Shell dissolution rates of Mytilus trossulus and Mytilus californianus from Penn Cove, WA, and Carmet Beach, CA, collected January 2020–December 2023

Website: https://www.bco-dmo.org/dataset/1006705
Data Type: Other Field Results
Version: 1
Version Date: 2026-08-31

Project
» Invertebrate calcification and behavior in seawater of decoupled carbonate chemistry (OA decoupling)

Contributors	Affiliation	Role
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Abstract
Marine mussels display differential habitat preferences, with species like Mytilus californianus favoring fully saline environments and Mytilus trossulus inhabiting sites with greater freshwater input. Determining abiotic dissolution rates of these species under ocean acidification is essential for predicting future consequences of climate change for coastal populations. We examined shell dissolution rates of these congeners under a range of pH (6.5-9.3) and aragonite saturation states (0.1-9.0). We additionally quantified experimentally the relative importance of dissolution from interior versus exterior shell surfaces. M. trossulus obtained from Penn Cove, WA exhibited 4x higher shell dissolution rates than M. californianus collected from Carmet Beach, CA. When the shell interior was sealed against seawater exposure, dissolution rates decreased significantly in both species, indicating high abiotic dissolution on the shell interior. Results demonstrate that dissolution rates can vary between congeners inhabiting the same biogeographic region. Our finding that freshwater-tolerant M. trossulus has higher abiotic dissolution under ocean acidification is important because low salinity may further slow calcification, altering future intertidal population structure along freshwater-influenced coastlines.

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Coverage

Location: Northwest Pacific: Carmet Beach, California (38 N 123 W) and Penn Cove, Washington (48 N 122 W)
Spatial Extent: **N**:48.2398215 **E**:-122.6732249 **S**:38.3743603 **W**:-123.0763912
Temporal Extent: 2020-01-13 - 2024-03-26

Methods & Sampling

Naturally settled *M. californianus* (urn:lsid:marinespecies.org:taxname:367837) were manually collected from Carmet Beach, CA, USA between January 2020 and April 2022. Mussels were dissected immediately upon arrival at Bodega Marine Laboratory (BML), CA (<0.5 h transit time) to remove all body tissue. Remaining organic materials (byssal threads, epibionts) were removed by drying shells in an oven for 24 h at 60°C. *M. trossulus* (urn:lsid:marinespecies.org:taxname:140482) of 20–75 mm length (target length consistent with *M. californianus* shells) were collected from Penn Cove Shellfish Farm in Penn Cove, WA, USA in September and December of 2023. Mussels from Penn Cove were maintained in a moist, cool and insulated environment during shipment to BML (< 1 day), and were dissected immediately upon arrival at the lab using methods described above.

Abiotic dissolution experiments were conducted on mussel shells between March 2020 and March 2024. All mussel shells were incubated in seawater manipulated to a target aragonite saturation state of $\Omega_{aragonite}$ = 0–9 (actual $\Omega_{aragonite}$ = 0.05–9.03). To separate contributions of the inner or outer shell surface to dissolution, we coated the inside of a subset of shells of each species with a clear, silicone waterproof sealant (Loctite), applying a single, thin layer to the nacre. For the incubations, we first added ambient seawater to a 1 L mixing vessel, then added variable doses of sodium hydroxide (NaOH) and Hydrochloric acid (HCl) to manipulate pH and $\Omega_{aragonite}$. We mixed the treatment water thoroughly and subsampled 150 ml of this water to characterize chemical conditions before incubation (described below). The remaining 850 mL of treatment water was inverted into a glass incubation jar containing a mussel shell and the jar was sealed immediately and placed in a dark incubation chamber. We removed mussel shells after a target of 42−45 h, though 25% of incubations occurred in tandem with prior experiments and had an incubation period of 108−115 h; we accounted for this difference by normalizing abiotic dissolution by time (dissolution rate). After incubation, a 150 mL subsample was again extracted from jars and used to measure chemical conditions after incubation. The treatment water mass and shell mass were recorded, with water mass derived using the equation (total mass = jar mass + shell mass +water mass).

