).

16. When an application is submitted to the Board, the Minister is required pursuant to s. 16 of the Regulations to submit a Report on the outcome of any consultations undertaken. For this application, the Network consultation report entitled "Report on the Outcomes of Consultation" was submitted to the Board by the Department on July 9, 2024.

17. Feedback from the Network partners that is related to the regulatory factors for the Board to consider are described below.

Technical Review (Verification and Evaluation)

18. The Review Team conducts the Department's internal review of the technical feasibility of the application and its ability to align with the regulatory framework for aquaculture in Nova Scotia. The technical review analysis includes the assessment of information relevant to the factors the Board must consider pursuant to s. 3 of the Regulations. The conclusions reached by the Review Team as part of this review are summarized below in accordance with the relevant factor set out in s. 3 of the Regulations.

Section 3(b): Contribution to Community and Provincial Economic Development

19. The Review Team looks at a number of aspects of the application under this factor, including the production plan, infrastructure, services/suppliers, employment, etc.

20. The production plan forms the basis of the applicant's Development Plan.

Production Plan

21. C&G proposes to culture American oyster, bay scallop, quahog/hard-shell clam and razor clam, which all are acceptable species to be cultivated in Nova Scotia. The primary species proposed for cultivation by C&G is oysters.

22. C&G proposes multiple culture methods. This includes suspended culture, bottom culture with gear and bottom culture without gear. The type of culture equipment differs based on species of shellfish, life stage and locations within the proposed lease space.

23. The primary culture equipment for oyster culture is called "Benefit of Being Round" (BOBR) and OysterGro cages. The information provided by C&G includes infrastructure types and dimensions, stocking density, and floatation. The Review Team was satisfied that this equipment is suitable for shellfish culture at the proposed lease site.

24. C&G intends to source seed through natural collection or from other operators in the area. If sourcing wild spat outside of proposed lease boundaries, a spat collection permit would

be required from DFO. If it were from other farmers, this would require an Introductions and Transfers (I&T) Permit from DFO and a Fish Buyer's licence from the Department.

25. C&G's application provided total gear stocking information for the lease space and divided it up into different zones. This includes areas where year-round culture will take place and where seasonal culture will occur. This information allowed the Review Team to assess the applicants' general knowledge of farming, the different types of infrastructure to be used on the farm in the various environmental conditions, for various species and in conjunction with the farming cycle.

26. C&G provided the Department with the following chart estimating the volume of production for the lease site:

Species	Gear Type	Max Number of Gear Units	Max Number of Lines	Length of Lines (m)	Max Number Introduced	Time to Achieve Max Production
Oyster	BOBRs	7,360	32	150	10,000,000 to 12,000,000	7 to 10 years
	OysterGros	1,120	32	150		
	Finishing cages	720	9	120		
	ABS Floats	10	2	10		
	Bags/Trays on Bottom	400 (including what goes on racks)	N/A	N/A		
	Racks/Tumblers	20	N/A	N/A		
	Bottom	N/A	N/A	N/A		
Quahog	Bottom	N/A	N/A	N/A	250,000 to 500,000	7 to 10 years (dependent on seed)
	Finishing cages	Shared with above	N/A	N/A		
	Bags/Trays	Shared with above	N/A	N/A		
Bay Scallop	Lantern nets	80	1	120	~50,000 to 100,000	7 to 10 years (dependent on seed)
Razor Clam	Bottom	N/A	N/A	N/A	10,000	-

27. The Review Team assessed the site design, including whether the lease layout and proposed infrastructure are reasonable for the level of production estimated by C&G. The Review Team determined this estimate was reasonable for the initial establishment of the site. Ultimately the maximum number of lines, cages, tumblers etc., will be determined by how the site performs in its biological ability to support shellfish aquaculture.

28. In addition to the infrastructure, the Review Team also assessed whether the level of production (number of shellfish) proposed was reasonable. The Review Team concluded it is feasible and aligns with standard industry practices.

29. The Review Team also examined whether the expected time to reach maximum production proposed by C&G was reasonable. The Review Team concluded that time estimated by C&G aligns with standard industry practices in Nova Scotia.

30. The applicant will focus production on oysters, with an intended production cycle length of approximately 4 years, which is reasonable to attain a marketable oyster. The applicant also indicates that the site will reach its full production potential in 7-10 years, which illustrates the applicant's willingness to develop their operation in a methodical stepwise fashion. This approach allows ongoing assessments of the site's potential, and changes to be made in the production cycle and husbandry practices to best suit the site.

Infrastructure

31. The Review Team assessed the adequacy of the infrastructure that C&G intends to use. The identified infrastructure includes a nearby wharf of a current operator as well as other wharfs and water access in the broader area that could be utilized if need be.

32. The Review Team concluded that the existing infrastructure is acceptable for the development of this proposed lease.

Services and Suppliers

33. Small to medium-sized aquaculture operations such as the one described in this application have shown a reliance on local suppliers and services ranging from fuel, marine services, and industrial manufacturers to food, legal and scientific equipment suppliers.

34. C&G identified local and Atlantic Canadian services and suppliers relevant to the proposed operation. C&G is a sole proprietorship of Mr. Alex Bouchie. It is understood that Mr. Bouchie is currently working in the aquaculture industry in Merigomish Harbour. The Review Team found that the applicant identified well-known service suppliers in the aquaculture industry.

Employment

35. C&G plans to employ 1-2 full-time staff and 2 seasonal staff. The applicant indicated additional employees may be hired, as needed. The Review Team found this to be a reasonable estimate for the size and scale of the proposed operation.

Other Economic Contributions to the Local Community and Province

36. The potential economic contributions to the community and the province are dependent on a number of factors including, but not limited to the success of the farm, and sales of aquaculture products.

37. The Review Team found that, given the scale of the proposed operations, the primary economic contribution of C&G's proposed aquaculture operation would be employment, both full time and seasonal. There may also be potential spinoffs from service support of farming, processing and sales.

Section 3(c): Fisheries Activities in the Public Waters Surrounding the Proposed Aquacultural Operations

38. The applicant indicated there are commercial fishing activities in the vicinity of the proposed site, including lobster and groundfish. Most of this fishing takes place outside of Merigomish Harbour. There are also commercial fisheries for oysters and quahogs that take place within the harbour. Quahogs are also collected by recreational harvesters in the vicinity of the site. C&G conducted public engagement in preparing its application for this lease which outlines some of the overlap with commercial and recreational shellfish harvesting.

39. During the Review Team's consultation process, none of the Network reviewers raised concerns with the proposed lease site interfering with other fisheries in the surrounding public waters. Commercial fishing/wild harvest falls under the jurisdiction of DFO, who did not comment on fisheries activities in Merigomish Harbour in their review of the application.

Section 3(d): Oceanographic and Biophysical Characteristics of the Public Waters

40. The Review Team assessed many aspects of the oceanographic and biophysical characteristics of the public waters where the lease site is located, including the following:

Wind Data

41. The wind data presented by C&G was assessed by the Review Team and concluded that given the sheltered nature of the proposed location, and the low structural profile of the lease infrastructure, typical wind regimens should not be problematic.

Wave Data

42. The Review Team assessed whether there might be a risk to the structural integrity and animal health of the operation from waves or current.

43. The wave information provided by C&G showed approximate maximum wave height of 1 to 1.2 m. Generally, in Nova Scotia, the optimal wave height for oyster culture is one (1) metre or less. Given this information, the sheltered nature of the proposed location, and the low structural profile of the infrastructure, the Review Team anticipates that typical wave regimens at the proposed site should not be problematic for the proposed culture.

Current Data

44. C&G has estimated that the current speed at the proposed aquaculture site ranges from 15 to 35 cm/s. The Department was involved in a study conducted by AGRG and cited by C&G in its application, "AGRG. 2017. Topo-bathymetric Lidar Research for Aquaculture and Coastal Development in Nova Scotia: Final Report. Technical report, Applied Geomatics Research Group, NSCC Middleton, NS." This report included current speeds and directions with some speeds exceeding 50 cm/s. However, these currents were measured at the main channel at the mouth of the Merigomish Harbour where current speeds would be highest. The Review Team concluded that because the location of the proposed site is near the end of the eastern branch of the Merigomish Harbour, the proposed aquaculture site would expect to see water currents within the ranges identified by the applicant.

45. The site will incorporate a number of different culture techniques. The equipment at the proposed aquaculture site will use screw anchors and concrete moorings and will be anchored and situated in a sheltered bay, away from the main channel. The Review Team found that the proposed site presents a minimal risk to the structural integrity of the proposed equipment nor is it anticipated that animal health will be impacted by the water currents at the proposed site.

Salinity

46. Optimal salinity for American oyster growth is 20 to 30 ppt with minimum and maximum 5 and 35 ppt, respectively.

47. The salinity near the proposed aquaculture site was recorded over a two-month period with a minimum recording of 11.3 ppt, maximum of 23.2 ppt and an average of 18.9 ppt. These were recorded by a data logger deployed at nearby site AQ#1086 (680 m away) by ShanDaph Oysters Co. Inc., who worked with Dalhousie University and Cape Breton University. Though not directly at this location, the Review Team would expect that the salinity profiles would be very similar.

48. Oysters are adapted to surviving low salinity conditions for short periods of time (days) with no negative impacts. The Review Team also considered the presence of natural shellfish populations in the Merigomish Harbour and active wild and recreational fisheries which indicates that the salinity is acceptable for shellfish culture.

Water Temperature

49. The area of the lease is natural habitat for oysters and other shellfish. The applicant identified the water temperature recorded in the proposed lease area ranged between -2 to 29 Degrees Celsius. The Review Team found that this temperature range is within the known tolerance for shellfish and is not expected to produce feeding or health related issues.

50. If water temperatures exceed the tolerable range for oysters and they appear to be affecting animal health and/or behaviour, husbandry and culture practices can be adjusted.

