Preliminary carrying capacity analysis of current and future aquaculture scenarios in Malpeque Bay (Prince Edward Island)

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2014

Canadian Technical Report of Fisheries and Aquatic Sciences 3081

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Canadian Technical Report of Fisheries and Aquatic Sciences

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Canadian Technical Report of
Fisheries and Aquatic Sciences 3081

2014

PRELIMINARY CARRYING CAPACITY ANALYSIS OF CURRENT AND FUTURE AQUACULTURE SCENARIOS IN MALPEQUE BAY (PRINCE EDWARD ISLAND)

by

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Cat. No. Fs97-6/3081E-PDF ISBN 978-1-100-23519-6 ISSN 1488-5379

Correct citation for this publication:

Filgueira, R., Guyondet, T., and L.A. Comeau. 2014. Preliminary carrying capacity analysis of current and future aquaculture scenarios in Malpeque Bay (Prince Edward Island) Can. Tech. Rep. Fish. Aquat. Sci. 3081: vii + 28 p.

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Mussel aquaculture in Prince Edward Island (PEI) has grown rapidly into a vital industry since the 1970s. Presently, however, there are very few sites in PEI where water is sufficiently deep to support new farming operations. There is also a societal consensus that any further development must be carried out in an ecologically-sustainable manner. Malpeque Bay on the northern side of the island has been identified as one of the last available areas for mussel culture expansion. The present study investigated the mussel carrying capacity of Malpeque Bay by means of computer modeling. A full spatial hydrodynamic-biogeochemical coupled model, integrating a series of known interactions between the cultured mussels and their environment, was developed. The main objective was to gauge the impact of current and future aquaculture scenarios on phytoplankton food resources (chlorophyll *a*). Preliminary results suggest the addition of new leases (870 ha) would not deplete phytoplankton resources in any part of the Malpeque system. However, the outcome also highlighted important aspects that must be accurately defined before a final and comprehensive assessment can be made. Among others, the impact of land-based nutrients on estuarine primary production, as well as the relevant role of the sea lettuce *Ulva* sp. as a potential sink of dissolved nutrients, should be addressed.

RÉSUMÉ

Filgueira, R., Guyondet, T., and L.A. Comeau. 2014. Preliminary carrying capacity analysis of current and future aquaculture scenarios in Malpeque Bay (Prince Edward Island) Can. Tech. Rep. Fish. Aquat. Sci. 3081: vii + 28 p.

L'essor de la mytiliculture à l'Île du Prince Édouard (IPE) depuis les années 1970 a fait de cette industrie un acteur majeur de l'économie locale. De nos jours, il ne reste que très peu de sites à l'IPE qui soient suffisamment profonds pour accueillir de nouvelles fermes mytilicoles. De plus, un consensus semble s'établir au sein de l'opinion publique pour que tout nouveau développement de cette industrie se fasse de façon durable. La Baie de Malpèque, située sur la côte nord de l'île, a été identifiée comme une des dernières régions disponibles pour une éventuelle expansion de l'activité mytilicole. L'objet de ce rapport est l'étude de la capacité de support de la Baie de Malpèque pour la mytiliculture par le biais de la modélisation numérique. Le modèle spatial du couplage hydrodynamique-biogéochimie qui a été développé, intègre les connaissances actuelles des interactions entre les moules de culture et leur environnement. Le principal objectif de cette étude était d'évaluer les impacts de l'activité conchylicole actuelle ainsi que d'un possible scénario d'expansion sur les ressources phytoplanktoniques (chlorophylle *a*). Les résultats préliminaires suggèrent que l'ajout de nouvelles concessions (870 ha) ne devrait réduire la disponibilté en nourriture phytoplanctonique dans aucune partie de la Baie de Malpèque. Toutefois, les résultats font également ressortir plusieurs aspects importants qu'il convient de décrire précisément avant d'aboutir à une évaluation complète et définitive. Parmi eux, l'influence des apports riverains de sels nutritifs sur la production primaire et également le rôle potentiel de la laitue de mer, *Ulva* sp., comme puits de sels nutritifs semblent nécessiter une attention particulière.

1.0. INTRODUCTION

While bivalve aquaculture provides ecosystem services that humans want and need, there are concerns that feeding activity and faeces production of cultured animals alter particle and nutrient fluxes in coastal ecosystems. Carrying Capacity (CC) allows the exploration of these effects, providing a framework to minimize potential alterations while maximizing bivalve growth and, consequently, aquaculture production. CC has been defined using four components: physical, ecological, production and social (McKindsey et al. 2006). Grant et al. (2007) and Grant and Filgueira (2011) have combined the ecological and production components into the following definition of CC: the bivalve stocking density at which growth is not food limited and some measure of ecosystem health is not compromised. Nevertheless, setting the acceptable limits that guarantee ecosystem health has been a challenge (Duarte 2003; Fisher et al. 2009). Recently, Filgueira et al. (2013) have suggested a framework to establish sustainable thresholds based on resilience thinking. This approach assumes that the most relevant trophic interaction, in this case shellfish feeding on phytoplankton, should remain within the bounds of natural variation, which in turn is assumed to be within the resilience tipping points (Figure 1). Keeping the state of the system within resilience tipping points guarantees ecosystem functioning and, consequently, ecosystem services. The use of natural variation as a precautionary management threshold is increasingly being employed to assess CC of bivalve aquaculture in Eastern Canada (e.g. Filgueira and Grant 2009; Filgueira et al. 2013, 2014).

The sustainability of bivalve aquaculture has been commonly evaluated based on the top-down trophic interaction of shellfish feeding on phytoplankton by means of the well-known concept of phytoplankton depletion (see Cranford et al. 2012). This concept assumes that excessive phytoplankton depletion can compromise coastal sustainability. However, the control of phytoplankton populations and the concomitant reduction of other seston particles can also improve water quality in eutrophicated environments (Landry 2002; Coen et al. 2007). Therefore, a comprehensive analysis of bivalve phytoplankton interaction must take into account both aspects: reduction of seston concentration, which could exert beneficial effects by mitigating eutrophication, as well as an excessive reduction that could lead to severe and negative phytoplankton depletion. This balance is critical in Prince Edward Island coastal embayments, which receive a significant amount of nutrients via river discharge that have triggered eutrophication related problems, such as anoxic events (Bugden et al. in press). The use of fertilizers in agricultural activities, as well as the increase of potato acreage in the 1990s (Cairns 2002), has led to an increase of nitrate concentration in freshwater in PEI (Bugden et al. in press). The discharge of nutrient-rich freshwater can lead to phytoplankton blooms and/or proliferation of macro-algae species in coastal estuaries. In fact, Meeuwig (1999) established an empirical relationship between estuarine chlorophyll and land-use patterns in PEI.

The Malpeque Bay system (Figure 1) is a large embayment composed of several basins emplaced in the North shore of PEI. An intricate river system discharges into Malpeque at several different points. The system is opened to the Gulf of St. Lawrence through multiple connections. The total area of Malpeque Bay is 19,640 ha of which 1,400 ha (~ 7%) are currently leased for shellfish aquaculture (Figure 2, PEI ALP 2013). The PEI Lease Management Board is currently engaged in a planning exercise regarding the potential addition of new mussel leases in Malpeque Bay. New lease applications represent a total area of 870 ha (Figure 3). Granting every application would augment the shellfish farming area to 11.6% of the total bay area. In this study, a fully spatial hydrodynamic-biogeochemical coupled model has been developed for the Malpeque system with the aim of assessing bivalve phytoplankton trophic interactions within this embayment. A hypothetical scenario has been constructed based on the PEI Lease Management Board (Fig. 3) in order to proactively evaluate the effects of new leases on phytoplankton dynamics and carrying capacity.

2.0. MATERIAL AND METHODS

2.1. Study area and available data

Five rivers were considered in the current model (Figure 4). River flows were obtained from Environment Canada (http://www.ec.gc.ca). Nutrient time series in these rivers were generated using the Department of Environment, Labour and Justice of PEI database (http://www.gov.pe.ca/environment). Multi-year data were pooled together in order to generate continuous time series that represent average conditions in the different rivers. Given that there is no nutrient data available for River 5 (Figure 4), the same values used for River 1 were used to force River 5. The uncertainty related to the lack of information on nutrients to force River 5 is discussed below.

Monthly temperature, chlorophyll, seston and nutrient samples were collected from 24 May to 20 November 2012 at four stations inside the bay (MQ1 – MQ4) and one external station (MQext) that was used as a boundary condition (Figure 2). Water samples for chlorophyll analyses were collected in duplicate. Samples were filtered through 25 mm Whatman GF/F filters, and then kept frozen (-20 ºC) until analysis, which was performed following EPA Method 445.0. Chlorophyll concentration was converted to carbon units assuming a carbon:chl of 50:1. Total Particulate Matter (TPM) was measured gravimetrically on pre-ashed (500 ºC, 4 h) 47 mm Whatman GF/F filters. Two replicates were collected at each sampling point. The filters were dried at 70 ºC for 24 h and weighed to determine the TPM. Particulate Organic Matter (POM) was determined after ashing the filters for 6 h at 500 ºC. The detrital carbon was calculated by multiplying the POM value by 0.5 and subtracting the phytoplankton carbon. Pre-filtered water samples (syringe filters, 0.8 μm) were analysed in duplicate at each station for nutrient concentrations with a Seal Automatic Analyser III (SEAL Analytical Inc., Mequon, Wisconsin, USA) and following the colorimetric methods described by Strickland

and Parsons (1972).

Mussel density was assumed to be 250 individuals per m^2 (Comeau et al. 2008) even though some leases were not fully utilized during the study period. A single cohort was simulated, assuming an initial length of 35 mm and total wet weight of 3.33 g. The fully-coupled model was run from 24 May 2012 to 7 October 2012 (137 days). The end of the simulated period was determined by the lack of river nutrient data beyond that date.

2.2. Hydrodynamic model

A two-dimensional, vertically-averaged finite element model was developed for Malpeque Bay using the RMA suite of models (http://ikingrma.iinet.net.au). This model was used to reproduce water circulation within Malpeque Bay in response to tidal, meteorological (wind and atmospheric pressure) and river forcing. RMA-10 solves the Reynolds form of the Navier-Stokes equations for momentum, the continuity equation and a convection-diffusion equation for transport of heat, salinity and any dissolved or suspended matter. The triangular mesh for Malpeque Bay contained 11,488 nodes and 5,171 triangles.

