High-frequency measurements of mussel gaping behavior and dissolved oxygen across flow treatments in laboratory flume experiments at Friday Harbor Laboratories from October to December 2023

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Data Type: experimental
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Project
» Collaborative Research: Microscale interactions of foundation species with their fluid environment: biological feedbacks alter ecological interactions of mussels (Microscale Mussels)

Contributors	Affiliation	Role
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Abstract
This dataset contains quality-controlled, hourly-averaged measurements of mussel gaping behavior and dissolved oxygen differences collected during controlled laboratory flume experiments conducted at Friday Harbor Laboratories (University of Washington) in autumn 2023. Experiments were designed to quantify how unidirectional flow speed influences oxygen gradients within mussel aggregations and associated valve gaping metrics for three mytilid mussel species: Mytilus trossulus, Mytilus galloprovincialis, and Mytilus californianus. For each species, a monolayer aggregation of mussels was exposed to 10 flow treatments (1.5 to 30 cm s-1), with each maintained for 24 hours; the dataset includes 23 hourly observations per treatment, after removal of the initial flow equilibration period. The primary data table provides one record per species, flow treatment, and hour, with the following aggregated metrics: avg_mm (mean valve gape distance, averaged across all instrumented mussels for that hour), Prop_open (mean proportion of time mussels were open during that hour, averaged across instrumented mussels), and avg_diffDO (mean hourly difference in dissolved oxygen between ambient water and interstitial water within the aggregation). Each record also includes the corresponding hourly timestamp (DateTime_h), flow treatment identifier, and flow speed (speed, cm s-1). A biomass density variable (bio.density) is included to facilitate , mcomparisons among species and flow treatments. A companion table provides mussel morphometric and mass measurements used to characterize individual size and biomass.

Table of Contents

Coverage

Location: Friday Harbor Laboratories, Friday Harbor, Washington
Spatial Extent: **Lat**:48.546389 **Lon**:-123.011111
Temporal Extent: 2023-10-06 - 2023-12-12

Methods & Sampling

Laboratory flume experiments were conducted at Friday Harbor Laboratories (University of Washington, Friday Harbor, WA, USA; 48°32'45.7249" N, 123°00'46.9262"W) in late Fall 2023 to quantify mussel gaping behavior and dissolved oxygen dynamics under controlled flow conditions. Experiments used monolayer aggregations of three mytilid mussel species: Mytilus trossulus, Mytilus galloprovincialis, and Mytilus californianus. The mussels were obtained from three different locations. Both bay mussel species were ordered from commercial suppliers-- M. trossulus (MT) from Penn Cove Shellfish Farm (Coupeville, WA, USA; 48°13'06.5579" N, 122°42'25.4331"W) and M. galloprovincialis (MG) from Taylor Shellfish Farm (Totten Inlet, WA, USA; 47°08'23"N 123°05'26"W). California mussels (MC; Conrad, 1837) were obtained from Cattle Point on San Juan Island, WA (48°26'59.6811"N, 122°57'51.9358”W). All mussels were maintained in sea tables (66 × 135 × 32 cm) at ambient seawater temperature with a constant flow of seawater prior to experimentation.

For each species, a single-species mussel aggregation was assembled on a flat experimental platform (100 × 36 × 2 cm, L × W × H) constructed from a 1.3 cm plexiglass sheet atop a 0.7 cm egg crate louver and placed in the working section of a recirculating laboratory flume (152 × 38 × 51 cm; Rolling Hills Research Corporation, Model 1520 Water Tunnel). Flow moved unidirectionally across the mussel aggregation before recirculating as the flume operated as a semi-closed system, continuously flushing and cooling the 1520 L recirculating volume with ~2 $L \cdot min^{-1}$ of seawater from the Friday Harbor Laboratory supply, which kept temperatures between 10–12°C across trials. Aggregations of each species were tested in an independent 10-day trial, and flow treatments were randomized within each trial to avoid confounding flow speed with day-of-experiment. We intentionally did not impose an identical flow sequence across species because doing so would systematically link particular flow speeds with specific trial days (e.g., early vs. late in the experiment), introducing potential order effects such as acclimation, fatigue, or cumulative stress. Our primary design priority was to prevent behavioral responses at a given flow speed from being confounded with its position in the treatment sequence. Randomizing flow within each species ensures that responses reflect the imposed flow speed rather than time-dependent effects within the 10-day trial. While species may differ in their physiological responses to flow, the purpose of this design choice was to minimize within-species sequence effects; interspecific differences in sensitivity to flow are evaluated in the results and are not driven by treatment order.