51. Since shellfish thrive in the natural conditions of Mergomish Harbour, the Review Team did not raise any concern with the water temperature at the proposed lease site.

Water Depth

52. Water depth was examined by the Review Team. The tidal range for this area is approximately 0.1 to 1.8 m. Acceptable oyster culture depth for suspended culture is 1 to 6 m.

53. The depths provided by the applicant in the Development Plan ranged from 2.39 to 2.59 m at lease corners 2 and 3. These corners are the outside (deeper) corners of the lease. Depths at the near shore lease corners, corners 1 and 4, were not provided, likely because the lease extends into the inter-tidal zone. The applicant has divided the proposed lease area into five production zones, with the ability to utilize specific zones depending on the season. Shallow water zones of the lease cannot be utilized during the winter months, when ice cover could cause damage to submerged animals and infrastructure. Effects of ice cover on the health of the animals and infrastructure integrity should not occur if the applicant is able to utilize the deeper water areas of their lease for overwintering animals and infrastructure or removes infrastructure from these seasonal zones. The Review Team was satisfied that the water depth at this proposed site is appropriate for the intended purposes.

Environmental Carrying Capacity

54. Generally, environmental carrying capacity refers to the maximum population of a species that can be sustained in any given environment. Seston in the environment would inform environmental carrying capacity of an area. Seston is composed of small organic particles (plant matter), small photosynthetic organisms (phytoplankton), as well as plankton and inorganics (minerals). It is the initial building blocks or support system of an ecosystem and these small particles are the feed for bivalves like oysters. If too many oysters are put in an area, they will remove the seston and the system will eventually crash. However, if an area has too much seston, it can lead to systems crashing due to excess loading resulting in oxygen depletion. Oysters can be beneficial in areas where there is excess loading as they feed on the seston and maintain the balance of the ecosystem. Each ecosystem is unique and other variables influence carrying capacity like the hydrodynamics of an area.

55. Three areas in Nova Scotia were the subject of a recent study done by Filgueira et al., entitled "The effect of embayment complexity on ecological carrying capacity estimations in bivalve aquaculture sites" published in the Journal of Cleaner Production in 2021. The study looked at three areas in Nova Scotia where active farming is taking place that varied in hydrodynamics and geophysical coastal attributes. This provided a range of conditions that are most likely to be seen across Nova Scotia. Mainly, areas that

are deep and relatively open, areas that are open and shallow to choked and shallow. The Review Team found that Merigomish Harbour would fall somewhere between open and shallow and choked and shallow, and at a proposed lower percentage of leased area than what was present in the study by Filgueira et al. Overall, the models considered by the Review Team show that farming in these areas (7.3 to 21.7% lease area farmed) could increase up to 20% with minimal concern.

56. The study by Figueira et al. is attached to this Affidavit as **Exhibit A**.

57. The total area of the lease space of all aquaculture leases in Merigomish Harbour combined is approximately 2.72% of the area of Merigomish Harbour. The proposed lease AQ#1448 will add an additional 0.84% to the farming area. Based on work conducted for other sites in Nova Scotia and around Atlantic Canada, the Review Team found that the risk of cumulative effects of these sites having an impact on primary production in Marigomish Harbour is low. There is a significant amount of tidal flushing in the Merigomish Harbour as well as freshwater input sources, and anthropogenic influences, all of which continually supply the harbour with seston and nutrients to support the ecosystem.

58. Nova Scotia Department of Agriculture raised that there is significant agricultural activity occurring around Merigomish. As a result, nutrient runoff has the potential to increase nutrient loads in the Merigomish Harbour and primary production. The Review Team found that the proposed oyster farm will help mitigate the potential impacts of nutrient loading or increased nutrient loading in the future by filtering out the phytoplankton that utilizes nutrients being loaded in the Merigomish Harbour and reduce the chance of events like algal blooms or increased epiphyte growth. The successful culture of American Oysters in the vicinity of the proposed lease areas, suggests sufficient primary production to support viable production capacity.

Water Quality

59. Water quality was examined by the Review Team. There are three classifications under the Canadian Shellfish Sanitation Program (CSSP): approved, closed, and unclassified.

60. Approved means that you can harvest freely with no concerns.

61. Closed has a number of implications, it can mean that due to water quality oysters cannot be harvested for human consumption. Closed can also mean there are restrictions due to concerns about water quality and, as a result, oysters harvested must be cleansed or "depurated" before human consumption.

62. The CSSP classification for Merigomish Harbour, in the area of the proposed lease, is "approved".

Baseline Environmental Monitoring

63. The underwater baseline video footage provided by C&G indicates the presence of eelgrass. This footage is required by the Department to establish baseline conditions for

the Environmental Monitoring Program (EMP) and was shared with DFO as part of the Network Consultation. DFO reviews the baseline information to determine whether the proposed development is likely to result in changes to fish and fish habitat, aquatic species at risk, and aquatic invasive species.

64. DFO raised concern that the proposed farming infrastructure considering water depths and potential ice cover will most likely have some impact on eelgrass. However, DFO provided mitigation measures that could be implemented by the applicant to minimize these impacts, which include sinking gear during winter in the area of the lease where eelgrass is not present and general avoidance of eelgrass habitat while overwintering under ice. DFO also considered the impacts on eelgrass on a bay wide scale and that it is unlikely that the operation of this farm would result in severe impacts on eelgrass in Merigomish Harbour.

Site Design

65. The Review Team was satisfied that oceanographic and biophysical characteristics were considered in the applicant's site design. Zone drawings have been provided that outline the site design and the infrastructure to be placed in these areas based on species, and production cycles in accordance with oceanographic and biophysical characteristics.

66. During the Network review, CCTH noted there are 12 pre-contact archaeological sites recorded in the vicinity of the proposed lease area. Two (2) of those sites intersect with the proposed lease area. CCTH recommended an archaeological assessment be conducted prior to operation of the proposed site. Following CCTH's review of the side scan sonar data collected by the Department, CCTH did not have any archeological concerns but recommended that a marine archaeologist with demonstrated expertise assess and confirm that there are no anomalies that may be disturbed by infrastructure used to support the site design of the proposed lease area.

67. A review of the side scan sonar data was completed by a marine archeologist and an environmental geoscientist with demonstrated expertise. Based on their review, given the bathymetric data and the assessment of geomorphological conditions at and near the proposed site, it is likely that the location of the proposed lease and associated activity has low potential for impacting a pre-contact settlement.

Section 3(e): The Other Users of the Public Water Surrounding the Proposed Aquacultural Operation

68. Other users of the waters surrounding the proposed site have been identified by the applicant and include recreational fishers and boaters. There is a campground approximately 3.3 km east of the proposed site. The applicant has experience working in the area at the nearby ShanDaph Oysters Co. Inc. sites and would be familiar with the local and seasonal visitors to the area.

69. C&G has conducted public engagement, which is described in their Development Plan and Scoping Report.

Impacts to Wildlife

70. The Review Team also considered impacts to wildlife under this factor. To determine potential impacts to wildlife from the proposed operation, the Review Team relies on feedback from Network consultation. The Department received feedback from two network partners regarding the potential impact to wildlife: CWS and DNRR.

71. DNRR had no concerns with the proposed application.

72. CWS provided feedback regarding different types of birds that have been identified historically in the area or that may be in the area. With respect to proposed lease AQ#1448 no *Species at Risk Act* (SARA) listed species were identified in the areas adjacent to this site but were in the broader area on Big Island.

73. CWS also provided some management practices that could be implemented by C&G should the application be approved.

74. Should the application be approved, the Department will be able to work with C&G to incorporate operational management practices into their Farm Management Plan (FMP).

Impacts to Other Users

75. The Review Team was satisfied that the applicant has consulted with the other users of the proposed development area through their public engagement process.

76. The Review Team noted that during the applicant's public engagement, some concerns were raised by other users including recreational kayakers, recreational fishers and landowners. The applicant acknowledged their concerns and provided suggestions that may allow for mutual use of the area without compromising their proposed development or use by others.

Negative Impacts by Other Users

77. Possible impacts from roosting sea birds were identified and are a general concern of the shellfish industry. This is addressed by the use of the culture equipment being deployed on the lease sites, it will have a near neutral buoyancy which deters birds from roosting on it and handling practices required by the CFIA also help mitigate this impact.

Section 3(f): Public Right of Navigation

78. Transport Canada was consulted regarding any potential impacts on the public right of navigation. They have not raised any concerns.

79. C&G will need a valid *Canadian Navigable Waters Act* approval before it can commence the development of its proposed site.

80. Transport Canada will complete its approval process if the Board approves C&G's application.

Section 3(g): Sustainability of Wild Salmon

81. The applicant identified one salmon run river approximately 3 km from the proposed site. Another river, approximately 4.5 km away from the proposed site was also identified by the applicant that may be a potential salmon run river. There were no concerns related to interactions with wild salmon raised by DFO during their Network review of the application. The Review Team was satisfied that the proposed operation is unlikely to impact the sustainability of wild salmon.

Section 3(h): The Number and Productivity of Other Aquacultural Sites in the Public Waters Surrounding the Proposed Aquacultural Operation

82. There are eleven other aquaculture leases in Merigomish Harbour, all of which include bottom culture oyster aquacultural operations. The total issued lease areas are 77.71 hectares or 2.72% of Merigomish Harbour (2861.07 hectares). The proposed site AQ#1448 (24.06 hectare) would represent 0.84% of the total area of Merigomish Harbour.

83. As noted in paragraph 57, the Review Team was satisfied that the proposed aquaculture operation will not affect the production of other existing aquaculture sites in the area.

84. I was not physically present before Ms. Menczel-O'Neill when I affirmed this affidavit. I was linked with Ms. Menczel-O'Neill using video conferencing technology.