Instruments were moored during summer-fall 2011 (August 19 to November 16) at different locations both outside and inside the bay in order to collect the necessary data to respectively force and validate the model. Sea level fluctuations forcing the hydrodynamic model were recorded using tide gauges (Water Level Data HOBO Logger, Onset Computer Corporation Inc. Bourne, MA, USA) at outside stations L1 and L2 located off-shore of the two main inlets and at the connection with Cascumpec Bay (L6, Figure 2). Inner stations (LC3, L4, L5, L7 and L8) shown on Figure 2 were equipped with HOBO tide gauges and one of them (LC3) with a current meter (Workhorse Sentinel, Teledyne RD Instruments, Poway, CA, USA) and were used for validation purposes. Meteorological data were retrieved from the Environment Canada station located in Summerside, 10 km south of the study site. No active gauges were deployed on the rivers during the study period. Hence, freshwater discharge rates were derived from the Environment Canada station (01CC002) on Winter River (60 km east of the study area) to which the adequate watershed ratios were applied.

Once validated, the model was run under tidal and river forcing only to derive information on long term circulation required for the coupling with the biogeochemical model.

2.3. Biogeochemical model

The hydrodynamic model developed in RMA-10 was coupled to a biogeochemical model constructed in Simile (http://www.simulistics.com) following Filgueira et al. (2012). Three conservative tracer experiments were carried out to evaluate the performance of the coupling scheme. The biogeochemical model (Figure 5) was based on Grant et al. (1993, 2007, 2008), Dowd (1997, 2005) and Filgueira and Grant (2009) but the Scope For Growth mussel submodel has been substituted by the Dynamic Energy Budget (DEB) model described in Rosland et al. (2009) and Filgueira et al. (2011). The model contains the following submodels, Phytoplankton (P), Nutrients (N), Detritus (D) and Mussel (M), which follow (Table 1):

$$\frac{dP}{dt} = +P_{growth} - P_{mortality} - M_{grazing} \pm P_{mixing} \qquad \text{Eq. 1}$$

$$\frac{dN}{dt} = +N_{river} + D_{remineralization} + M_{excretion} - P_{uptake} \pm N_{mixing} \qquad \text{Eq. 2}$$

$$\frac{dD}{dt} = +D_{resuspension} + M_{feces} + P_{mortality} - D_{sinking} - D_{remineralization} \pm D_{mixing} \qquad \text{Eq. 3}$$

$$\frac{dM}{dt} = +M_{grazing} - M_{excretion} - M_{feces} \qquad \text{Eq. 4}$$

The model is characterized in terms of mg C m^{-3}, with the exception of dissolved nutrients, which are expressed in mg N m^{-3}. A value of 1.3 µg chla l^{-1} was used for the half-saturation coefficient of the food ingestion function, X_K, the only parameter that is site-specific in this version of mussel DEB.

Given that there are no direct estimations of primary productivity in Malpeque, *in situ* values collected at a nearby location, Tracadie Bay, were used. Both bays share the same latitude, which is crucial for the daily light cycle and therefore for primary production. Primary production patterns in both locations were compared using satellite imagery. Monthly time-series of the mean net primary productivity for Malpeque and Tracadie Bay were constructed using monthly averages of global 9 km net primary productivity imagery obtained from the Ocean Productivity website for both locations (Behrenfeld and Falkowski 2007, www.science.oregonstate.edu/ocean.productivity/index.php). Both satellite-generated time series followed the same pattern (Figure 6) and consequently *in situ* Tracadie Bay values were directly used in this exercise. Nevertheless, preliminary results of the model reported extremely high values of chlorophyll, which could be related to the extrapolation of primary productivity and/or nutrient levels, which also showed higher values than expected. The high values in chlorophyll and nutrients were partially corrected by increasing phytoplankton mortality, which reduced chlorophyll concentration. This tuning also reduced nutrients, which were removed from the system via phytoplankton sedimentation and burial. This model adjustment is discussed below.

2.4. Depletion/enrichment indices

Depletion/enrichment indices (%) for nutrients, chlorophyll and POM were calculated according to Filgueira et al. (2014):

$$\text{Depletion/enrichment index} = \frac{[X]_i}{[X]_{\text{far field}}} \times 100 - 100 \qquad \text{Eq. 5}$$

where $[X]_i$ and $[X]_{\text{far field}}$ are nutrient, chlorophyll or POM concentration in the *i* element and far field, respectively. Values below 0% indicate depletion and above 0% indicate enrichment of X in the *i* element compared to the far field.

3.0. RESULTS

3.1. Hydrodynamic model validation

The hydrodynamic validation was based on the comparison of observations and model results in terms of water levels and currents at all inner stations. As shown on Figure 7 a good agreement was reached for both currents along their principal axis (C3) and water levels all around Malpeque Bay. The model explains more than 80% of the total variance in water level fluctuations at all stations except L8 (Table 2). River 3 influence at this station may not be well enforced by the river discharge imposed in the model as it was not derived from observations made for this particular river (see Method section for details). Overall these results suggest that the model captures the main features of the hydrodynamics of the bay and its exchange with the Gulf of St. Lawrence. Moreover, tidal propagation within the system is well reproduced by the model as shown by the results of the harmonic analysis (Foreman 1977) of observed and predicted water level time series at all inner stations (Table 2). This result is of particular importance for the present work as tides were the main forcing considered in the coupling of the hydrodynamic and biogeochemical models.

3.2. Hydrodynamic – biogeochemical model coupling validation

A simple test was carried out to determine if Simile is correctly assimilating the hydrodynamics generated by RMA. Both Simile and RMA models were set up in the same way to run a simulation in which a conservative tracer was the only component of the model. Assuming a constant concentration of the tracer at the boundaries and river and a homogeneous distribution inside the bay at the beginning of the simulation, the models were run for a certain period of time and the tracer distribution in Simile and RMA were compared. Tracer concentration in the model domain after 30 days is presented in Figures 8, 9 and 10 for the three conservative tracer experiments that were carried out. In general, the comparisons of RMA and Simile plots showed a good agreement in the main water body. The larger discrepancies were located in the mouths of the rivers. For example, in the second tracer experiment (Figure 9) RMA simulations showed a steeper gradient than Simile. This is related to the different way in which RMA and Simile define river discharge. Due to the characteristics of the coupling scheme, Simile requires several elements to define river boundary, while in RMA a single element can be used to define this boundary. Nevertheless, these differences were rapidly diluted downstream and the tracer concentration became similar in both simulations in the critical areas of the system, that is, where the culture is located.

3.3. Field observations

Field sampling indicated that Malpeque is a well-mixed system in term of nutrients, chlorophyll and POM (Fig 11a, c and e respectively). In most samplings the standard deviations of the measurements from different stations overlapped. Regarding nutrient availability (Figure 11a), the four stations inside the bay as well as the boundary followed a similar pattern. Two exceptions are stations MQ1 and MQ4, the closest stations to aquaculture site: in the last sampling (20th November) extremely high values were observed.

High variability in chlorophyll concentration was observed among the bay stations in the different samplings, especially in August and September (Figure 11c), the months with highest values. The most significant feature in the dataset was the pattern at the boundary, which followed a different trend than the stations inside the bay. The values at the boundary were lower than inside the bay from May to September (MQext, Figure 11c), which resulted in consistent chlorophyll enrichment in the bay stations compared to the boundary (MQext, Figure 11d). MQ4, which is close to an aquaculture site, showed the highest enrichment, a surprising result because chlorophyll depletion forced by bivalve filtering activity was expected in the proximity of aquaculture sites.

Spatial or temporal patterns in POM were not clearly observed (Figure 11e). A concentration of approximately 2.3 mg l^{-1} summarizes POM conditions over space and time. The differences among inner stations and the far field were lower (Figure 11f) than the observed for nutrients and chlorophyll. In this regard and in the same way as for chlorophyll, MQ4 showed the highest enrichment in POM.

3.4. Modeling of current scenario

The model was not able to simulate the observed absolute values of nutrients, chlorophyll and POM. Nevertheless, the model coarsely reproduced enrichment patterns within the system (Figure 11b, d, f). For example, the model was able to reproduce the nutrient enrichment pattern observed at aquaculture vs non-aquaculture sites. Predictions for stations MQ1 and MQ4, close to aquaculture sites, suggested enrichment compared to non-aquaculture sites, stations MQ2 and MQ3, albeit the predicted enrichment was substantially higher than observed

(Figure 11b). The best agreement between modeled and observed values was obtained with chlorophyll (Figure 11d), even though the model overestimated chlorophyll enrichment at the non-aquaculture sites (stations MQ2 and MQ3) and underestimated it at aquaculture sites (Figure 11d). Given that the spatial and temporal variability in POM values was lower than for nutrients and chlorophyll, the absolute discrepancies in POM enrichment between model and observations were lower (Figure 11f). The model was able to explain the spatial pattern with the exception of station MQ3, in which POM enrichment is predicted but the observations suggested depletion compared to boundary values (MQext, Figure 11f).

The spatial distribution of chlorophyll enrichment (Figure 12) highlighted the significant influence of river discharge on phytoplankton dynamics. Rivers, which are important sources of nutrients, triggered steep gradients in chlorophyll concentration, with high values close the mouth that became rapidly diluted downstream. The main water body of the system was quite homogeneous in terms of chlorophyll and only the dense farming areas located in the northeast of the bay showed lower chlorophyll concentration than the inner part of the bay. This lower enrichment followed the expected pattern caused by mixing of inner chlorophyll-rich waters and lower chlorophyll values at the far field. This pattern could also have been intensified due to the filtration activity of mussel populations, which are located in the proximity of the main open boundary.

3.5. Modeling a future scenario

The effect of new leases (see Figure 3) on chlorophyll concentration is shown in Figure 13. According to the model new leases would not deplete phytoplankton resources in any part of the Malpeque system. New leases would only curtail chlorophyll enrichment within the system. This effect can be seen by the lowest enriched area located close to the main mouth of the bay being extended towards the West. New leases #12, 17 and 52 would cause the highest local change, attenuating the enrichment in the Western part of the system. The enrichment close to River 4 would also be attenuated by the inclusion of the new leases in the model.