Flow treatments (F1-10) spanned flow speeds from 1.5 to 30 cm s-1 and were maintained continuously for 24 hours. Between each flow treatment, the flume was flushed by increasing the flow speed to 35 cm s-1 for 15 minutes (flushing periods were not included in the data). Experiments were conducted sequentially by species, with identical flow protocols applied to each aggregation.

At the end of each trial, we counted the mussels in the aggregation and recorded mortality rates. We measured several morphometric parameters for a subset of mussels (all mussels with a gape sensor plus a random sample of 30 mussels, n = 46). Specifically, we measured mussel shell length (l), width (w), and height (h) to the nearest 0.1 mm using calipers, and dry weight of body tissue removed from the shell and dried to a constant weight for 72 hours at 65°C. Mussel biomass density (g cm^{-2}) was calculated as dry weight per planform area, assuming an elliptical shape (for a vertically oriented mussel) with shell width and height as the major and minor axes, respectively (Bell and Gosline,1997). This functional trait of an individual mussel can be readily scaled up to whole bed biomass density (also in g cm-2), a metric of interest to benthic ecologists, by multiplying by π/4 (the ratio of the area of an ellipse to its bounding rectangle).

We measured both dissolved oxygen (DO) and mussel gaping behavior throughout each species trial. We measured DO at 1-minute intervals during each trial using HOBO loggers (HOBO U26-001; Onset, MA-USA) placed within the interstitial zone (in bed) and upstream of the mussel aggregation. We affixed the loggers within the interstitial zone to the center of the plexiglass platform supporting the mussel aggregation. Before each species trial, we calibrated the sensors using the manufacturer’s recommended methods and corrected offsets between loggers before analysis.

We measured mussel gaping behavior using gape sensors composed of magnetic Hall Effect sensors (Allegro Microsystems A1393, Worcester, MA, USA) and a circular magnet (part number 8195-Radial Magnet Inc. Boca Raton FL). We attached the gape sensor to the posterior end of one valve and the circular magnet to the opposite valve using marine epoxy (Splash Zone, KOP-COAT Inc., Rockaway, NJ, USA). We sampled gape sensor output of the distance between the valves every 5 seconds, a sampling rate our preliminary observations determined to be sufficient to characterize gape behavior dynamics. We equipped a total of 16 mussels per species with gape sensors for each trial, spaced more than 10 mussel body lengths apart to

prevent sensor interference. Gape sensors were continuously monitored during each trial using a MusselTracker datalogging system (Miller and Dowd, 2017). At the end of each trial, each gape sensor was calibrated by severing the mussel's adductor muscle and using calipers to set valve gape from 0 to 20 mm in 1 mm increments while measuring the sensor's voltage output. An exponential function was then fit to this calibration data to estimate gape in millimeters (mm) from the voltage output for each sensor, with a sensor resolution of < 0.1 mm. Because each sensor is built by hand and has its own calibration curve, data for both the calibration and raw voltages are not included here but can be requested by contacting the author.

Data Processing Description

Hour of experiment: There are only 23 hours per flow treatment period because the first hour of measurements was removed to allow the dissolved oxygen signal to achieve equilibrium at the given flow treatment.

Average_gape_distance: Hourly averaged gape distance in millimeters derived from higher-frequency measurements (5-second intervals) from files titled: 'gape.sec_MT.csv', 'gape.sec_MG.csv', 'gape.sec_MC.csv'. We first calculated the hourly average distance for each mussel across all flow treatments. We then calculated the mean of these hourly values for all mussels (n=16) in the flow treatment. So, the average gape distance is the hourly average across 16 mussels, treating the mussel with the gape sensor as a true replicate.