Affirmed before me by videoconference from Shelburne (location of affiant) to Halifax, Nova Scotia (location of lawyer taking oath) on the 1st day of November 2024.

[redacted]

Caitlin Menczel-O'Neill
A Barrister of the Supreme Court
of Nova Scotia

[redacted]

Na[redacted]

TAB A

This is Exhibit “A” referred to in the
Affidavit of Nathaniel Feindel
affirmed before me by videoconference
on November 1, 2024

[redacted]_______

Signature
CAITLIN MENCZEL-O’NEILL
A Barrister of the Supreme Court of Nova Scotia

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The effect of embayment complexity on ecological carrying capacity estimations in bivalve aquaculture sites

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A R T I C L E I N F O

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A B S T R A C T

Bivalve aquaculture requires the alteration of natural populations of filter-feeders by artificially increasing their density. A bivalve farm could have negative consequences for the ecosystem if the filtration pressure of stocked biomass surpasses the capacity of the system to replenish the depleted resources. The concept of ecological carrying capacity, understood as the magnitude of aquaculture activity in a given area that can be supported without leading to unacceptable changes in the aquatic environment, is commonly used to inform management and regulatory decisions of bivalve aquaculture. In this study, a hydrodynamic model has been coupled to an ecological model that simulates the main dynamics of organic seston to evaluate the effects of bivalve aquaculture on seston supply and assess ecological carrying capacity. The spatially-explicit model allows the identification of areas where organic seston could be reduced beyond precautionary thresholds of ecosystem resilience. The model has been applied to three coastal embayments in Nova Scotia (Canada) that differ in water circulation and inlet/coastal complexity. The outcomes of the model suggest that the current aquaculture operations in Sober Island, Wine Harbour, and Whitehead are within the ecological carrying capacity of the ecosystem for bivalve aquaculture. The simulation of additional hypothetical stocking scenarios had demonstrated the relevance of local water circulation to the ecological carrying capacity of the system, and consequently for aquaculture operations. Accordingly, the placement of leases in areas with optimal circulation should be considered for planning purposes. The capability of the model to explore hypothetical scenarios could be used as a tool to guide management decisions in regard to site selection for new aquaculture sites.

1. Introduction

A simple question has prevailed in the scientific literature about bivalve aquaculture in the last 20 years: 'how much is too much?'. This question has been posed by managers and regulators to quantify how many bivalves can be farmed in a bay without causing negative ecological impacts. The underlying goal of this question is to determine the carrying capacity of the ecosystem and concomitantly ensure the sustainability of farming activity. The scientific community has answered this question with different approaches, ranging from numerical models that simulate current or hypothetical aquaculture scenarios (Ferreira et al., 2008; Byron et al., 2011), to monitoring programs that aim to infer the environmental effects of aquaculture based on a suite of indicators (Filgueira et al., 2013a, 2014). One of the key outcomes from the scientific literature on this topic is the influence of local conditions, particularly water circulation, on ecosystem functioning and consequently on the estimation of ecological carrying capacity (ECC) for bivalve aquaculture (Dame and Prins, 1998; Smaal et al., 1997); although this statement is highly dependent on the specific local conditions (e.g. Filgueira et al., 2016; Sainz et al., 2019). For example, the ECC for mussel aquaculture in Tracadie Bay (Canada) increased after a storm opened a breach in the barrier inland at the mouth of the bay, which was attributed to the increase

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in water exchange with the open ocean, and the concomitant impact on phytoplankton renewal within the bay (Filgueira et al., 2013b). The relevance of local hydrodynamics has also been recognized in decision support tools for bivalve aquaculture planning (e.g. Silva et al., 2011; Gangnery et al., 2020). These findings confirm the need for spatially explicit hydrodynamic models to fully understand bivalve-environment interactions, and consequently to estimate ECC.

Although ECC has been defined with slightly different emphasis in the context of bivalve aquaculture, ECC could generally be understood as the magnitude of aquaculture activity in a given area that can be supported without leading to unacceptable changes in ecological processes, species, populations, communities, and habitats in the aquatic environment (Byron and Costa-Pierce, 2013). The definition of thresholds for unacceptable changes is the key challenge in ECC studies, given that it requires qualitative and quantitative decisions. Qualitatively, it is crucial to define the environmental variable(s) that should be used to characterize an unacceptable change. Bivalve aquaculture could potentially exert a series of changes on the ecosystem. Firstly, feeding activity of filter-feeding bivalves could exert a top-down control on phytoplankton populations (Petersen et al., 2008; Timmermann et al., 2019). Similarly, the feeding activity could exert competition with zooplankton (Maar et al., 2008) or direct predation on zooplankton (Froján et al., 2016), which could cause a direct effect on the larvae of certain species and trigger cascade effects in the food web, although this field of research is still in its infancy. Finally, bivalve biodeposits sink to the bottom, increasing organic loading, which can alter the biochemistry of sediments and local benthic populations (Newell, 2004; Smyth et al., 2018). Feedback of altered nutrient cycles to phytoplankton populations could limit the available energy for higher trophic levels in the water column (Jiang and Gibbs, 2005; Kluger et al., 2017), including the cultured species (Grant, 1996; Bacher et al., 2003). As benthic effects have a limited spatial extension compared to pelagic effects (Newell, 2004; Weitzman et al., 2019), ECC has usually focused on the bivalve-phytoplankton interaction (McKindsey, 2013). Particularly, the reduction of phytoplankton populations, or organic seston assuming that phytoplankton is the largest component of the seston, as a consequence of bivalve filtration have been used as a benchmark to assess ECC at aquaculture sites (reviewed by McKindsey, 2013).

The definition of ECC thresholds becomes even more complex from a quantitative perspective. The definition of these thresholds should be framed in the context of the Ecosystem Approach to Aquaculture (EAA, Soto et al., 2008), which defines accepted principles for sustainable management of farming activities, acknowledging that aquaculture is part of a broader social-ecological system. Accordingly, the holistic principles of EAA include social, economic, and ecological aspects. From the ecological standpoint, EAA encourages that aquaculture should be carried out taking into account the resilience of the ecosystem to ensure that functions and the delivery of services are not compromised. However, the precise quantification of the tipping points at which a small perturbation can exceed resilience and compromise performance of the ecosystem is not straightforward (Fischer et al., 2009). Furthermore, given that these limits are site specific, it is difficult to perform field measurements to empirically determine these tipping points without manipulating the ecosystem. To overcome this issue, Grant and Filgueira (2011) suggested using the natural variation of an ecosystem variable as the precautionary limit beyond which the resilience of the system could be compromised. The application of natural variation of phytoplankton populations as a precautionary limit has been used to assess ECC (Filgueira et al., 2015; Bricker et al., 2016) and inform management decisions (DFO, 2015) at bivalve aquaculture sites.

As stated above, given the difficulty in carrying out empirical assessments, ecosystem modelling has become the standard tool to explore carrying capacity and the potential effects of different aquaculture scenarios on the environment (Dabrovski et al., 2013; Brigolin et al., 2017). Although models vary in complexity, ranging from simple ratios (Dame and Prins, 1998; Comeau, 2013) to ecosystem models (Guyondet et al., 2010; Pete et al., 2020), Filgueira et al. (2015) demonstrated that a spatially explicit model that simulates the dynamics of organic seston as a whole (e.g. Dowd, 2003; Guyondet et al., 2013) could provide the same output as a more complex ecosystem model that captures the dynamics of nutrients, phytoplankton, and seston independently. Representing seston dynamics at the proper spatial resolution is imperative given the relevance of local hydrodynamics for the replenishment of seston in farming areas, and consequently for the delivery of food to bivalve farms (Nunes et al., 2011; Filgueira et al., 2016). Therefore, simulating organic seston as a single variable aims to capture food dynamics without added complexity, parameterization, and validation resulting in an optimal solution to exploring ECC.

The main objective of this study is to explore ECC for oyster aquaculture in embayments with different hydrodynamic conditions that affect bivalve-environment interactions. To address this objective, three embayments from Nova Scotia (Canada), Sober Island Pond, Wine Harbour, and Whitehead, that currently hold active farms of the Eastern oyster *Crassostrea virginica* were selected as case-studies. The three embayments are located on the Eastern Shore of Nova Scotia, and it is assumed that the seston dynamics would be similar from a biogeochemical perspective; however, the three bays are very different from a geophysical perspective, ranging from deep and relatively open (Whitehead), to open and shallow (Wine Harbour), and choked and shallow (Sober Island). Accordingly, this study allows the evaluation of the relevance of water circulation to seston dynamics and particularly the estimation of ECC in bivalve aquaculture sites. For that purpose, a model that represents the dynamics of organic seston was coupled to a hydrodynamic model, and a series of simulations, covering current aquaculture development and hypothetical scenarios, were explored and analyzed in terms of reduction of organic seston. The outcomes of this study can be directly used to inform aquaculture managers as well as further our understanding on the role of local hydrodynamics on the resilience of aquaculture sites. These results demonstrate operational use of carrying capacity as a tool in aquaculture regulation.

2. Methods

The dynamics of organic seston were simulated by coupling a series of convection-diffusion equations to the outcomes of a hydrodynamic model constructed using the unstructured-grid Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2007). The next sections provide 1) a general description of the study area, including the level of bivalve aquaculture in the three simulated embayments, 2) the details of the FVCOM model, including the data collected for their validation, 3) the equations that define the organic seston dynamics model, and 4) the scenarios that were analyzed.