4.0. DISCUSSION

This study presents the results of a fully-spatial physical-biochemical coupled model that has been configured to explore mussel carrying capacity of the Malpeque Bay system. The current model has been successfully applied to several bays in Atlantic Canada (Filgueira and Grant 2009; Filgueira et al. 2013, 2014). However, the results obtained for Malpeque present a high level of uncertainty. The model was not able to reproduce observed time series and averaged conditions presented some mismatches (Figure 11b, d and f). Such an outcome was obtained despite our effort to adjust the model core. More precisely, phytoplankton mortality was initially increased in an attempt to improve results. However, based on our present knowledge of Malpeque Bay, there is no objective rationale for modifying phytoplankton mortality. Phytoplankton mortality was chosen to tune the model because in preliminary simulations it seemed that the system was also enriched in nutrients. Therefore phytoplankton mortality allowed for a simultaneous control of phytoplankton populations but also removal of nutrients from the system via sedimentation and burial of dead phytoplankton cells. Other alternatives, such as altering primary productivity and/or nutrient availability could perhaps be considered in future modeling exercises for this embayment.

Several other factors may explain the lack of agreement between field observations and predicted values. Known sources of uncertainty in the dataset as well as in the model design are as follow:

- Meteorological forcing was not included in the hydrodynamic-biogeochemical coupled model, which might explain part of the spatial/temporal discrepancy between model and observations. Although meteorological forcing represents a source of uncertainty, it is unlikely that it alone can explain the substantial mismatches reported in this paper.
- It has previously been demonstrated that the tidal cycle is crucial for phytoplankton dynamics in dense bivalve aquaculture areas. Grant et al. (2008) observed a different spatial pattern in phytoplankton carbon concentration when longitudinal transects were carried out in Tracadie Bay during ebb, high and low tide. The four sampling stations inside Malpeque Bay, as well as the boundary station were collected during the same day. The time required for collecting the samples and moving to the next station could be significant, biasing the comparison of observations among stations.
- High nutrient levels could be related to our characterization of river discharge. First, nutrient concentration in rivers was characterized using multi-year samplings carried out by the Department of Environment, Labour and Justice of PEI, but they are not specific for 2012. In addition, data for River 5 were extrapolated from River 1, which inherently introduced uncertainty into the modelling results. Secondly, river nutrients were not necessarily measured precisely where river gauges were located, which can undoubtedly lead to a wrong estimation of total nutrients discharge. These two sources of uncertainty could have erroneously increased nutrient levels in the bay. However, the rivers with a watershed smaller than 25 km^2 have not been included in the model for simplification. Although these are the smallest rivers that empty in Malpeque and theoretically the smallest sources of riverine nutrients, this simplification inherently leads to an imbalance in the spatial distribution of nutrient inputs and an underestimation of the total discharge of nutrients.
- The model has been successfully applied to different bays in Atlantic Canada; however, this does not guarantee that the same set of

parameters can be applied to every location. For example, remineralization, primary productivity, phytoplankton mortality, sinking rates and/or fouling activity, among others, could differ significantly among proximate bays. Similarly, DEB parameters could require adjustments to reflect local conditions. The set of parameters that was used in this study has been previously used in Tracadie Bay. However, X_K, the half-saturation constant, needs to be calibrated for every location (Filgueira et al. 2011). Although major differences are not expected between Tracadie Bay and Malpeque, a fine-tuning of DEB may improve predictions.

- Phytoplankton productivity is limited by nitrogen in the current version of the model, an assumption that perhaps needs to be revisited due to high nutrient availability and the effects of turbidity observed in Malpeque (See Figure 5 and Table 6 in Meeuwig et al. 1998). Turbidity generally reduces primary productivity by limiting light availability in the water column, particularly in the deeper areas of the system. In addition, iron-rich soils of PEI (MacDougall et al. 1988) could trap phosphorus by adsorption, limiting the availability of this nutrient for phytoplankton (Meeuwig et al. 1998). The direct effect of turbidity on light limitation as well as the indirect control of phosphorous availability could be necessary inputs for the model in order to successfully simulate phytoplankton and nutrient dynamics.
- The model includes phytoplankton as the only primary producer, yet in PEI embayments the growth of the sea lettuce *Ulva* sp. could play an important role on productivity and nutrient dynamics (Raymond et al. 2002; Bugden et al. in press). Macroalgae can be the dominant producer in shallow temperate estuaries (Valiela et al. 1997). Raymond et al. (2002) reported that sea lettuce populations typically occur at freshwater entry points to the estuary, precisely the areas in which our model predicts extremely high enrichment of chlorophyll (Figure 12 and 13). The presence of *Ulva* sp.in the model could minimize this enrichment and constitute a sink for nutrients via sedimentation and decomposition of rotting sea lettuce in the benthic environment (Bugden et al. in press).

In conclusion, it is noteworthy that Malpeque Bay is the largest coastal embayment of PEI. Its current lease coverage, 7%, is significantly below that in other bays such as Tracadie Bay or St. Peter's Bay, with approximately 39 and 36% coverage, respectively. This difference may be crucial to the understanding ecosystem functioning and specifically nutrient, phytoplankton and bivalve dynamics. In intensive culture areas, bivalve feeding activity can control phytoplankton populations (Dame and Prins 1998) and bivalve excretion can accelerate the turnover of phytoplankton (Cranford et al. 2007). In addition, filtration activity in intensive culture areas can reduce water turbidity (Landry 2002), which in turn can enhance primary productivity (Meeuwig et al. 1998). Ecosystem functioning is very sensitive to the bivalve submodel in intensive culture areas such as Tracadie Bay (e.g. Filgueira and Grant 2009) and St. Peter's Bay (T. Guyondet, unpublished data). However, in Malpeque Bay, where bivalve aquaculture is less developed, other parameters such as phytoplankton mortality, turbidity and/or the presence of *Ulva* sp. populations may be crucial for understanding the system.

With the current state of knowledge of Malpeque Bay it seems that the increase of aquaculture acreage, 870 ha, proposed in Figure 3 would not cause major changes in ecosystem functioning compared to the current scenario. However, given the uncertainties discussed above, further research is necessary to improve prediction capabilities of the model.

5.0. ACKNOWLEDGEMENTS

The authors gratefully acknowledge Rémi Sonier, Arthur Smith, Thomas Landry, and Lori Cuddy for input and advice at various stages of the project. Thanks are also due to Tina Sonier and André Nadeau for their assistance in the field and in the lab. This project was funded by DFO's Program for Aquaculture Regulatory Research (PARR project 2011-G-04).

6.0. REFERENCES

Behrenfeld, M.J., and Falkowski, P.G. 1997 Photosynthetic Rates Derived from Satellite-Based Chlorophyll Concentration. Limnol. Oceanogr. 42: 1-20.

Bugden, G., Jiang, Y., van den Heuvel, M.R., Vandermeulen, H., MacQuarrie, K.T.B., Crane, C.J. and Raymond, B.G. Nitrogen Loading Criteria for Estuaries in Prince Edward Island. Can. Tech. Rep. Fish. Aquat. Sci. in press.

Cairns, D.K. 2002. Effects of land use practices on fish, shellfish, and their habitats on Prince Edward Island. Can. Tech. Rep. Fish. Aquat. Sci. No. 2408. 157p.

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H, Powers, S.P., and Tolley, S.G. 2007. Ecosystem services related to oyster restoration. Mar. Ecol. Prog. Ser. 341: 303-307.

Comeau, L.A., Drapeau, A., Landry, T., and Davidson, J. 2008. Development of longline mussel farming and the influence of sleeve spacing in Prince Edward Island, Canada. Aquaculture 281: 56-62.

Cranford, P.J., Kamermans, P., Krause, G., Mazurié, J., Buck, B.H., Dolmer, P., Fraser, D., Van Nieuwenhove, K., O'Beirn, F.X., Sanchez-Mata, A., Thorarinsdótir, G.G., and Strand, Ø. 2012. An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts. Aquacult. Environ. Interact. 2: 193-213.

Cranford, P.J., Strain, P.M., Dowd, M., Hargrave, B.T., Grant, J., and Archambault, M.C. 2007. Influence of mussel aquaculture on nitrogen dynamics in a nutrient enriched coastal embayment. Mar. Ecol. Prog. Ser. 347: 61-78.

Dame, R.F., and Prins, T.C. 1998. Bivalve carrying capacity in coastal ecosystems. Aquat. Ecol. 31: 409-421.

Dowd, M. 1997. On predicting the growth of cultured bivalves. Ecol. Model. 104: 113-131.

Dowd, M. 2005. A bio-physical coastal ecosystem model for assessing environmental effects of marine bivalve aquaculture. Ecol. Model. 183: 323-346.

Duarte, P. 2003. A review of current methods in the estimation of environmental carrying capacity for bivalve culture in Europe. *In* Determining environmental carrying capacity of coastal and marine areas: progress, constraints and future options. Edited by H. Yu and N. Bermas. PEMSEA Workshop Proceedings No. 11. pp. 37-51.

Filgueira, R., and Grant, J. 2009. A box model for ecosyste-level management of mussel culture carrying capacity in a coastal bay. Ecosystems 12: 1222-1233.

Filgueira, R., Grant, J., Bacher, C., and Carreau, M. 2012. A physical-biochemical coupling scheme for modeling marine coastal ecosystems. Ecol. Inform. 7: 71-80.

Filgueira, R., Grant, J., Stuart, R., and Brown, M.S. 2013. Operational models for Ecosystem-Based Management of bivalve aquaculture sites in data-poor environments. Aquacult. Environ. Interact. 4: 117-133.

Filgueira, R., Guyondet, T., Comeau, L.A., and Grant, J. 2014 Physiological indices as indicators of ecosystem status in shellfish aquaculture sites. Ecol. Indic. 39: 134-143.

Filgueira, R., Rosland, R., and Grant, J. 2011. A comparison of Scope For Growth (SFG) and Dynamic Energy Budget (DEB) models applied to the blue mussel (*Mytilus edulis*). J. Sea Res. 66: 403-410.

Fisher, J., Peterson, G.D., Gardner, T.A., Gordon, L.J., Fazey, I., Elmqvist, T., Felton, A., Folke, C., and Dovers, S. 2009. Integrating resilience thinking and optimization for conservation. Trends Ecol. Evol. 24(10): 549-554.

Foreman, M.G. 1977. Manual for tidal heights analysis and previsions. Pacific Marine Science Report 77-10.

Grant, J., Bacher, C., Cranford, P.J., Guyondet, T., and Carreau, M. 2008. A spatially explicit ecosystem model of seston depletion in dense mussel culture. J. Mar. Syst. 73: 1555-1568.

