PNNL-32811

Quantifying Nitrogen Bioextraction by Seaweed Farms – A Real-time Modeling-Monitoring Case Study in Hood Canal, WA

April 2022

Taiping Wang[1], Zhaoqing Yang[1], Jonathan P. Davis[2], Scott J. Edmundson[1]

[1]Pacific Northwest National Laboratory

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[2]Hood Canal Mariculture Inc.

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Award Details

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Project Team Members:	Jonathan Davis, Hood Canal Mariculture Inc. (HCM)
Program Director:	Dr. Simon Freeman
Principal Investigator:	Taiping Wang
Contract Administrator:	Kendyl Foster
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Public Executive Summary

Anthropogenic nitrogen input is the leading cause of increasing marine eutrophication. Cultivating seaweed at large scales may provide a viable solution for mitigating eutrophication especially when nitrogen extraction is achieved as an added environmental benefit of biofuel and food production. As the first step to promoting and implementing this solution, it is important to quantify and assess the effectiveness of nitrogen removal by existing seaweed farms. Pacific Northwest National Laboratory and Hood Canal Mariculture Inc. conducted a case study by applying a coupled modeling-monitoring approach to quantify nitrogen bioextraction by a one-hectare commercial sugar kelp farm in Hood Canal, WA. Through this two-year effort, the project team conducted intensive field monitoring at the farm site and analyzed the samples in the laboratory. The team also applied a coupled hydrodynamic-macroalgal growth model to simulate kelp growth and nitrogen bioextraction over the two kelp growing seasons. The model results showed an overall good comparison with the field monitoring data. Both model simulations and field data confirmed the effects of nitrogen removal by the kelp farm. Lastly, the established modeling-monitoring approach can be transferable to support broader research activities in macroalgal farming and eutrophication mitigation.

Acknowledgements

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Accomplishments and Objectives

Objectives

The overall objective of the project was to use a coupled modeling-monitoring approach to quantify nitrogen bioextraction by the Hood Canal sugar kelp farm. Specific objectives include:

1. Refining Hood Canal hydrodynamic model to simulate the kelp farm site;
2. Conducting intensive field monitoring using both *in situ* data sensors and "grab" samples of water and biomass;
3. Simulating kelp farm hydrodynamics, biomass growth and nitrogen uptake;
4. Quantifying nitrogen bioextraction by the kelp farm based on both model simulations and field observations.

Accomplishments

A series of tasks, milestones and actual performance against the stated tasks/milestones are summarized below in Table 1.

Table 1. Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Hood Canal model refinement	**Q1: Hood Canal model refinement** – Refine Hood Canal model grid with finer spatial resolutions for the farm site, acquire environmental forcing input and configure the model. **Actual Performance:** (Completed 3/31/2021) PNNL refined the Hood Canal model grid for the kelp farm site with finer spatial resolutions. Three sets of model grids were generated with resolutions varying from 1.5 to 20 meters at the farm site. Specifically, the 1.5-m resolution grid was designed for simulating the hydrodynamic effect of the kelp canopy while the coarser grids were used for simulating kelp growth and nitrogen bioextraction because of its improved computational efficiency. PNNL acquired environmental forcing inputs from various data sources (i.e., observed and modeled meteorological and oceanographic datasets), configured the Hood Canal model for two kelp growing seasons, conducted model simulations for hydrodynamics, and calibrated the model for tidal elevation and velocity.
Task 2: Field data collection and analysis	**Q1: Field data collection and analysis** – Design field monitoring plan, conduct field data collection and subsequent laboratory analysis. **Actual Performance:** (Completed 90% as of 3/31/2022) The project team conducted a site visit and designed the field monitoring plan for the first growing season right before the pandemic started. HCM deployed *in situ* data sensors and collected water and biomass samples at the farm. Despite the significant disruption caused by the pandemic, the team managed to finish field sampling and preserve the water samples in the freezer for subsequent laboratory analysis by ALS and PNNL-Sequim laboratories. In Year 2, the team improved the sampling plan and conducted the sampling work. The team also tried hard to deploy *in situ* nitrate and phosphate sensors loaned from PNNL's Marine and Coastal Research laboratory inside the kelp canopy to detect high-frequency nutrient uptake signal, but unfortunately just missed the growing season due to an extended permitting process caused by the pandemic. As of the project close date, all the data collected by *in situ* sensors and grab water samples have been processed, which include temperature, salinity, current, chlorophyll, dissolved oxygen, and nutrients. The main remaining item is the analysis of nutrient