2.1. Study area

Sober Island Pond, Wine Harbour, and Whitehead are located within a section of 100 km on the eastern shore of Nova Scotia (Fig. 1). Following Greenlaw et al. (2011), these embayments differ from the geophysical perspective and ecological representation. Sober Island is a small lagoon isolated from the ocean by a narrow

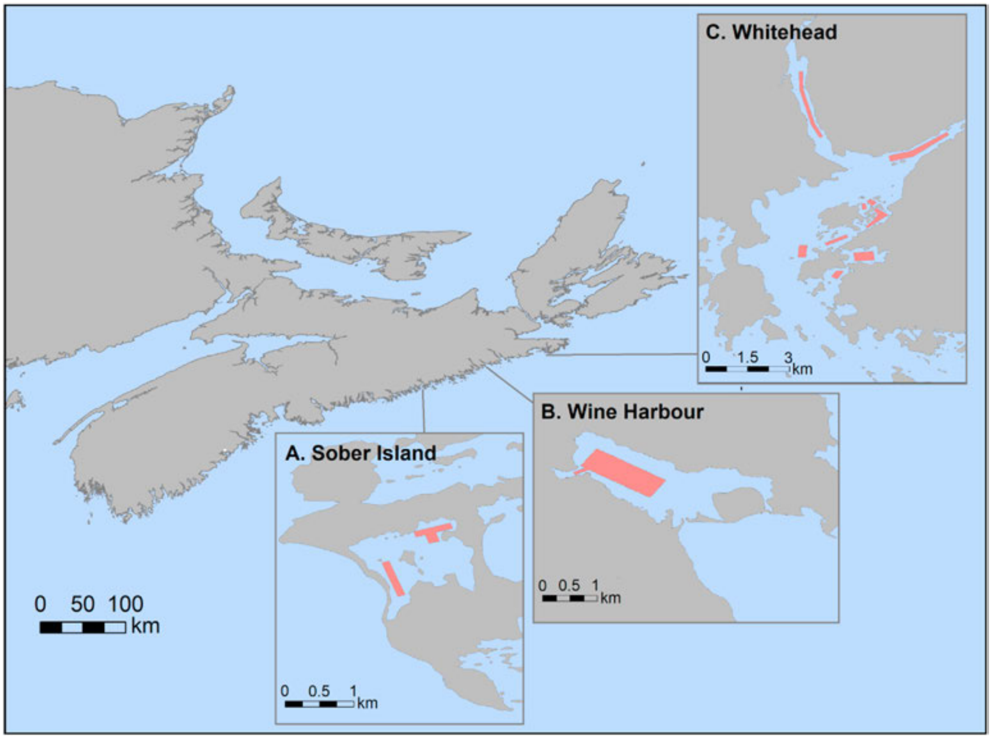

Fig. 1. Location of the three study sites - Sober Island, Wine Harbour, and Whitehead, within Nova Scotia (Eastern Canada). Current oyster leases are in red polygons. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

inlet through a gravel bar with minimal freshwater input. Therefore, this embayment does not fit within any category described by Greenlaw et al. (2011) regarding hydrographic characteristics, namely bay, estuary, and cove. Accordingly, lagoon is a better term to characterize Sober Island. Regarding complexity, Sober Island qualifies as intermediate, with a central large body of water, but also complex morphology generated by small islands, and areas with variable depth. Finally, taking into account the low percentage of intertidal area and its average depth, it is expected that the production within the lagoon has contribution from both benthic and pelagic environments. Wine Harbour is a “simple intermediate estuary” (Table 1) with low habitat heterogeneity, and high productivity based on the contribution of freshwater runoff and the restricted exchange with the open ocean, which also reduces the degree of exposure to waves and tides. Whitehead is a “complex pelagic bay” (Table 1) with high habitat heterogeneity, potentially supporting high species diversity, a dominance of pelagic over benthic production, with low contribution from the river and medium exposure to oceanic conditions. Although the outer bay is highly exposed, there are multiple islands with inner embayments protected from ocean waves. One of these inner basins is among the first bays worldwide to have been assessed for carrying capacity (Carver and Mallet, 1990). The three bays also differ in depth and extension, with Whitehead being the deepest and largest and Sober Island the shallowest and smallest (Table 1).

Oyster farms are currently active in the three embayments, but the spatial coverage of the leased area is heterogenous across them, ranging from 7.3% in Whitehead to 21.7% in Wine Harbour, respectively (Table 1). The farming technique also differs across sites. While oyster cages are used in Whitehead and Wine Harbour, a mix of oyster cages and floating bags are used in Sober Island. However, for the sake of comparability across embayments, and taking into account that the use of oyster cages is becoming the most popular farming method, the oyster density in this study has been adjusted to represent the typical values used in cages.

2.2. Hydrodynamic model

Although a single hydrodynamic model domain was initially planned to be used for the three systems, the hydrodynamics at the narrow (~20 m) and shallow (~1 m) entrance of Sober Island resulted in numerical instability at the time step that was required to ensure computational efficiency. Accordingly, two hydrodynamic models were constructed to accommodate these particular conditions. A first hydrodynamic model was constructed for Sober Island (hereafter, Sober Island Model) in which the fine spatial resolution

Table 1
Description of the embayments in terms of complexity, production regime and hydrographic characteristics based on Greenlaw et al. (2011) (see text), and physical characteristics, included the percentage of the bay that is leased for aquaculture purposes. *Lagoon is not originally in Greenlaw et al. (2011), see text for explanation.

Embayment	Complexity	Production regime	Hydrographic	Average depth (m)	Area (km^2)	Leased area (%)
Sober Island	Intermediate	Intermediate	Lagoon*	2.9	0.90	9.6
Wine Harbour	Simple	Intermediate	Estuary	4.0	1.95	21.7
Whitehead	Complex	Pelagic	Bay	9.0	14.12	7.3

allowed for an execution at a short time step without impacting computational efficiency (Figure A1). The second hydrodynamic model was constructed for Wine Harbour and Whitehead (hereafter Wine Harbour/Whitehead Model) covering approximately 120 km of the Eastern Shore.

The grid for Sober Island Model (Figure A1) included 2260 triangular elements with 1263 nodes. Given the lack of precise bathymetry data for this location in existing charts, an echosounder survey was carried out in the lagoon during July 2019 (Biosonics MX). The readings were interpolated to the nodes from FVCOM and smoothed to meet the hydrostatic conditions. The model included a total of 11 sigma layers to describe the vertical dimension. The model was forced at the boundary using tidal elevations calculated from sea surface height observations made at the boundary using an ADCP (Table A1). The tidal constituents used in the model were M2, S2, K1, O1, and N2, which were the five major constituents based on observations. The model was forced without winds to minimize mixing within the domain, which is aligned with the goal of representing the worst-case scenario in maximizing the reduction of organic seston by oyster filtration. Finally, a 500 m wide sponge layer was used at the open boundary to limit spurious reflections and other instabilities originated at the boundary.

The grid for Wine Harbour/Whitehead Model was defined by 40,895 triangular elements with 22,086 nodes. The depth was interpolated from the existing Canadian Hydrographic Service NONNA dataset (https://open.canada.ca/data/en/dataset/d3881c4c-650d-4070-bf9b-1e00aabf0a1d) to the nodes and smoothed to meet the hydrostatic conditions. Given the dynamic nature of some shallow areas, particularly at the mouth of Wine Harbour, farm operators validated the bathymetry in key locations during the current meter deployment (Table A1), to ensure that the model represented the conditions existing during the data acquisition. Similar to the Sober Island Model, a total of 11 sigma layers were used to describe the vertical dimension. The model was forced with tidal elevations calculated using WebTide and interpolated to the mesh open boundary. The tidal constituents used were M2, S2, K1, O1, and N2, which were the five major constituents based on observations. Following the same approach described above, winds were not part of the forcing. A 200 m wide sponge layer was used at the open boundary to limit spurious reflections and other instabilities.

For both Sober Island Model and Wine Harbour/Whitehead Models, the simulations were initialized from rest, and run for 30 days in total. In both hydrodynamic models, the conditions were ramped up linearly over the first 5 days to prevent any spurious oscillations due to a sudden start. Accordingly, these first 5 days were not considered for validation and numerical calculations of seston dynamics. A total of eight current profilers and single point current meters were deployed in the region during 2019 for validation purposes. Deployments were synchronous within each bay, but asynchronous across bays (Table A1). All of them were configured to measure velocity and pressure. The raw data were binned using 1 m vertical bins for the profilers. An ensemble interval of 900 s was used at each deployment. Ping rate of 0.5 Hz was used in burst mode for 300 s. The deployment period was at least 45 days at each location. The duration of each deployment together with the sampling rate of 0.5 Hz was estimated to be sufficient for analysis of the tidal elevations for the major constituents and used to validate the hydrodynamic model. Depth was only available for the current profilers due to a malfunctioning of the pressure sensor in the single point current meter detected after the deployments.

The water renewal time distribution within the three systems was calculated from the FVCOM outputs and numerical tracer experiments that quantified water exchange between each bay and the far-field, following Koutitonsky et al. (2004).

2.3. Seston dynamics model

The outputs of the hydrodynamic model for each bay were coupled to a convection-diffusion equation previously used by Dowd (2003) and Guyondet et al. (2013) to simulate the dynamics of organic seston. The original equations in Guyondet et al. (2013) for a 2-dimensional bay were extended to a 3-dimensional representation as follows:

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial S}{\partial z}\right)+\alpha-\beta S \tag{1}$$

where S is the organic seston concentration (mgC m^{-3}); u, v and w are the current speeds in directions x, y and z (m s^{-1}), respectively; D_x, D_y and D_z are the dispersion coefficients proportional to u, v and w, respectively, α is the phytoplankton primary production rate (mgC m^{-3} d^{-1}), and β is the oyster population clearance rate (d^{-1}) (see further details in Guyondet et al., 2013). The organic seston dynamics model was parameterized with existing data from the literature. The primary production rate α was kept constant in the three bays, and the average value was based on a depth-integrated 2.5 g C m^{-2} d^{-1}, typical of summer conditions in Nova Scotia waters (Platt, 1991). The bivalve population clearance rate β was calculated as the product of individual bivalve clearance rate (m^3 ind^{-1} d^{-1}) and density of bivalves in the farm area (ind m^{-3}). It was assumed that oysters filtered at a constant rate of 5 L h^{-1} (or 0.12 m^3 d^{-1}), which is assumed to be representative of suspension culture oysters of 57 mm (Comeau, 2013) at a temperature of 17 °C (mean temperature observed at the study sites over the months of June to September). A constant density of 25 ind m^{-2} was assumed for all leases under the current aquaculture scenario and cultured oysters were distributed over the top 0.5 m of the water column in accordance with the local husbandry practice. The organic seston dynamics model outer boundary was forced with a constant concentration of organic seston typical of local waters during the summer, $S_\infty = 400$ mg C m^{-3} (Carver and Mallet, 1990).