Grant, J., Curran, K.J., Guyondet, T.L., Tita, G., Bacher, C., Koutitonsky, V., and Dowd, M. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entrée, iles-de-la-Madeleine, Québec. Ecol. Model. 200: 193-206.

Grant, J., Dowd, M., Thompson, K., Emerson, C., and Hatcher, A. 1993. Perspectives on field studies and related biological models of bivalve growth and carrying capacity. *In* Bivalve Filter Feeders in Esluarine and Coastal Ecosystem Processes. Edited by R.F. Dame. Springer- Vedag. Berlin NATO ASI Series. 33, pp. 371-420.

Grant, J., and Filgueira, R. 2011. The application of dynamic modelling to prediction of production carrying capacity in shellfish farming. *In* Shellfish aquaculture and the environment. Edited by S. Shumway. Wiley-Blackwell Science Publishers. Ames, Iowa, pp. 135-154.

Landry, T. 2002. The potential role of bivalve shellfish in mitigating negative impacts of land use on estuaries. *In* Effects of Land Use Practices on Fish, Shellfish and Their Habitats on Prince Edward Island. Edited by D.K. Cairns. Can. Tech. Rep. Fish. Aquat. Sci. 2408. pp. 155-157.

MacDougall, J., Veer, C., and Wilson, F. 1988. Soils of PrincevEdward Island: Prince Edward Island Soil Survey No. 83-54. Ministry of Supply and Services, Ottawa.

McKindsey, C.W., Thetmeyer, H., Landry, T., and Silvert, W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. Aquaculture 261: 451-462.

Meeuwig, J.J. 1999. Predicting coastal eutrophication from land-use: an empirical approach to small non-stratified estuaries. Mar. Ecol. Prog. Ser. 176: 231-241.

Meeuwig, J.J., Rasmussen, J.B., and Peters, R.H. 1998. Turbid waters and clarifying mussels: their moderation of empirical chl:nutrient relations in estuaries in Prince Edward Island, Canada. Mar. Ecol. Prog. Ser. 171: 139-150.

PEI ALP (Prince Edward Island Aquaculture Leasing Program). 2013. Advancing mussel aquaculture in Malpeque Bay, Prince Edward Island. Draft consultation strategy for the development of a mussel aquaculture spatial plan. Fisheries and Oceans Canada

Raymond, B.G., Crane, C.S., and Cairns, D.K. 2002. Nutrient and chlorophyll trends in Prince Edward Island estuaries. *In* Effects of Land Use Practices on Fish, Shellfish and Their Habitats on Prince Edward Island. Edited by D.K. Cairns. Can. Tech. Rep. Fish. Aquat. Sci. 2408. pp. 142-153.

Rosland, R., Strand, Ø., Alunno-Bruscia, M., Bacher, C., and Strohmeier, T. 2009. Applying Dynamic Energy Budget (DEB) theory to simulate growth and bio-energetics of blue mussels under low seston conditions. J. Sea Res. 62: 49-61.

Strickland, J.D.H., and Parsons, T.R. 1972. A practical handbook of seawater analysis. Fisheries research board of Canada, Vol 167.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., and Foreman, K. 1997. Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. Limnol. Oceanogr. 42: 1105-1118.

Table 1. Ecosystem model terms.

Term	Definition	Reference
dP/dt	Phytoplantkton change rate (mgC m^{-3} d^{-1})	
P_{growth}	Phytoplankton growth	Eq. 7 in Grant et al. (2007)
$P_{mortality}$	Phytoplankton mortality	
$M_{grazing}$	Mussel grazing on phytoplankton	
P_{mixing}	Exchange of phytoplankton with adjacent elements and/or far field	
dN/dt	Nitrogen change rate (mgN m^{-3} d^{-1})	
N_{river}	Nitrogen river discharge	River discharge x River Nitrogen concentration
$D_{remineralization}$	Detritus reminiralization	See Dowd (2005)
$M_{excretion}$	Mussel nitrogen excretion	Eq. 17 in Grant et al. (2007)
P_{uptake}	Phytoplankton nitrogen uptake	Eq. 15 in Grant et al. (2007)
N_{mixing}	Exchange of nitrogen with adjacent elements and/or far field	
dD/dt	Detritus change rate (mgC m^{-3} d^{-1})	
$D_{resuspension}$	Detritus resuspension forced by wind	See Filgueira and Grant (2009)
M_{feces}	Mussel feces production	Eq. 5 in Grant et al. (2007)
$P_{mortality}$	Phytoplankton mortality	See above
$D_{sinking}$	Detritus removal by sinking	Eq. 5 in Grant et al. (2007)
$D_{remineralization}$	Detritus remineralization	See text
D_{mixing}	Exchange of detritus with adjacent elements	
dM/dt	Mussel change rate (mgC m^{-3} d^{-1})	
$M_{grazing}$	Mussel grazing on phytoplankton	DEB model (Rosland et al., 2009; Filgueira et al., 2011)
$M_{excretion}$	Mussel nitrogen excretion	
M_{feces}	Mussel feces production	

Table 2: Harmonic analysis of observed and predicted water level time series with 95% confidence intervals for the three main tidal constituents (O1, K1 and M2) and fraction of the total variance of observed level fluctuations explained by the model at all sampled stations inside the domain.

	Amplitude (m)		Phase (°)			Amplitude (m)		Phase (°)	
	Observed	Predicted	Observed	Predicted		Observed	Predicted	Observed	Predicted
	O1					**K1**			
LC3	0.17 ± 0.05	0.17 ± 0.06	248.1 ± 13.0	240.1 ± 18.0	LC3	0.17 ± 0.05	0.15 ± 0.05	285.6 ± 17.2	278.6 ± 21.6
L4	0.16 ± 0.05	0.17 ± 0.04	262.6 ± 19.4	254.5 ± 16.9	L4	0.15 ± 0.05	0.16 ± 0.04	299.5 ± 21.3	293.1 ± 17.4
L5	0.17 ± 0.05	0.17 ± 0.05	249.8 ± 21.4	252.5 ± 19.4	L5	0.17 ± 0.06	0.17 ± 0.06	284.9 ± 22.7	292.1 ± 20.6
L7	0.17 ± 0.06	0.18 ± 0.06	251.5 ± 21.3	251.5 ± 19.4	L7	0.17 ± 0.07	0.16 ± 0.06	289.2 ± 19.9	294.2 ± 18.8
L8	0.17 ± 0.07	0.17 ± 0.06	254.7 ± 20.5	257.4 ± 15.3	L8	0.17 ± 0.06	0.16 ± 0.05	289.2 ± 24.3	300.3 ± 19.4
	M2					**Variance explained (%)**			
LC3	0.14 ± 0.04	0.15 ± 0.04	205.6 ± 14.1	195.6 ± 14.7	LC3	93.7			
L4	0.12 ± 0.04	0.12 ± 0.04	231.9 ± 14.7	213.3 ± 21.2	L4	84.2			
L5	0.18 ± 0.05	0.16 ± 0.04	217.0 ± 15.6	222.1 ± 13.3	L5	88.9			
L7	0.18 ± 0.04	0.17 ± 0.04	218.8 ± 15.0	220.1 ± 15.3	L7	89.5			
L8	0.18 ± 0.05	0.16 ± 0.05	226.2 ± 16.3	232.8 ± 15.7	L8	77.0			

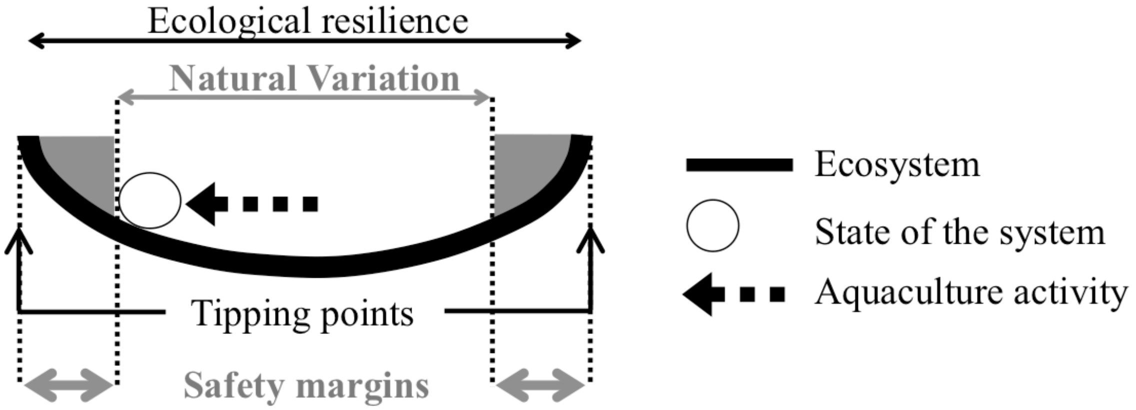


Figure 1. Scheme of natural variation in the context of ecological resilience (see text for further explanation).