Proportion_time_open: There were 16 mussels equipped with gape sensors for each species trial. Proportion of time spent open (prop open) was calculated from calibrated gape sensor values (voltage-to-mm conversions), not from visual observations. Valve gape was classified as open when gape distance exceeded 0.5 mm. At each 5-second interval, gape state (open or closed) was determined for each mussel. For each individual, the proportion of time spent open was calculated within each hour. These hourly proportions were then averaged across all instrumented mussels (n = 16) within a species to generate a single hourly value. For example, a value of 0.97 indicates that mussels were open for 97% of that hour, on average.

DO_corrected: To account for oxygen depletion on a per-unit-biomass basis, enabling direct comparison among species with different biomass densities 'DO_corrected' was calculated by first assigning each mussel species a species-specific biomass density (g cm^{-2}) based on measured morphology (in separate csv file 'Morphology': MT:0.538, MG:0.287, MC: 0.312), then normalizing the observed dissolved oxygen difference (avg_diffDO) by that biomass density per hour.

Bio.density: Mussel biomass density ($g \times cm^{-2}$) was calculated as dry weight per planform area, assuming an elliptical shape (for a vertically oriented mussel) with shell width and height as the major and minor axes, respectively (Bell and Gosline 1997).

BCO-DMO Processing Description

- Imported file "flume_hourlyavg.csv" into the BCO-DMO system
- Modified parameter (column) names to conform with BCO-DMO naming conventions for interoperability
- Added column for scientific name
- Matched parameter/column names to standard terms in ontologies

Problem Description

For Mytilus trossulus (MT), the mussel fitted with Hall0 sensor died during experiment and was not included. Thus there is no column for Hall0 in the 'gape.sec_' data, and no body weights or biomass density in the 'morphometrics' because there was no live tissue to measure for 'Bio.density'

[table of contents | back to top]

Related Publications

Bell, E., & Gosline, J. (1997). Strategies for life in flow:tenacity, morphometry, and probability of dislodgment of two Mytilus species. Marine Ecology Progress Series, 159, 197–208. https://doi.org/10.3354/meps159197

Methods

Miller, L. P., & Dowd, W. W. (2017). Multimodal *in situ* datalogging quantifies inter-individual variation in thermal experience and persistent origin effects on gaping behavior among intertidal mussels (*Mytilus californianus*). Journal of Experimental Biology. https://doi.org/10.1242/jeb.164020
Methods

Murie, K. (2025). Flow as a Mediator of Ecosystem Engineering: Hydrodynamics Shape Chemical Modification by Kelp and Mussel Beds [Order No. 32286608]. (3292761520). http://library.proxy.mbl.edu/dissertations-theses/flow-as-mediator-ecosystem-engineering/docview/3292761520/se-2
https://www.proquest.com/docview/3292761520?%20Theses&fromopenview=true&pq-origsite=gscholar&sourcetype=Dissertations%20#
Methods

[table of contents | back to top]

Parameters

Parameter	Description	Units
ISO_Datetime_UTC	Timestamp of observation in Coordinated Universal Time	unitless
ISO_Datetime_PST	Timestamp of observation in Pacific Standard Time	unitless
Scientific_name	Scientific name of the Mytilid mussel species used in the experiment	unitless
Sample_species	Mussel species sampled during separate experiments. MT is Mytilus trossulus , MG is Mytilus galloprovincialis, and MC is Mytilus californianus	unitless
Flow_treatment	Flow treatment identifier F1 to F10 run in numerical order, but with varying flow speeds	unitless
Hour	Hour of the experiment in which the measurements and observations were made. From 1 to 23, since the initial hour was for equilibration.	unitless
Speed	Flow speed assigned to a given flow treatment. Speeds were applied in different orders for the three species. See PDF for more information	centimeters per second (cm x s-1)
Gape_distance_avg	Hourly averaged gape distance in millimeters derived from higher-frequency measurements (5-second intervals) from files titled: ‘gape.sec_MT.csv’, ‘gape.sec_MG.csv’, ‘gape.sec_MC.csv’. We first calculated the hourly average distance for each mussel across all flow treatments. We then calculated the mean of these hourly values for all mussels (n=16) in the flow treatment. So, these values are the hourly average distance across 16 mussels, treating the mussel with the gape sensor as a true replicate	millimeters (mm)