When the organic seston dynamics model reached steady state, the outcomes of the model were extracted and summarized using a Seston Reduction Index (SRI) that compares, at each node n of the model domain (SRI_n) the organic seston concentration over the last tidal cycle (S_n), with the average concentration in a scenario without aquaculture (S_0) as follows:

$$SRI_n = 100 \times \frac{S_0 - S_n}{S_0} \tag{2}$$

Accordingly, positive values of SRI indicate a reduction in organic seston availability caused by oyster filtration.

2.4. Scenarios

A series of scenarios were designed to explore current aquaculture development as well as potential future scenarios of expansion, which in turn also inform the ecological carrying capacity of each system for oyster aquaculture. Both oyster stock and feeding activity were parameterized using existing management practices and existing data on oyster feeding activity to simulate the worst-case scenario in terms of overall feeding pressure. It was assumed that all leases were occupied with adult oysters of 57 mm at a density of 25 ind m^{-2} to simulate the biomass that a farm could hold using current aquaculture practices. Furthermore, some scenarios with higher density, 37.5 ind m^{-2}, were simulated to characterize the maximum feeding pressure that could be

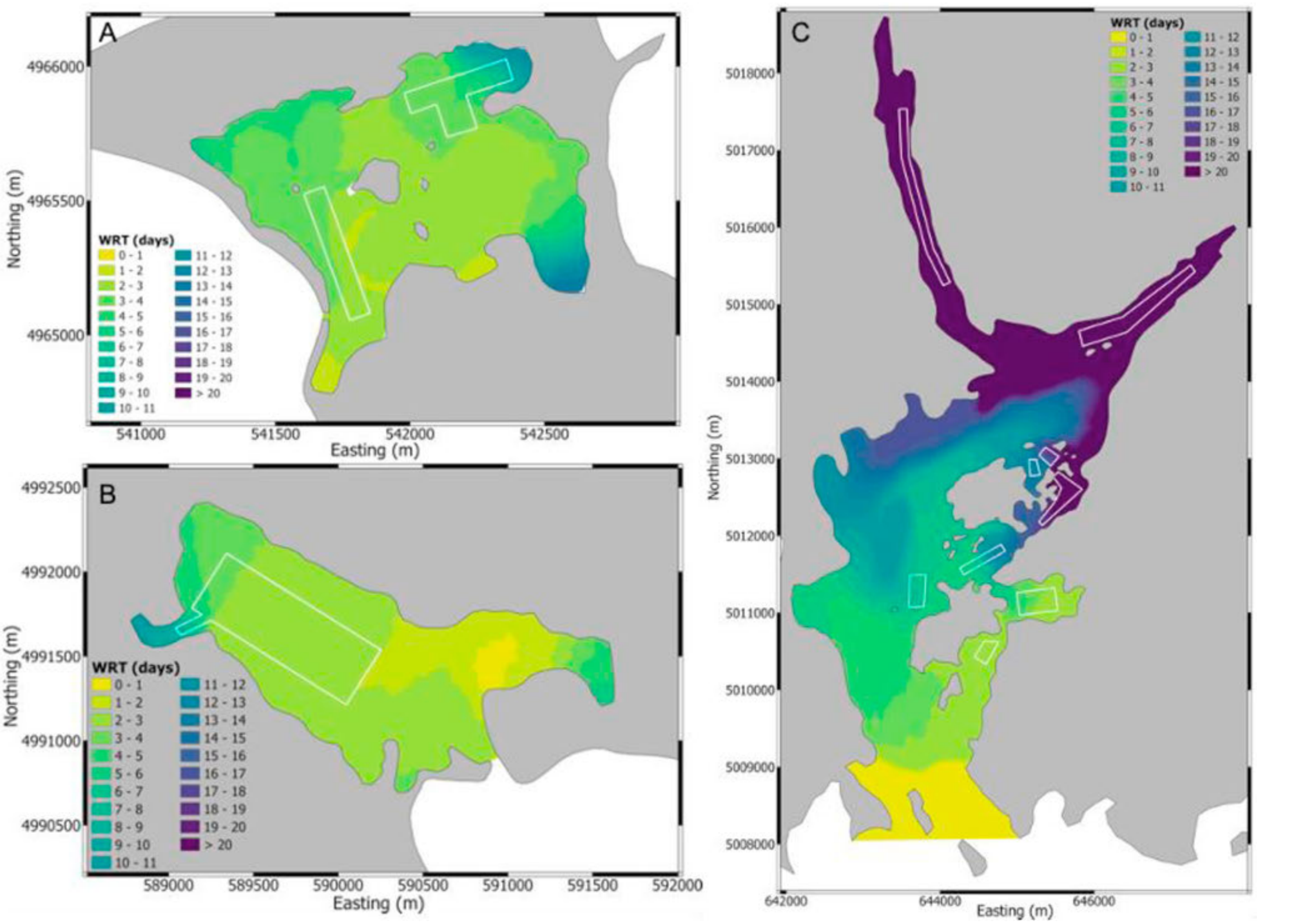

Fig. 2. Water Renewal Time (WRT, days) for the three study sites: Sober Island Pond (A), Wine Harbour (B), and Whitehead (C). Current oyster leases in white polygons.

reached with current leased area, using technical guidelines for maximum density in oyster cage farms. Regarding feeding activity, the assumed constant clearance rate of 5 L h^{-1} aims to simulate the maximum feeding pressure that an oyster of 57 mm can exert on the ecosystem. The combination of maximum biomass and clearance rate represents the worst-case scenario for the estimation of oyster feeding pressure, which embraces the precautionary principle that is needed to account for uncertainty, and provide a precautionary estimation of the ecological carrying capacity.

A total of six different scenarios were simulated per embayment that varied in the percentage of area that was occupied with oyster leases (five scenarios) and stocking density (1 scenario). These scenarios included one that represented a system without aquaculture, which was used to represent the background conditions without aquaculture, one that represented the current leases in the embayment, three additional scenarios with a leased area of 10, 20, and 30% of the bay, and an additional scenario with the current leases but stocked at the maximum oyster density (37.5 ind m^{-2}). The distribution of the leased area in the three hypothetical scenarios followed the most realistic approach for a potential expansion of current leases, as well as potential reduction in the case of Wine Harbour. Furthermore, four additional scenarios were explored in each embayment to evaluate the sensitivity of the model to changes in the parameters α, primary production, and β, oyster clearance rate. These four scenarios tested the impact of an increase and decrease of these two parameters by 10% on the average SRI at the bay scale using the current aquaculture scenario as a reference.

3. Results

3.1. Hydrodynamic model

Model spinup period was 5 days and only the last 25 days were analyzed for model verification purposes. The comparison between observed and simulated tidal elevations for the main constituents resulted in a normalized root mean squared error of 6.6% (Table A1). At Sober Island, the model predicted a daily maximum tidal range of around 0.7 m (Figure A4). Due to the malfunctioning of the pressure sensor on the single point current meter deployed close to the mouth of the lagoon, a full quantitative validation of tidal elevation could not be performed; however, this maximum tidal range matched the qualitative observations from the farmer in this location (Trevor Munroe, personal communication). Although the qualitative observation from the farmer cannot replace the quantitative validation from the current meter, his experience is valuable to constraint uncertainty. The magnitude of simulated velocity at the mouth was in good agreement with observations, although directionality did not match perfectly (Figure A5). This was not considered problematic given that observations included the effect of the wind, which was not included as forcing in the model, and, more importantly, velocity at this location is highly affected by the sedimentary dynamics of the barrier of the lagoon, which changes in shape and depth over short periods of time (Trevor Munroe, personal communication). Therefore, the observed velocities in this shallow and dynamic area are highly affected by local climatology, detailed bathymetry, and the precise location of the current meter deployment, which cannot be easily prescribed in the model. Accordingly, the good agreement in the magnitude of the observed and simulated velocities rather than the directionality was deemed to be sufficient to validate the model.

Regarding Wine Harbour, the model was successfully able to simulate the water elevation within the harbour (Figure A6). In terms of water velocity, the model successfully predicted magnitude and direction right outside and in the innermost location of the harbour, as well as magnitude close to the entrance, but direction was not well predicted at this location (Figure A7). This mismatch could be caused by the same reasons mentioned for Sober Island given that the location close to the entrance is subjected to strong currents, influence by climatology, fine-scale bathymetry, and a precise deployment location. Furthermore, the North of the compass of the current meter flipped 180° at the end of the deployment. These data were not used for validation and it was ascribed to potential physical damage, but raises uncertainties regarding the compass. Therefore, more weight was put on the magnitude than on the directionality of this deployment. Finally, the model was able to successfully simulate both the tidal elevation (Figure A8) and magnitude and direction of water velocity (Figure A9) in the three current profiler deployments for Whitehead.