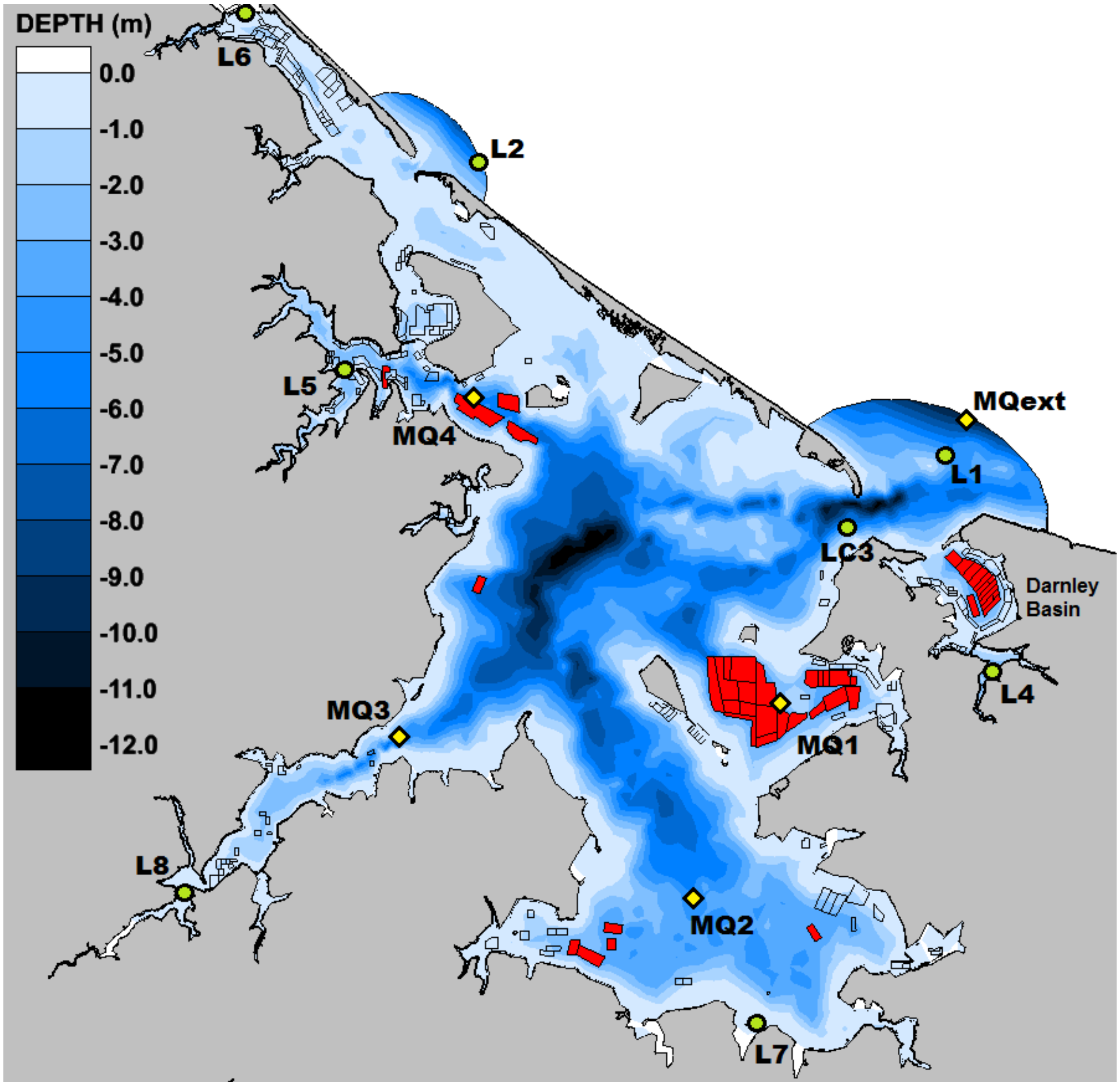


Figure 2. Map of Malpeque, including bathymetry, current leases (red polygons), sampling stations (MQ1, MQ2, MQ3, MQ4 and MQext) as well as hydrodynamic stations (L1, L2, LC3, L4, L5, L6, L7 and L8. L = Water level. C = Current meter).

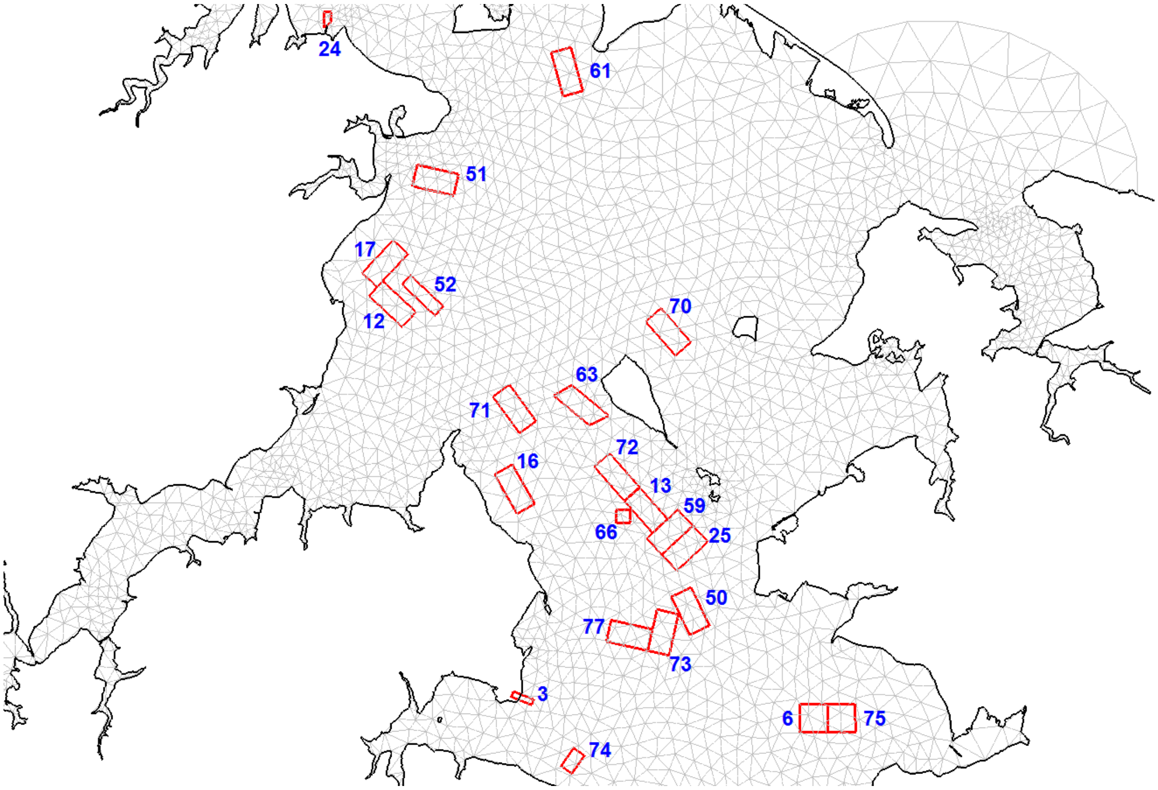


Figure 3. New leases included in the future scenario.

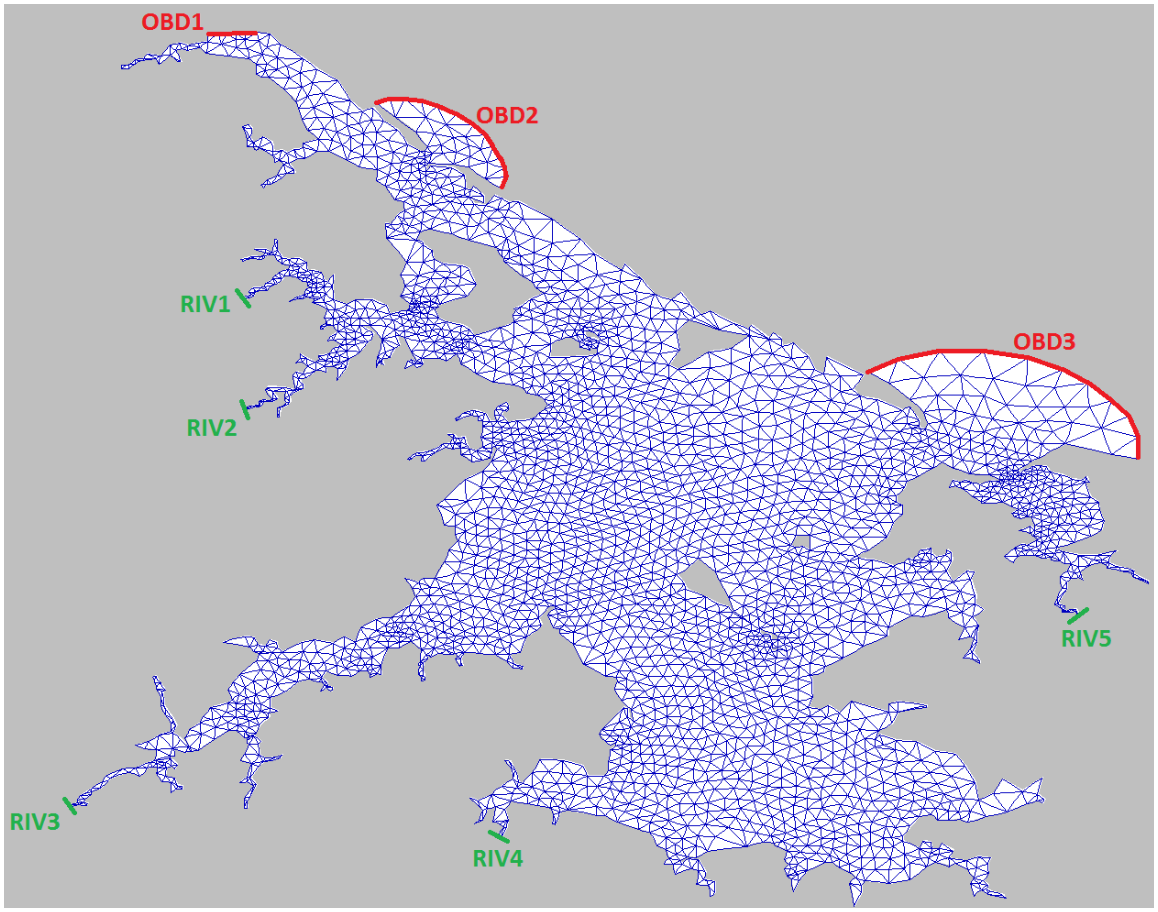
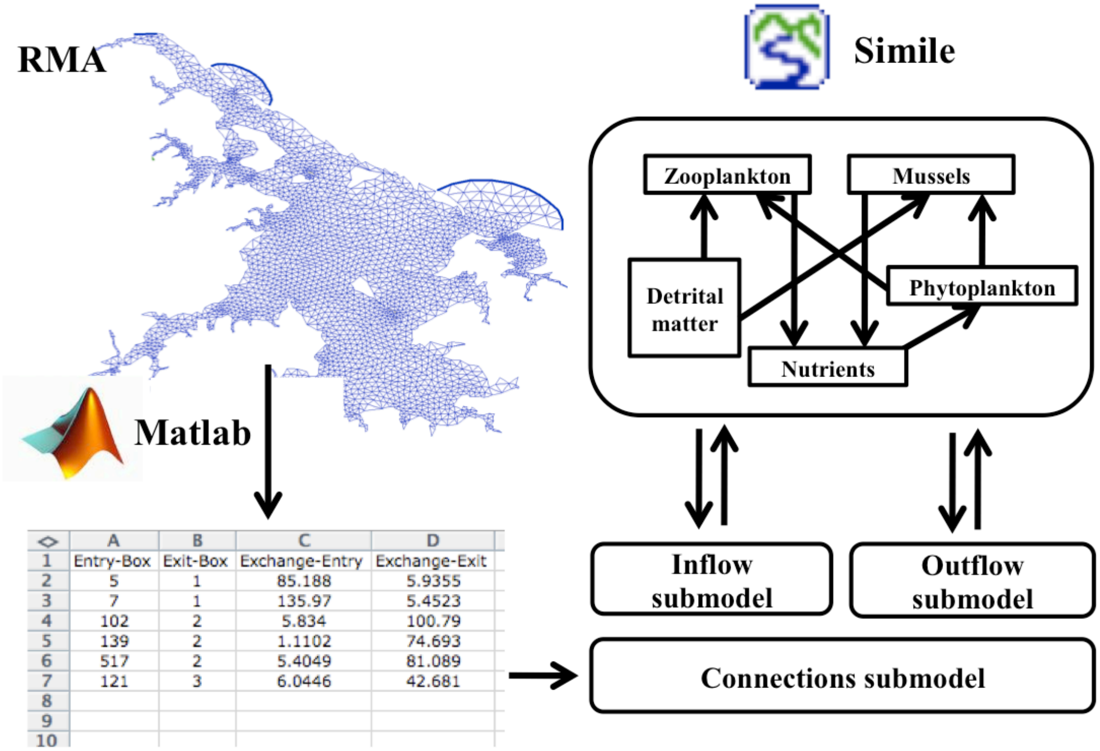