Proportion_time_open	Proportion of time mussels were open (>0.5 mm gape) within each hour. There were 16 mussels equipped with gape sensors for each species trial. Proportion of time spent open (prop open) was calculated from calibrated gape sensor values (voltage-to-mm conversions), not from visual observations. Valve gape was classified as open when gape distance exceeded 0.5 mm. At each 5-second interval, gape state (open or closed) was determined for each mussel. For each individual, the proportion of time spent open was calculated within each hour. These hourly proportions were then averaged across all instrumented mussels (n = 16) within a species to generate a single hourly value. For example, a value of 0.97 indicates that mussels were open for 97% of that hour, on average.	unitless
DO_diff_avg	Average difference between ambient and within-bed dissolved oxygen (DO_ambient - Bed_DO) in milligrams per liter	milligrams per liter (mg x L-1)
DO_corrected	Corrected dissolved oxygen values. To account for oxygen depletion on a per-unit-biomass basis, enabling direct comparison among species with different biomass densities 'DO_corrected' was calculated by first assigning each mussel species a species-specific biomass density (g cm?²) based on measured morphology (in separate csv file 'Morphology': MT:0.538, MG:0.287, MC: 0.312), then normalizing the observed dissolved oxygen difference (avg_diffDO) by that biomass density per hour.	milligrams per liter (mg x L-1)
Flow_treatment_num	Flow treatment identifier (numerical only)	unitless

[table of contents | back to top]

Instruments

Dataset-specific Instrument Name	Gape sensors Allegro Microsystems A1393 (Worcester, MA, USA)
Generic Instrument Name	Allegro Microsystems A1393 Hall effect sensor
Dataset-specific Description	We measured mussel gaping behavior using gape sensors composed of magnetic Hall Effect sensors (Allegro Microsystems A1393, Worcester, MA, USA) and a circular magnet.
Generic Instrument Description	The Allegro Microsystems A1393 linear Hall-effect sensor is a device that detects magnetic fields and converts field data into voltage. The integrated circuits (ICs) provide a voltage output that is directly proportional to an applied magnetic field. Before amplification, the sensitivity of typical Hall-effect ICs (measured in mV/G) is directly proportional to the current flowing through the Hall-effect transducer element inside the ICs. https://www.allegromicro.com/en/insights-and-innovations/technical-docum...

Dataset-specific Instrument Name	calipers
Generic Instrument Name	calipers
Dataset-specific Description	Shell lengths, heights, and widths were measured using calipers.
Generic Instrument Description	A caliper (or "pair of calipers") is a device used to measure the distance between two opposite sides of an object. Many types of calipers permit reading out a measurement on a ruled scale, a dial, or a digital display.

Dataset-specific Instrument Name	MusselTracker datalogging system
Generic Instrument Name	MusselTracker data logger
Dataset-specific Description	Gape sensors were continuously monitored during each trial using a MusselTracker datalogging system (Miller and Dowd 2017).
Generic Instrument Description	MusselTracker is a custom datalogger system and valve gape monitoring system described in detail in Miller and Dowd (2017). The multimodal sensor array of the MusselTracker system is robust and power-efficient enough to enable long term (multi-week) continuous monitoring of marine mussel temperature and behaviors in wave-swept intertidal conditions. The system has a six-axis accelerometer and magnetometer sensor to enable the first high-resolution tracking of individual mussel movement over these time scales. Miller, L. P., & Dowd, W. W. (2017). Multimodal in situ datalogging quantifies inter-individual variation in thermal experience and persistent origin effects on gaping behavior among intertidal mussels (Mytilus californianus). Journal of Experimental Biology. https://doi.org/10.1242/jeb.164020

Dataset-specific Instrument Name	Dissolved Oxygen logger HOBO U26-001 (Onset, MA)
Generic Instrument Name	Onset HOBO U26-001 Dissolved Oxygen Data Logger
Dataset-specific Description	We measured dissolved oxygen (DO) at 1-minute intervals during each trial using HOBO loggers (HOBO U26-001; Onset, MA-USA) placed within the interstitial zone (in bed) and upstream of the mussel aggregation.
Generic Instrument Description	A dissolved oxygen sensor, temperature sensor, and integrated data logger. The HOBO U26-001 can be used in freshwater and saltwater conditions, and outputs dissolved oxygen (mg/L) and temperature (degC) measurements.