The calculation of water renewal time for the three embayments revealed differences among them, with Wine Harbour and Whitehead showing the shortest and longest time, respectively (Fig. 2). Sober Island and Wine Harbour presented similar patterns with most of the water body being renewed in under three days, and only small sections in the inner parts of the system having renewal times longer than 12 and 10 days for Sober Island (Fig. 2A) and Wine Harbour (Fig. 2B), respectively. In contrast, the renewal time at Whitehead is longer than 20 days for the innermost parts of the system (Fig. 2C). Whitehead is the only system with large oyster leases in areas with a renewal time longer than 3–4 days. Although no leases are present at the entrance of the system, the estimated water renewal time of under 1 day reveals a high exchange of water with the open ocean.

3.2. Current aquaculture scenarios

The Seston Reduction Index (SRI) calculations for Sober Island under the current aquaculture scenario revealed a maximum SRI of 50% at the head of the lagoon where the main oyster lease is located (Fig. 3A). The SRI was rapidly diluted following a spatial gradient towards the mouth of the lagoon where the second lease is located. Due to the proximity of the mouth, the SRI dropped to 18% in this lease. Under this scenario, the percentage of the bay with an SRI over 35%, which has been used as a proxy for ecological carrying capacity (see discussion), was 3.4% (Table 2). Considering the bay as a whole, the mean SRI was 15.6% (Table 2).

Regarding Wine Harbour under the current aquaculture scenario, the maximum SRI reached 42% in a small portion of the leased area on the western arm of the system (Fig. 3B). Due to the dimensions of the lease and its emplacement following the main longitudinal axis of the harbour, a strong SRI gradient was predicted, with a 10% SRI at the edge of the lease close to the mouth of the harbour. The predicted percentage of the bay with an SRI above 35% was 2.2%, and the mean bay-scale SRI averaged 20.1% (Table 2). The low percentage of the harbour with an SRI over 35% suggests a strong mixing within the system compared to Sober Island.

The size and complexity of Whitehead resulted in a very heterogenous system in terms of SRI (Fig. 3C). The maximum SRI of the three systems under current aquaculture scenarios was predicted for a small inlet on the Eastern side of Whitehead, reaching an SRI of 58%. This area of the embayment has a limited exchange of water with the open ocean. Furthermore, both connections with the main body of Whitehead have oyster leases, further increasing SRI. Accordingly, this area could be dominated by oyster filtration. The narrow arm on the Northern part of Whitehead was the second most affected area, with an SRI of 50%. The percentage of the bay with an SRI above 35% reached 12.1%, the highest of the three simulated systems (Table 2). However, due to the size and depth of Whitehead, the SRI at the bay-scale was the lowest of the three systems, averaging 9.2% (Table 2).

3.3. Development scenarios

A series of scenarios for the hypothetical expansion of the aquaculture operations were simulated (Table 2). In the case of Wine Harbour, and for the sake of comparison, some scenarios simulated a reduction in leased area. These simulations where the percentage of leased area is common for the three systems allows a better comparison of their performance under similar aquaculture pressure. It is important to note that the outcomes of the model could be affected by the position of the leases. The locations chosen for this hypothetical expansion followed the expected pattern based on current operations.

The location of new leases played a differential role in SRI dynamics depending on the site. For example, in the case of Sober Island, an increase of the leased area up to 20% of the lagoon would not affect the maximum predicted SRI compared to the current aquaculture scenario (Fig. 4A). Similarly, the new lease would only increase the percentage of area with an SRI above 35% up to 4.4%, and the bay-scale SRI would average 24.0% (Table 2). In Wine Harbour, the 20% leased area scenario implies a minimal reduction of the current operations, resulting in a very similar SRI distribution (Fig. 4B). Under this scenario, the whole system would be under the 35% SRI threshold, and the bay-scale SRI would average 18.9%, making Wine Harbour the least affected system in terms of SRI by the 20% development scenario (Table 2). Contrarily, Whitehead would be the most affected system by oyster filtration under the 20% development scenario. The development of new leases on the Western shore of Whitehead would cause localized SRI of 58% (Fig. 4C). The expansion would bring the percentage of the bay with an SRI over 35% up to 29.5%, and the bay-scale averaged SRI up to 28.7% (Table 2).

When summarizing all current and development scenarios (Table 2) in terms of averaged bay-scale SRI, the differences among systems emerge (Fig. 5A). In general, for the same level of development, Wine Harbour seems to be the system that is able to keep the bay-scale SRI at the lowest level; which is probably a consequence of having the main farming area close to the mouth of harbour, which ensures a quick renewal of water. Sober Island and Whitehead were similar; however, it is important to highlight that the pattern of bay-scale SRI with increasing leased area changed for both systems. While the SRI was lower at Whitehead than at Sober Island for the 10% development scenario, this was the opposite for the 20 and 30% scenarios, suggesting a larger effect of oyster filtration on seston dynamics at Whitehead compared to Sober Island under future and similar farming expansion.

3.4. Oyster stocking density

Given the uncertainty on aquaculture practices in terms of stocking density, all previous simulations were carried out

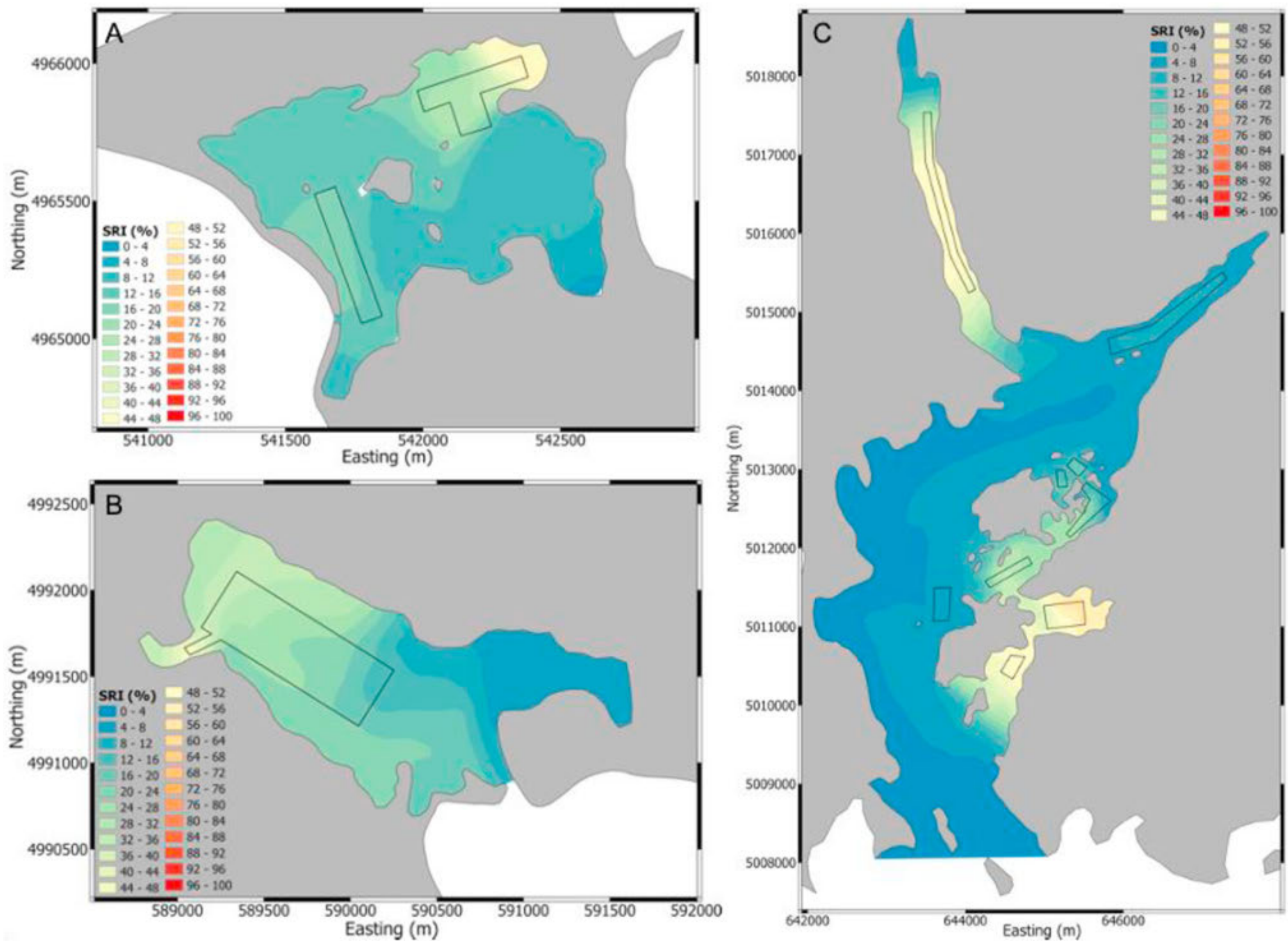

Fig. 3. Daily averaged Seston Reduction Index (SRI, %) using the standard aquaculture scenario in Sober Island Pond (A), Wine Harbour (B), and Whitehead (C). Current oyster leases in black polygons.

Table 2
Simulated scenarios in terms of percentage of leased area, total number of oysters using 25 oysters m^{-2}, and modelled Seston Reduction Index (SRI, %) summarized as a bay-scale average (mean, minimum, and maximum), and as the percentage of the bay with a SRI above 35%.