Figure 4. Model domain, unstructured grid used by RMA-10 and Simile, open boundaries (OBD1, OBD2 and OBD3) and rivers included in the model (RIV1, RIV 2, RIV3, RIV4 and RIV 5).



	A	B	C	D
1	Entry-Box	Exit-Box	Exchange-Entry	Exchange-Exit
2	5	1	85.188	5.9355
3	7	1	135.97	5.4523
4	102	2	5.834	100.79
5	139	2	1.1102	74.693
6	517	2	5.4049	81.089
7	121	3	6.0446	42.681
8				
9				
10				

Figure 5. Hydrodynamic-biogeochemical coupling scheme (modified from Filgueira et al. 2012).

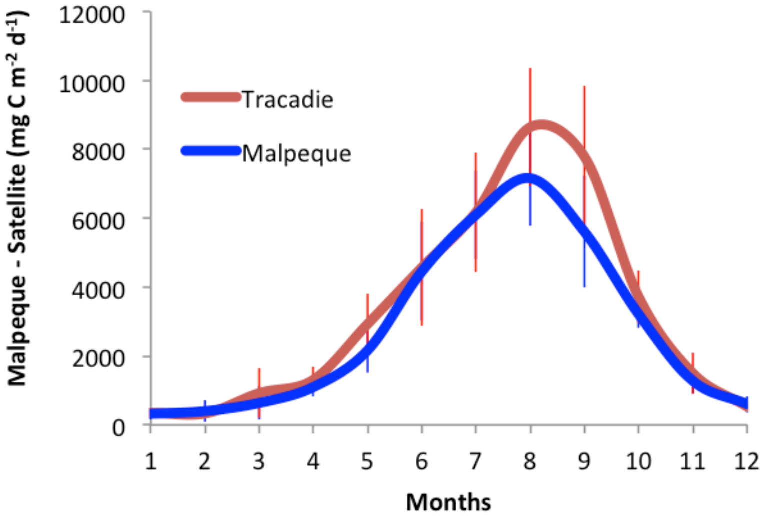


Figure 6. Annual primary production in Malpeque and Tracadie Bay measured using satellite remote sensing.

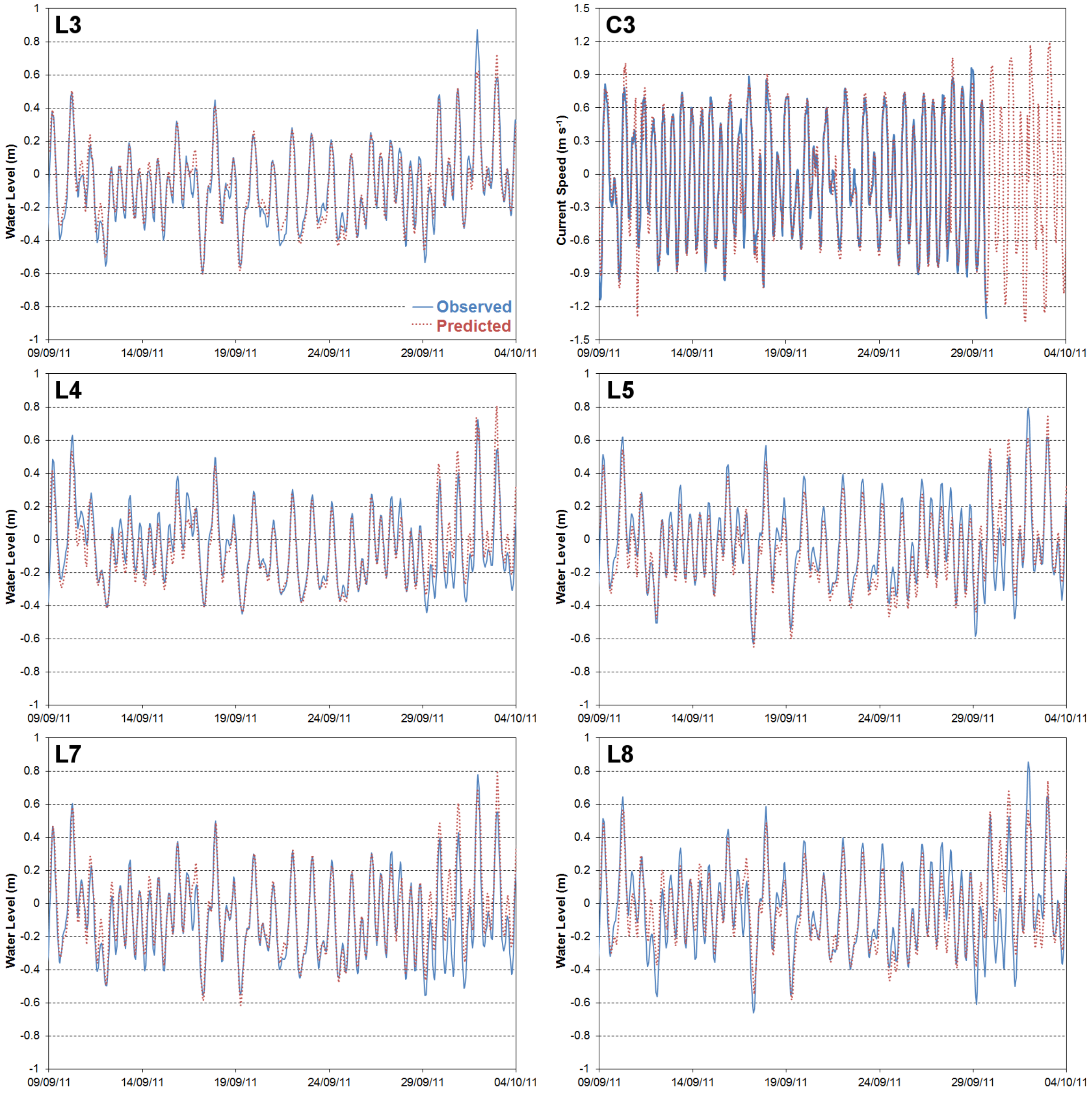


Figure 7. Comparison of observed and predicted water levels (stations L3,4,5,7,8) and currents (station C3).

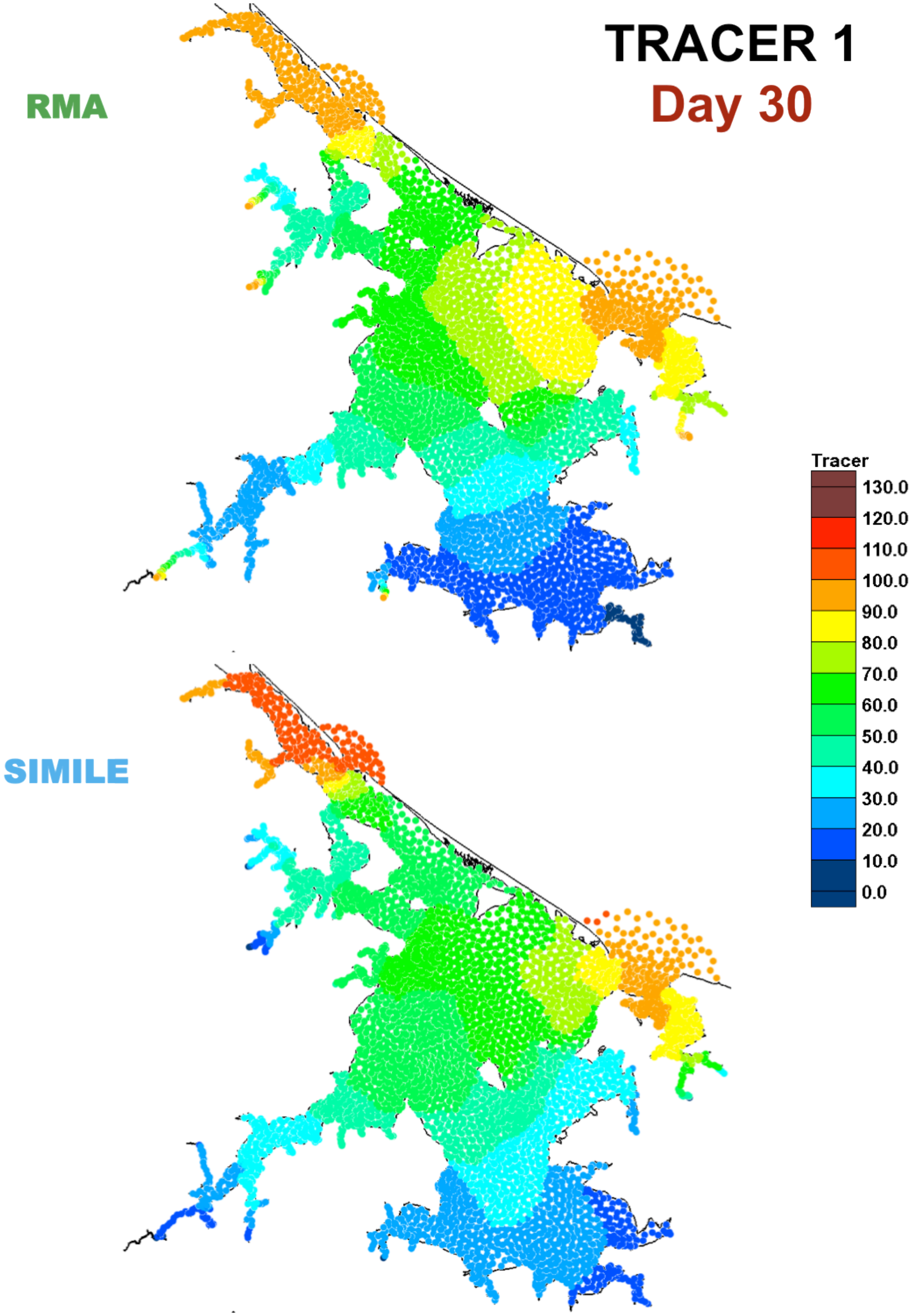


Figure 8. Conservative tracer concentration in conservative tracer experiment 1 after 30 days calculated with RMA and Simile. Initial concentration of conservative tracer at boundary, rivers and model domain has been established as 100, 100 and 0 units m^{-3}, respectively.