Tasks	Milestones and Deliverables
	content in the kelp tissue samples collected through the growing season, which has been delayed by the pandemic.
Task 3: Kelp farm simulation	**Q1: Kelp farm simulation** – Simulate kelp farm hydrodynamics, biomass growth and nitrogen bioextraction. **Actual Performance:** (Completed 3/31/2021) PNNL continued improving the macroalgal growth model that was initially developed in an earlier MARINER Cat 3 project (Award#: 17/CJ000/09/01) and applied it to the Hood Canal farm site. The team finished the model simulations for two kelp growing seasons and model-data comparisons for hydrodynamics and water quality parameters. The hydrodynamic simulation results suggested that the higher-resolution grid (i.e., 1.5 m) is needed to detect the fine-scale hydrodynamic effect of the kelp canopy. The kelp biomass growth simulation results agreed with field data very well for the standing stock at harvest. More model-data comparisons for kelp nutrient content time history can be conducted when the data become available.
Task 4: Quantifying N bioextraction	**Q1: Quantifying nitrogen bioextraction** – Quantify nitrogen bioextraction based on model simulations and field measurements. **Actual Performance:** (Completed 90% as of 3/31/2022) The project team quantified the amount of nitrogen extracted by the kelp farm, e.g., it was estimated that the total amount of nitrogen and carbon removed by the harvested kelp standing stock in Year 1 is approximately 50 kg and 525 kg, respectively. The model also predicted that the gross amount of nitrogen fixed by the kelp farm doubled that amount, as the other half was released back to the water as organic and ammonia nitrogen through the growing season. By using an improved field sampling plan, the measured nitrate and ammonium concentrations in Year 2 showed a visible gradient between the north and south end of the farm, which was due to the presence of the kelp farm.
Task 5: Final study report preparation	**Q5.: Final study report preparation** – Summarize the main findings in a final report. **Actual Performance:** (Completed 4/30/2022) The project team completed the final technical report and delivered to APRA-E.
Task 6: Technology transfer & outreach	**Q6: Technology transfer & outreach** – Share the research with the broader seaweed and science community. **Actual Performance:** (Completed: 3/31/2022) The research team presented the research work at two ARPA-E MARINER annual meetings and one ARPA-E summit. PNNL team leveraged the modeling tool developed in this project to support other research activities such as those related to DOE's Powering the Blue Economy Initiative.

Computer Models

This project relied on computer models to execute the project scope. Descriptions of the models, including key assumptions, validation details, and relevant peer reviewed publications, are provided below.

FVCOM (Finite Volume Community Ocean Model)

The Finite Volume Community Ocean Model (FVCOM) is a free-surface, three-dimensional primitive-equations coastal ocean model that simulates tides-, wind- and density-driven circulation with options for various turbulence closure schemes, generalized vertical terrain-following coordinates, and wetting-drying process (Chen et al. 2003). FVCOM solves the three-dimensional primitive Navier-Stokes equations to simulate water surface elevation, velocity, salinity, temperature, and other transport constituents. The unstructured-grid modeling framework and mass-conservative finite-volume numerical schemes give FVCOM a unique advantage for resolving complex coastlines and providing accurate hydrodynamic simulations with great computational efficiency (Chen et al. 2013, Yang et al. 2014, 2020). The FVCOM model provides the hydrodynamic and transport framework that can be used to drive many other process models, such as sediment transport and macroalgal growth.

FVCOM-Macroalgae

A macroalgal growth model was added to the FVCOM model framework with initial funding support through an earlier MARINER Cat 3 project (Award#: 17/CJ000/09/01). The model has been continuously improved in this study to simulate kelp biomass growth, nutrient uptake, and direct biophysical interactions with ambient flow field and water quality variables. Different from the standalone version of the macroalgal growth model that was applied to simulate free-floating macroalgal farms in an earlier study (Whiting et al. 2020), the macroalgal model used in this study was directly embedded within the hydrodynamic model framework. Therefore, the kinetics of nutrient uptake and macroalgae growth are simulated concurrently with the hydrodynamics in the same finite volume, unstructured-grid modeling framework of FVCOM. The effect of the kelp farm on ambient currents has been evaluated in the earlier work (Wang et al. 2014). In this study, model validation was performed by comparing the model results with field observation data of water level, currents, nutrients, and macroalgal biomass. In addition, the same model framework is being leveraged to examine the causes of hypoxia in Hood Canal.

Publications produced as a result of this research are listed below.

- Wang, T., Z. Yang, J. Davis, and S. Edmundson. 2022. "Quantifying Nitrogen Bioextraction by Seaweed Farms – A Case Study in Hood Canal, WA." *In preparation* (to be submitted to *Aquacultural Engineering*)
- Wang, T. and Z. Yang. 2022. "A Numerical Investigation of Hood Canal Hypoxia". *In Preparation* (to be submitted to *Estuarine, Coastal and Shelf Science*)

Project Activities

Large-scale marine macroalgal farms for biofuel/food production could have additional environmental benefits in mitigating coastal eutrophication through bioextraction of nitrogen. The overall objective of this project was to use a coupled modeling-monitoring approach (Figure 1) to study the effectiveness of nitrogen bioextraction by a commercial sugar kelp farm in Hood Canal, WA. The project was conducted mainly through the following tasks, which include conducting intensive field monitoring of water quality and hydrodynamic parameters in the kelp farm during the peak growing seasons, applying a high-resolution, hydrodynamic-macroalgal growth model to simulate kelp growth and nutrient uptake, and quantifying nitrogen bioextraction based on model predictions and field observations. The results suggested that the one-hectare farm could remove ~50 kg nitrogen from seawater at harvest while the gross extraction amount is even higher. Both model predictions and field observations indicated there was a small, yet detectable nitrogen concentration gradient attributed to kelp farm uptake.