Embayment	Leased area (%)	Oysters (million)	Averaged Bay-scale SRI			Area with SRI > 35% (%)
			Mean (%)	Min (%)	Max (%)	
Sober Island	9.6	2.2	15.6	14.3	16.9	3.4
	10	2.2	15.6	14.3	16.9	3.4
	20	4.5	24.0	22.6	25.7	4.4
	30	6.7	34.6	32.0	37.7	46.6
Wine Harbour	21.7	10.6	20.1	19.5	21.0	2.2
	10	4.9	11.3	10.8	11.9	0.0
	20	9.7	18.9	18.3	19.7	0.0
	30	14.6	25.1	24.5	26.1	16.9
Whitehead	7.3	25.8	9.2	8.6	9.7	12.1
	10	35.3	11.5	11.0	12.2	12.8
	20	70.6	28.7	28.0	29.2	29.5
	30	105.9	36.6	35.8	37.4	47.9

assuming a constant density of 25 oysters m^{-2} for 57 mm oysters (Table 2). A worst-case scenario was further simulated increasing the density up to 37.5 oysters m^{-2} for the current farm coverage (Table 3). The effects of this increase in stocking density on seston dynamics was heterogeneous across the three systems. While the bay-scale averaged SRI increased more or less proportionally for the three systems, the percentage of the area with an SRI above the 35% threshold differed among embayments (Fig. 5B). The change caused by oyster density in the area with an SRI above 35% was steeper in Wine Harbour than in Sober Island and Whitehead, while the latter two followed a similar pattern. The change in Wine Harbour from 2.2% up to 24.6% with the increase in stocking density from 25 up to 37.5 oysters m^{-2} can be seen as a consequence of the already higher level of development in this system (i.e. coverage-wise). Furthermore, the change also highlights the relevance of aquaculture practices on seston dynamics.

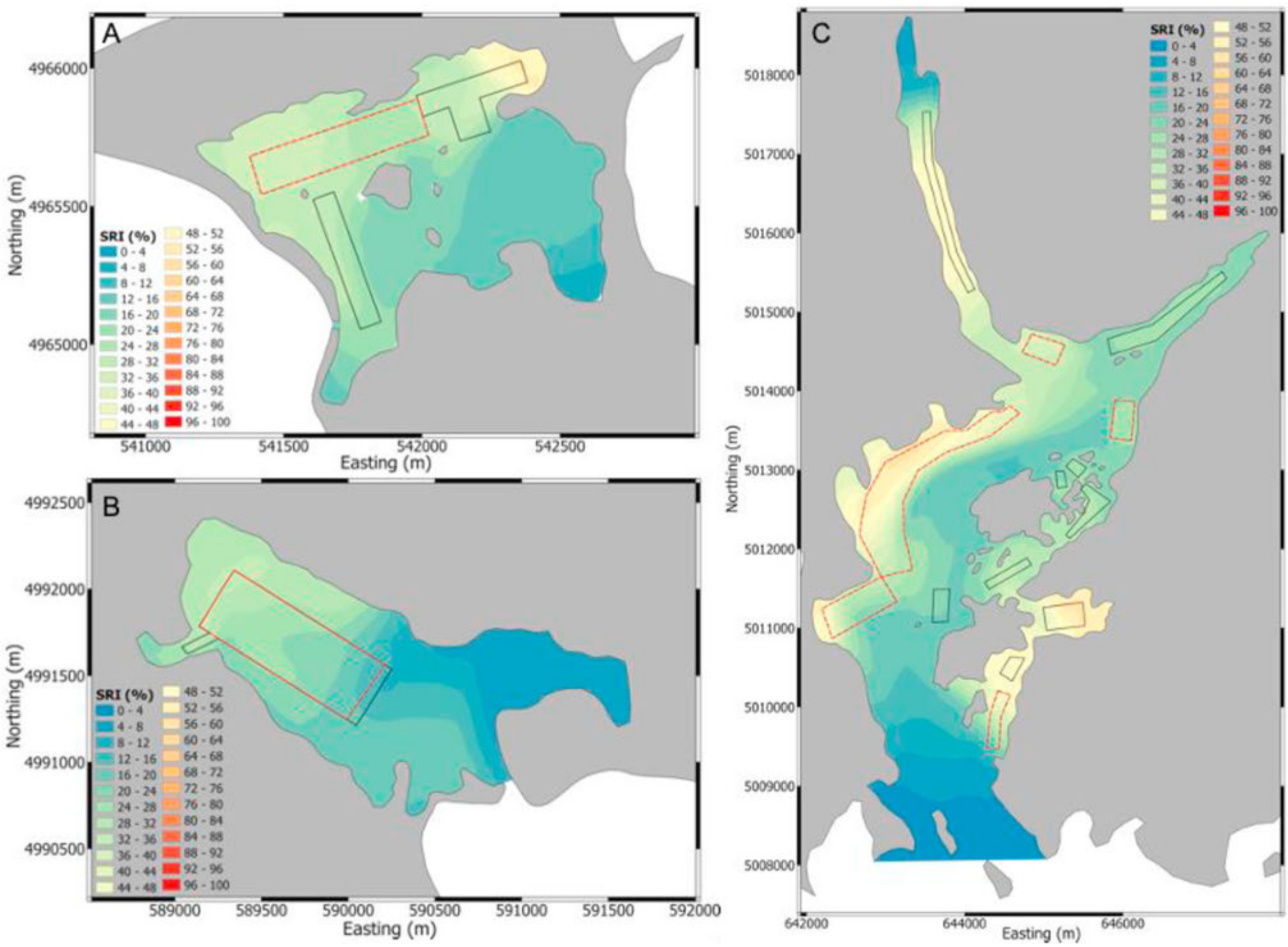

Fig. 4. Daily averaged Seston Reduction Index (SRI, %) using the development aquaculture scenario 20% in Sober Island Pond (A), Wine Harbour (B), and Whitehead (C). Current and hypothetical oyster leases are identified with black and red polygons, respectively. Note that the current lease in Wine Harbour is larger than 20%. Consequently, for the sake of comparison, the development lease implies a reduction in the current lease. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

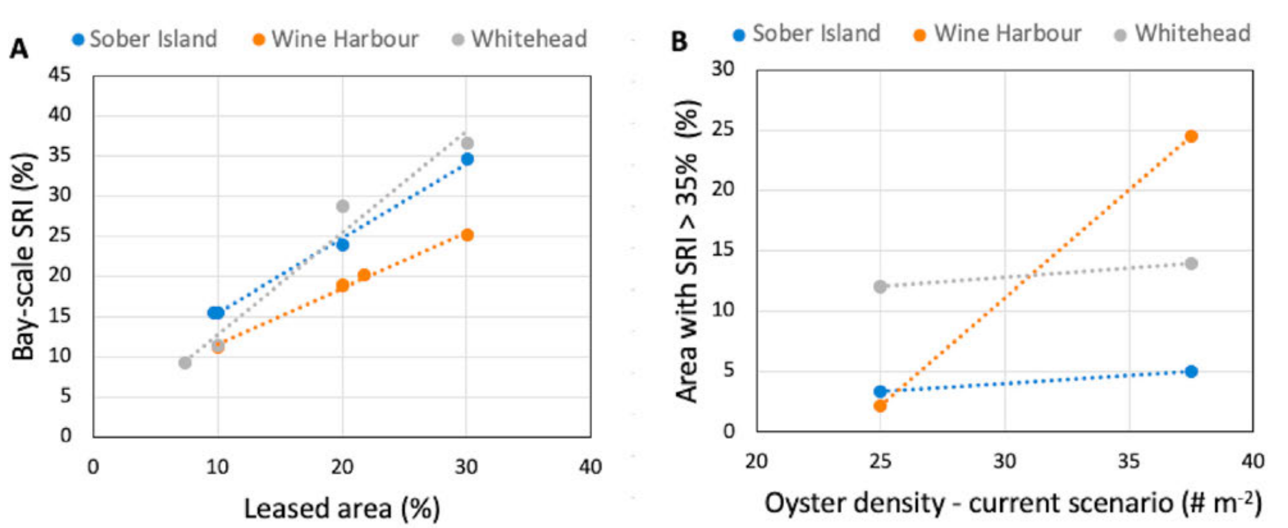

Fig. 5. Relationship between leased area (%) and bay-scale averaged Seston Reduction Index (SRI, %) for current and development aquaculture scenarios for the three embayments (A). Percentage of the bay with an SRI above 35% for the current aquaculture scenario in terms of leased area under different oyster stocking density for the three embayments (B). Dotted lines are for visualization purposes only.

Table 3
Simulated scenarios in terms of percentage of leased area, total number of oysters using 37.5 oysters m^{-2}, and modelled Seston Reduction Index (SRI, %) summarized as a bay-scale average (mean, minimum, and maximum), and as the percentage of the bay with a SRI above 35%.

Embayment	Leased area (%)	Oysters (million)	Averaged Bay-scale SRI			Area with SRI > 35% (%)
			Mean (%)	Min (%)	Max (%)	
Sober Island	9.6	3.2	20.3	18.7	21.9	5.0
Wine Harbour	21.7	15.9	26.2	25.4	27.4	24.6
Whitehead	7.4	38.6	11.5	10.8	12.3	14.0

Table 4
Percentage of change in Seston Reduction Index (SRI) when modifying the primary productivity and feeding rate by +10 and −10% under the current aquaculture scenario in terms of leased area and oyster density of 25 oysters m^{-2}.

Embayment	Primary productivity, α, +10%	Primary productivity, α, −10%	Feeding rate, β, +10%	Feeding rate, β, −10%
Sober Island	−2.0	+1.9	+6.7	−7.0
Wine Harbour	−1.2	+1.1	+6.8	−7.2
Whitehead	−1.4	+1.3	+5.4	−5.7
Average	−1.5	+1.4	+6.3	−6.6
Absolute average	1.5		6.5	

3.5. Sensitivity analysis

The sensitivity tests carried out to evaluate the impact of the most relevant parameters revealed that the influence was very similar across the three embayments (Table 4). As expected, the increase in primary productivity (+10%) and reduction in feeding rate (−10%) caused an average reduction in SRI of −1.5 and −6.6%, respectively. Similarly, the reduction in primary productivity (−10%) and increase in feeding rate (+10%) caused an average increase in SRI of +1.4 and + 6.3%, respectively. In absolute terms, the 10% change in primary productivity and feeding rate terms had an impact on SRI of 1.5 and 6.5%, respectively.