[table of contents | back to top]

Project Information

Collaborative Research: Microscale interactions of foundation species with their fluid environment: biological feedbacks alter ecological interactions of mussels (Microscale Mussels)

Coverage: University of Washington Friday Harbor Laboratories

NSF Award Abstract:
The project investigates how the metabolic activity of dense aggregations of marine organisms alter the water chemistry of their interstitial spaces, and how these microscale alterations feedback to affect the organisms' interactions in coastal ecosystems. The research team focuses on bivalve mussels, foundation species that form dense 'beds' typically known for facilitating other species by ameliorating harsh flow conditions. This ability can become a liability, however, if flow is not sufficient to flush the interstitial spaces and steep, metabolically-driven concentration gradients develop. The research evaluates whether corrosive chemical microclimates (such as low oxygen or low pH) are most extreme in low flow, high temperature conditions, especially for dense aggregations of mussels with large biomass and/or high respiration rates, and if they negatively impact mussel beds and the diverse biological communities they support. The research addresses a global societal concern, the impact of anthropogenic climate change on coastal marine ecosystems, and has potential applications to aquaculture and biofouling industries by informing adaptation strategies to "future-proof" mussel farms in the face of climate change and improved antifouling practices for ships, moorings, and industrial cooling systems. The project forges new collaborations with investigators from three campuses and integrates research and education through interdisciplinary training of a diverse group of graduate, undergraduate and high school students. STEM education and environmental stewardship is promoted by the development of a K-12 level science curriculum module and a hand's-on public exhibit of bivalve biology at a local shellfish farm. Research findings are disseminated in a variety of forums, including peer-reviewed scientific publications and research presentations at regional, national and international meetings.

The research team develops a framework that links environmental conditions measured at a coarse scale (100m-100km; e.g., most environmental observatories) and ecological processes at the organismal scale (1 cm – 10 m). Specifically, the project investigates how aggregations of foundation species impact flow through interstitial spaces, and how this ultimately impacts water chemistry immediately adjacent to the organisms. The research focuses on mytilid mussels, with the expectation that the aggregation alters the flow and chemical transport in two ways, one by creating a physical resistance, which reduces the exchange, and the other by enhancing the exchange due to their incurrent/excurrent pumping. These metabolically-driven feedbacks are expected to be strongest in densely packed, high biomass aggregations and under certain ambient environmental conditions, namely low flow and elevated temperature, and can lead to a range of negative ecological impacts that could not be predicted directly from coarse scale measures of ambient seawater chemistry or temperature. The team develops computational fluid dynamic (CFD) models to predict interstitial flows and concentration gradients of dissolved oxygen and pH within mussel beds. The CFD model incorporates mussel behavior and physiological activity (filtration, gaping, respiration) based on published values as well as new empirical work. Model predictions are compared to flow and concentration gradients measured in mussel aggregations in the laboratory and field. Finally, the team conducts several short-term experiments to quantify some of the potential negative ecological impacts of corrosive interstitial water chemistry on mussel aggregations, such as reduced growth, increased dislodgement, increased predation risk, and reduced biodiversity. Because the model is based on fluid dynamic principles and functional traits, the framework is readily adaptable to other species that form dense assemblages, thereby providing a useful tool for predicting the ability of foundation species to persist and provide desirable ecosystem services under current and future multidimensional climate scenarios.

This award reflects NSF's statutory mission and has been deemed worthy of support through evaluation using the Foundation's intellectual merit and broader impacts review criteria.

[table of contents | back to top]

Funding

Funding Source	Award
NSF Division of Ocean Sciences (NSF OCE)	OCE-2050273

[table of contents | back to top]