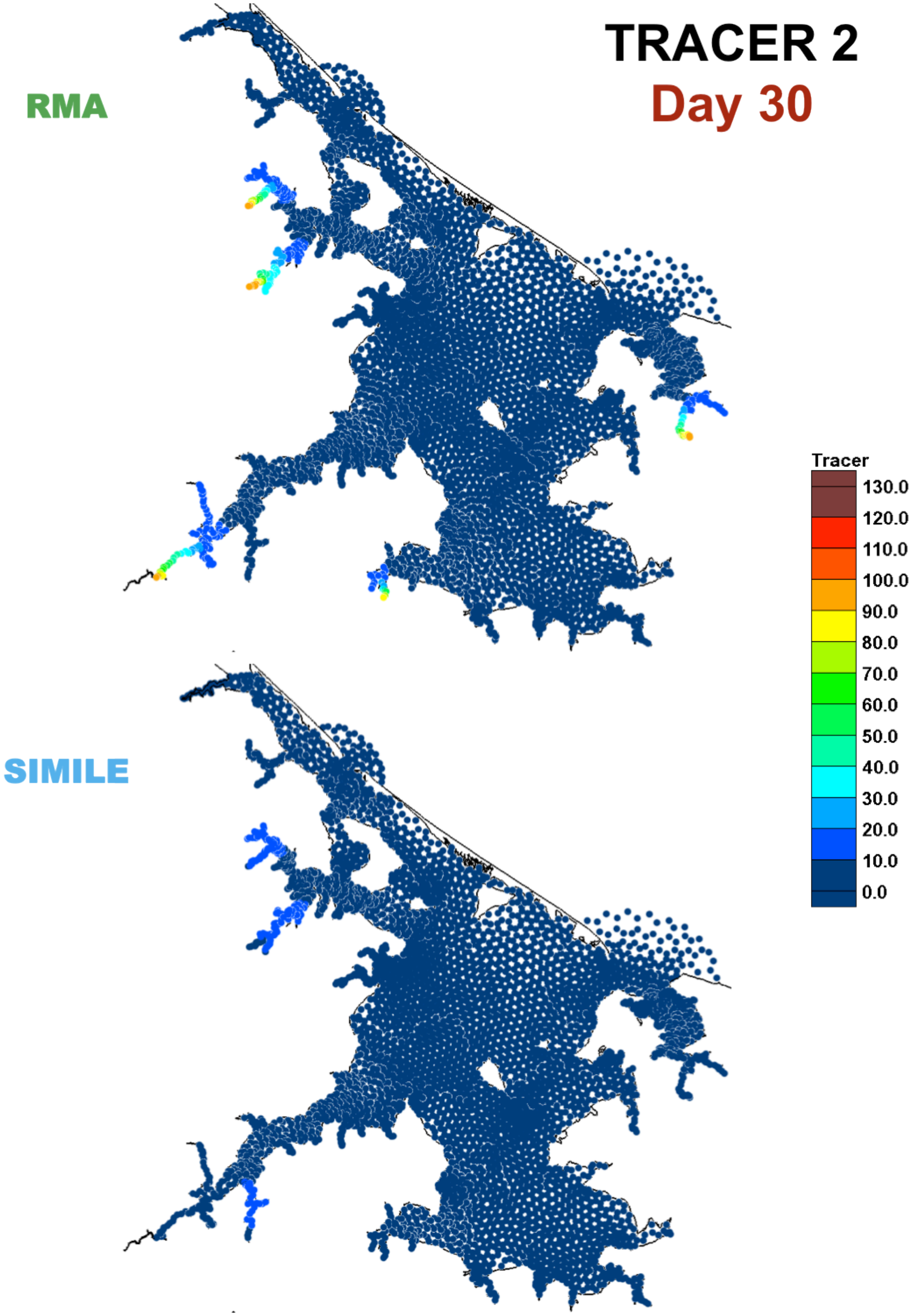


Figure 9. Conservative tracer concentration in conservative tracer experiment 2 after 30 days calculated with RMA and Simile. Initial concentration of conservative tracer at boundary, rivers and model domain has been established as 0, 100 and 0 units m^{-3}, respectively.

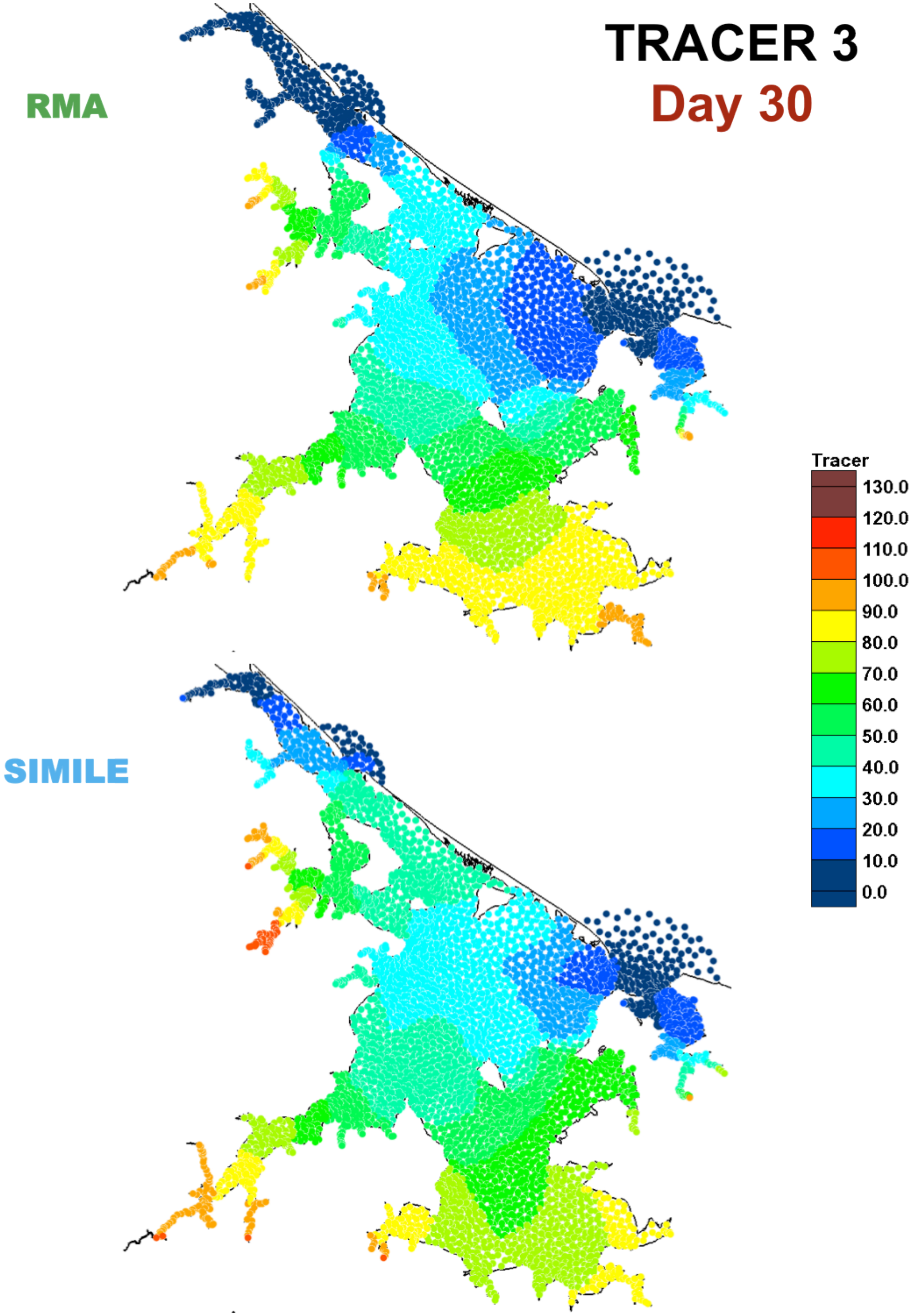


Figure 10. Conservative tracer concentration in conservative tracer experiment 3 after 30 days calculated with RMA and Simile. Initial concentration of conservative tracer at boundary, rivers and model domain has been established as 0, 100 and 100 units m^{-3}, respectively.