4. Discussion

The purpose of this study was to explore the effect of hydrodynamics on Ecological Carrying Capacity (ECC) estimations on oyster aquaculture sites using the simplest modelling approach that can precisely account for an accurate representation of a given embayment. The coupling of a three-dimensional FVCOM hydrodynamic model to a tracer model that represented the dynamics of organic seston using only two main parameters, namely primary productivity and oyster feeding rate, was determined as the simplest approach based on the scientific literature (Dowd, 2003; Guyondet et al., 2013; Filgueira et al., 2015). The outcomes of this modelling framework applied to three different embayments in Nova Scotia (Canada) revealed the relevance of water circulation on the ECC of the systems, suggesting that local hydrodynamics should be considered in leasing assessments.

The optimization of trade-offs in ecosystem modelling requires focusing on the key processes that drive most of the variance of the system. Focusing only on the primary productivity of the embayment and feeding rates limits the number of ecosystem-level interactions, but increases the operationalization of the method to data-poor environments where ecosystem level unknowns can jeopardize the parameterization of a complex ecosystem model. On the other hand, seston renewal is only dependent on local production and exchange with the open ocean, which limits other sources of food for the bivalves. For example, resuspension of organic matter or terrestrial inputs could be used by bivalves (Bacher and Gagnery, 2006), but they are neglected in this simple approach. Neglecting food sources could introduce uncertainty in the calculation of production carrying capacity due to the potential effect on bivalve growth. However, it should not constitute a major handicap for the estimation of ECC given that neglecting sources effectively acts as increasing sinks for organic seston, which represents the worst-case scenario for ECC estimations. Accordingly, the outcomes of the model should be understood as a theoretical simulation of relative changes of organic seston within the embayment with the ultimate aim of identifying the most sensitive areas affected by current bivalve aquaculture (e.g. Fig. 3) or hypothetical aquaculture scenarios (e.g. Fig. 4).

The fact that the assumptions of the model bias the outcomes towards representing the worst-case scenario could be considered an advantage when the goal is to generate management advice in the context of the precautionary principle. In the field of bivalve ECC, most of the ecosystem interactions to determine sustainability have been explored in the context of phytoplankton or seston utilization (see McKindsey, 2013). However, while most of these studies have discussed the implications of bivalve aquaculture on phytoplankton or seston dynamics, few of them have defined a quantitative threshold for ECC. Grant and Filgueira (2011) suggest that this threshold could be defined based on the bounds of natural variation of food availability. This threshold is grounded in the concept of ecological resilience by assuming that the natural variability of a component of the ecosystem sets the tipping points beyond which the resilience of the ecosystem is compromised. Accordingly, the natural variability of phytoplankton or seston concentration could be considered a precautionary threshold that preserves ecological sustainability (Grant and Filgueira, 2011). This threshold has been previously defined based on chlorophyll concentration, a proxy for phytoplankton concentration, by analyzing *in situ* and/or remotely-retrieved data using satellites and is established to be ~35% (average value from Filgueira and Grant (2009) Filgueira et al. (2013a, 2015), and Bricker et al. (2016)). Accordingly, an average SRI at the bay scale above 35% would indicate that the aquaculture activity could compromise the resilience of the ecosystem by impacting the dynamics of organic seston.

Using this threshold as a benchmark, the aquaculture levels carried out in the three embayments considered in this study are within the ecological carrying capacity, attending to the impact on organic seston. The model predicted that in some areas of the systems the filtration activity would cause a reduction of organic seston above this threshold, reaching values over 40% in all systems (Fig. 3). These values match previous studies carried out in other farming areas. For example, localized reductions in phytoplankton up to 45% and 72% were reported in mussel rafts in Galician Rías, Petersen et al. (2008) and Cranford et al. (2014), respectively. Similarly, reductions of 30% and 50% were measured in long-line mussel farms in Norwegian and Danish fjords (Strohmeier et al., 2005; Nielsen et al., 2016). While this localized reduction is relevant at the local scale due to potential negative effects on oyster growth, it could be argued that the reduction in a small area could be less relevant at the ecosystem scale. At the ecosystem scale, the three systems were below the 35% threshold (Table 2), which suggests that the feeding pressure of the aquaculture farms is not depleting the overall amount of organic seston in the embayments beyond a precautionary threshold. Looking at the embayment-scale rather than localized effects is recommended when aiming to manage in the context of an ecosystem approach to aquaculture (Soto et al., 2008). This is even more relevant when the criterion for ECC is affected by water circulation, given that the localized effects could spread beyond the domain of the farm.

A series of scenarios was carried out to explore the potential for expansion, and simultaneously compare the performance of the systems under the same level of aquaculture. The simulations suggest that moderate expansion of aquaculture on Sober Island and Whitehead is feasible and would not exceed the ECC of the system as the SRI would be under 35% (Table 2). However, the specific location of the leases during the expansion within each bay could greatly affect the bay scale SRI; accordingly, the scenarios generated in this study should be considered hypothetical situations to explore the performance of the systems rather than a plan for expansion. The simulations highlighted that the three embayments are different in terms of resilience capacity to hold oyster aquaculture, with Wine Harbour being the system that provided the lowest level of seston reduction under the same percentage of leased area (Table 2). Not surprisingly, Wine Harbour was the system with the shortest water renewal time (Fig. 2). It is well known that the dynamics of phytoplankton, a key component of organic seston and the main food source for bivalves (Bourlès et al., 2009; Rosland et al., 2011), are affected by water circulation, in turn affecting local production and advective exchange with the open ocean (Lucas et al., 1999; Paerl et al., 2006). Furthermore, it has been demonstrated that advection plays a critical role in ECC at bivalve aquaculture sites. Filgueira et al. (2013b) predicted an increase in the carrying capacity of Tracadie Bay (Prince Edward Island, Canada) for mussel aquaculture after a storm opened an additional breach in the barrier that protects the bay, shortening the water renewal time. The dynamics of bay barriers can be critical for Wine Harbour and Sober Island. As it was stated above, the highest uncertainty in the hydrodynamic model predictions were observed in the directionally of velocity at the entrance of both systems (Figure A5 and A7) due to the impact of coastal geomorphology and bathymetry on water circulation, and consequently organic seston advection. The uncertainty in directionality would be very relevant in farming areas because it would directly affect the propagation and location of the area affected by seston reduction, which could potentially result in an underestimation of SRI. The fact that the highest uncertainty in the hydrodynamic model occurs in the entrances of the system minimizes the impact on the predictions of the coupled model given that these areas do not suffer from high SRI. Nevertheless, further assessment of the condition of the bay barriers of these systems is important for bay-scale sustainability as they could impact the net exchange of water with the open ocean.

The bay-scale reduction in organic seston at Sober Island and Whitehead changed with the level of aquaculture development, with Whitehead being more resilient (lower SRI) than Sober Island at low aquaculture development but reversing this pattern at higher development (Fig. 5a). This outcome further exemplifies the relevance of coastal complexity and water circulation on the functioning of coastal systems. At low development, the size and depth of Whitehead could dominate the bay-scale assessment of ECC. However, at higher development, the shorter water residence time of Sober Island (Fig. 2) minimizes the reduction of seston by replenishing the seston faster than for Whitehead, resulting in a lower SRI (Fig. 5a). Another important aspect to consider is the heterogeneity within each system. The spatial complexity of Whitehead generates areas with different capacity to hold bivalves that are very close in terms of seaway distance, but very different in terms of water circulation, emphasizing the value of the spatially-explicit model for ECC estimations. This spatial heterogeneity not only affects the advection of seston, but it could also affect the local primary productivity, which is known to be influenced by horizontal transport (Lucas et al., 1999). Given the simplification adopted in this study, in which primary productivity is similar everywhere, the potential effects of local hotspots of primary production are not considered. Although the sensitivity test suggests that the uncertainty in primary productivity is smaller than the uncertainty in oyster feeding activity (Table 4), further refinement of the model could include a more precise spatial description of primary productivity.

5. Conclusions

The outcomes of this study are aligned with the broader literature highlighting the crucial role of water circulation for the functioning and resilience of coastal systems (Wolanski et al., 2004; Elliot and Whitfield, 2011), and particularly on bivalve aquaculture sites (e.g. Dame and Prins, 1998). The modelling framework used in this study allows for the exploration of ecological carrying capacity in bivalve aquaculture sites using the dynamics of organic seston as a benchmark. The application to Sober Island, Wine Harbour, and Whitehead suggests that the current aquaculture operations are within the ecological carrying capacity of the ecosystem for bivalve aquaculture. Given the differences among these three embayments in terms of water circulation, the model allowed to infer the relevance of spatial planning in aquaculture sites, suggesting that including a circulation model is critical for reliable estimations of carrying capacity. Although the model complexity could be increased to explore other ecosystem level effects, its simplicity could be considered a virtue for further operationalization, and consequently for informing aquaculture managers. The model has the capability to explore different aquaculture scenarios and inform the leasing process, which could be easily implemented in the context of marine spatial planning. The inherent limitations of a modelling exercise result in uncertainties during the decision-making process; however, this uncertainty could be overcome during the implementation stage by applying the precautionary principle to management. For example, a sensible recommendation for expansion would be a step-by-step expansion framed in the context of a robust monitoring program that ensures a sustainable development of the farming activity. In fact, the application of the precautionary principle should be cornerstone in all marine management processes that involve human intervention.

CRediT authorship contribution statement

Ramón Filgueira: Conceptualization, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Thomas Guyondet:** Conceptualization, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Pramod Thupaki:** Investigation, Methodology, Writing - original draft, Writing - review & editing. **Takashi Sakamaki:**

Investigation, Writing - review & editing. **Jon Grant:** Conceptualization, Funding acquisition, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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