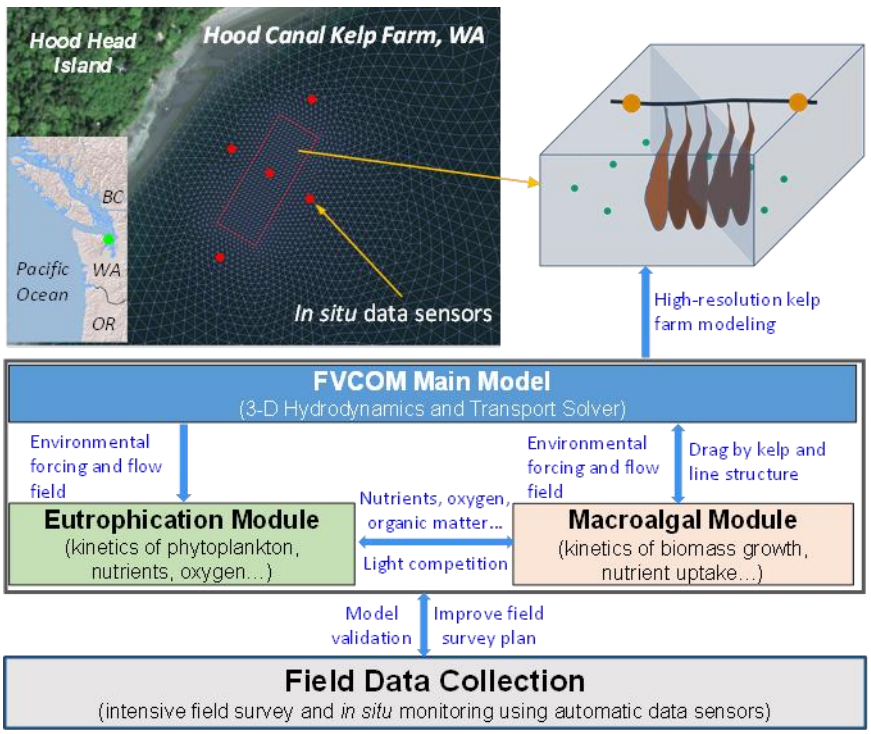

Figure 1. The coupled, modeling-monitoring approach used for studying nitrogen bioextraction by the Hood Canal kelp farm, WA.

Project Outputs

Journal Articles

- Wang, T., Z. Yang, J. Davis, and S. Edmundson. 2022. “Quantifying Nitrogen Bioextraction by Seaweed Farms – A Case Study in Hood Canal, WA.” *In preparation* (to be submitted to *Aquacultural Engineering*)
- Wang, T. and Z. Yang. 2022. “A Numerical Investigation of Hood Canal Hypoxia”. *In Preparation* (to be submitted to *Estuarine, Coastal and Shelf Science*)

Papers

None to disclose.

Status Reports

Quarterly reports throughout the period of performance of the project were submitted to ARPA-E through the online ePIC portal.

Media Reports

None to disclose.

Invention Disclosures

None to disclose.

Patent Applications/Issued Patents

None to disclose.

Licensed Technologies

None to disclose.

Networks/Collaborations Fostered

None to disclose.

Websites Featuring Project Work Results

None to disclose.

Other Products (e.g., Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

- *Models* – A directly coupled, macroalgal growth model has been continuously developed and tested through this project. The model is based on the finite-volume, community ocean model FVCOM (Chen et al. 2003), which has several added modules developed by PNNL, such as marine-hydrokinetics, age-of-water, and NPZD-type water quality modules. The macroalgal growth module is the newest addition. It will be further validated, cleaned, and documented before being shared with the broader mariculture and scientific communities.

Awards, Prizes, and Recognition

None to disclose.

Follow-on Funding

The project team submitted a proposal to ClimateWorks Foundation's RFP on Ocean Carbon Dioxide Removal in July 2020 by leveraging the modeling tool developed in this project. Unfortunately, the proposal did not get selected. We did not receive any other follow-on funding (Table 2).

Table 2. Follow-on Funding Received

Source	Funds Committed or Received
ARPA-E	None

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Chen, C., H. Liu, and R. Beardsley. 2003. An Unstructured Grid, Finite-Volume, Three-Dimensional, Primitive Equations Ocean Model: Application to Coastal Ocean and Estuaries. *Journal of Atmospheric and Oceanic Technology* 20: 159-186.

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