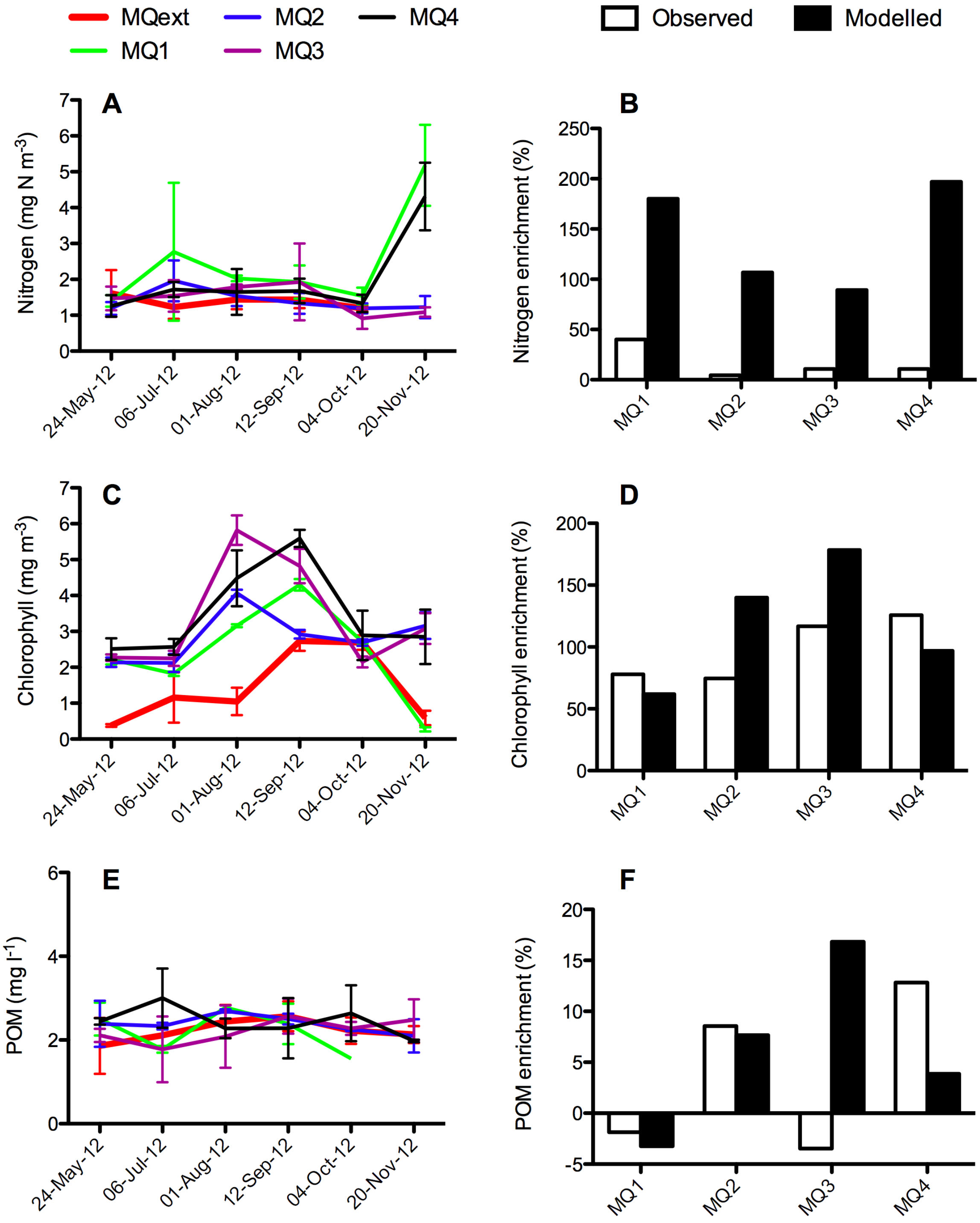


Figure 11. Field observations of nutrients (A), chlorophyll (C) and seston (E) at boundary and four sampling stations inside Malpeque (MQext, MQ1, MQ2, MQ3 and MQ4 in Figure 2) and enrichment/depletion index of nutrients (B), chlorophyll (D) and nutrients (F) at the same sampling stations calculated according to Eq. 5.

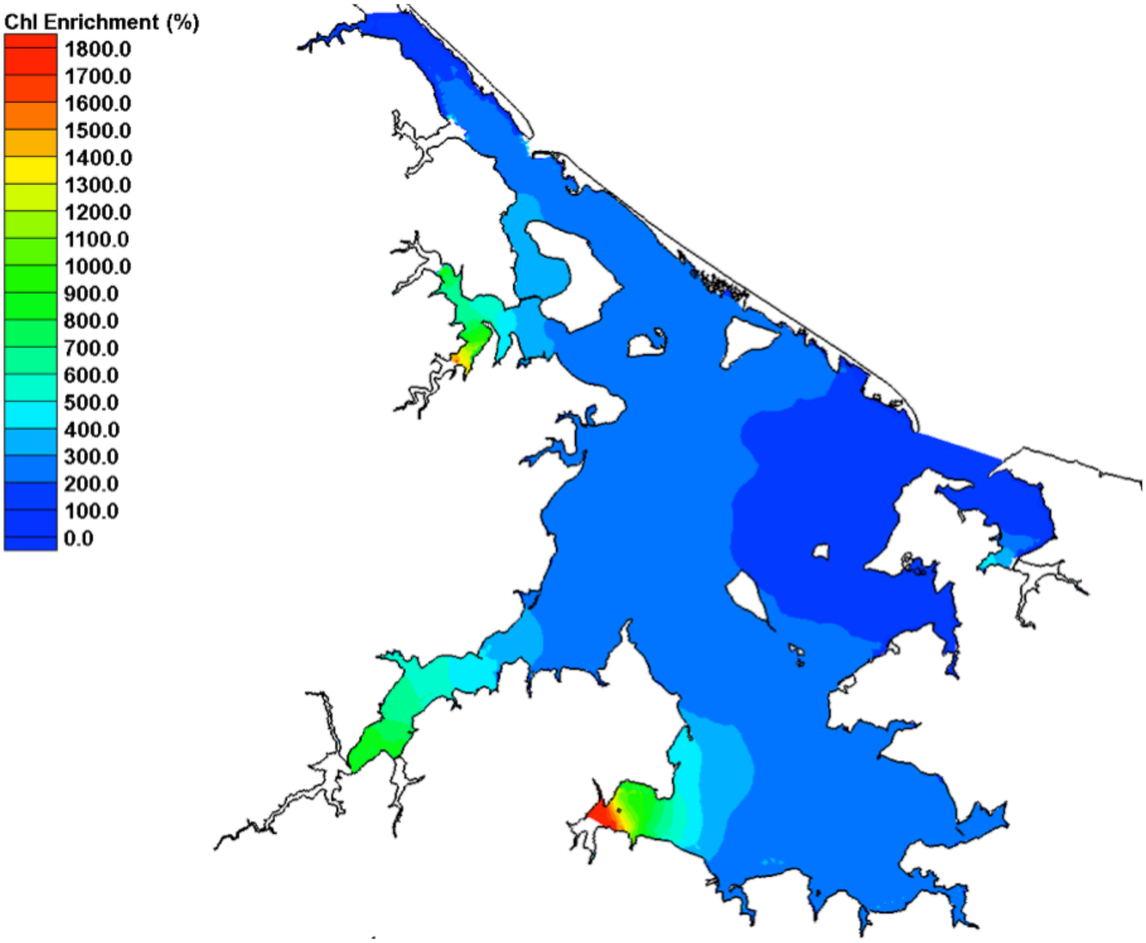


Figure 12. Spatial distribution of chlorophyll enrichment calculated following Eq. 5 in current aquaculture scenario.

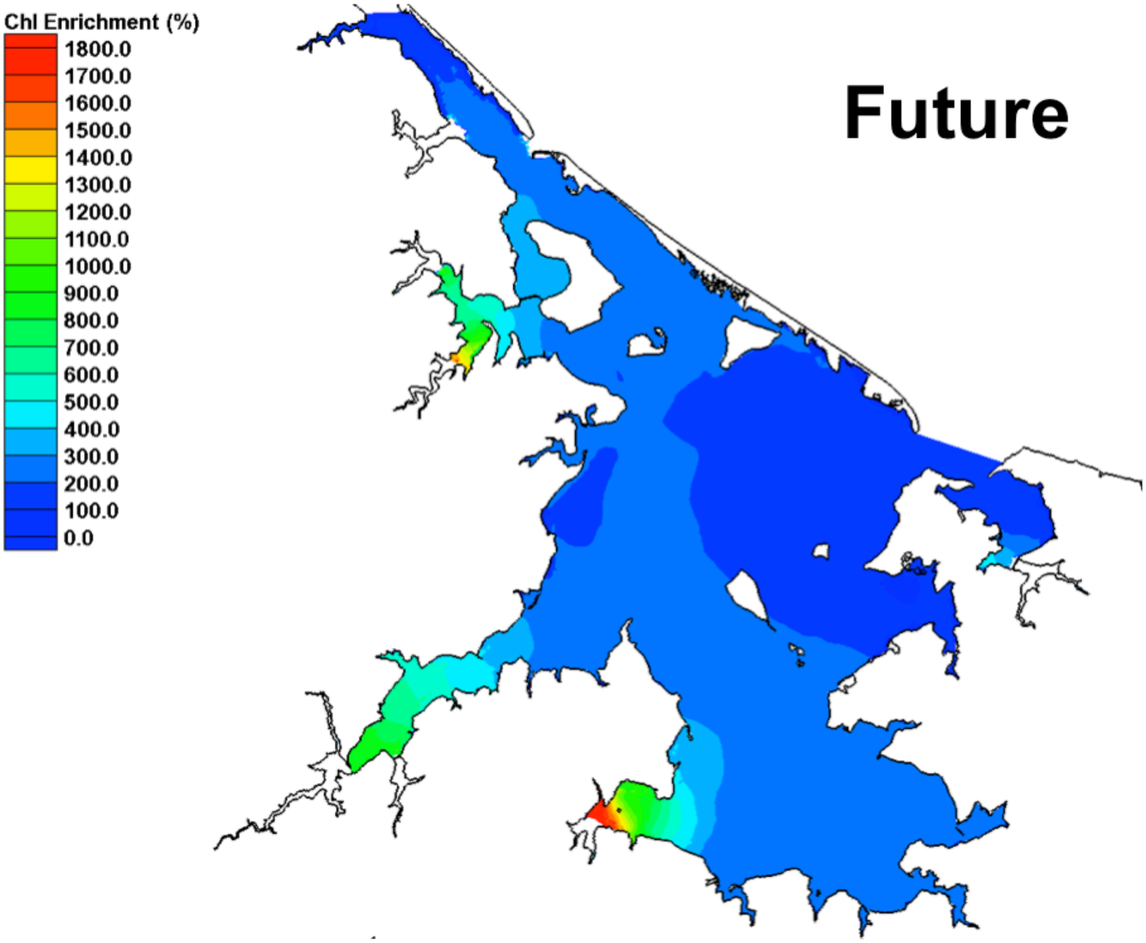


Figure 12. Spatial distribution of chlorophyll enrichment calculated following Eq. 5 in future aquaculture scenario.