Before and after incubation, we measured oxygen, temperature, salinity, total alkalinity and pH in each incubation vessel. The pH probe was used for routine measurements, while the Shimadzu spectrophotometer provided more precise pH measurements using m-cresol purple dye. Spectrophotometric measurements were conducted at incubation temperature periodically throughout the experiment and used to correct the probe measurements. Ammonia was measured before incubation from one of four carboys used to dispense ambient seawater for treatments (triplicate ammonia samples per carboy) and after incubation from each incubation vessel. Before and after incubation, our 150 mL subsamples were preserved in duplicate, using opaque bottles for alkalinity titration, which occurred within 24 h according to methods described in Ninokawa et al. (2024). TA was measured in triplicate, and the standard deviation among the three replicate titrations was calculated for each TA sample. Incubations were discarded if the standard deviation among the triplicate titrations exceeded 10 µmol kg^{-1}, resulting in 45 unsealed and 27 sealed *M. trossulus* shells and 46 unsealed and 25 sealed *M. californianus* shells used for analysis. Though waste excretion was not expected for abiotic shells, we measured ammonia to account for any biologically associated changes in alkalinity (i.e. microbial activity in water or on shells) using a salicylate spectrophotometric assay (Ninokawa et al. 2024).

Sealed *M. californianus* shells were tested during a separate experiment by Saley & Gaylord (2025) using the same analytical methods but targeting a narrow range of $\Omega_{aragonite} < 1$ and using approximately 300 mL of water. Therefore, in statistical analyses focused on comparisons across groups, our full dataset was subsampled to $\Omega_{aragonite} < 1$ for consistency. We also normalized dissolution (in µmol kg^{-1}) by water mass, multiplying alkalinity change by kg treatment water before finding dissolution rate per shell mass (µmol $CaCO_3$ hr^{-1} g^{-1}) across all treatments. Note that shell length but not mass was measured by Saley & Gaylord (2025); we therefore derived shell mass for this group based on the relationship between length and mass in a separate dataset of 558 *M. californianus* mussels initially measured for Ninokawa et al. (2024).

Data Processing Description

We calculated abiotic dissolution rate using the ammonia-corrected alkalinity anomaly technique, dividing $CaCO_3$ dissolution by incubation time and dry shell mass (Gazeau et al. 2015). We used chemical measurements to determine the carbonate chemistry of each incubation including $\Omega_{aragonite}$ and $\Omega_{calcite}$ using the package *seacarb* v 3.3.3 (Orr et al., 2003) in R v 4.5.0 (R Core Team, 2025) with constants from Lueker et al. (2000).

BCO-DMO Curation Notes

This section documents curation actions performed prior to publication review with the submitter, and additional information relevant to understanding and reusing this dataset. It distinguishes changes made to the submitted (meta)data from unresolved issues and/or enhancements that improve future reuse and interoperability.

CURATION ACTIONS PERFORMED ON DATA

- Loaded abiotic_dissolution_Mtrossulus_Mcalifornianus.csv, header row 1, declared "", "nd", and "NA" as missing value sentinels (needed since shell.length used "NA" for missing entries)
- Renamed columns shell.number, shell.wt, shell.length to shell_number, shell_wt, shell_length to normalize dot-separated names to underscore-separated, to conform with BCO-DMO parameter guidance
- Computed new species column: set to "Mytilus californianus" if treatment matched regex containing "californianus", "Mytilus trossulus" if treatment matched "trossulus" in order to provide more explicit labeling of treatment/species combinations
- Computed new paint_treatment column: default value "unpainted", set to "painted" if treatment matched regex containing "painted" in order to provide more explicit labeling of treatment/species combinations
- Reordered columns to: shell_number, treatment, species, paint_treatment, G, OmegaAragonite, duration, shell_wt, shell_length
- Output as 1006705_v1_abiotic_dissolution_mytilus.csv

CURATION ACTIONS PERFORMED ON METADATA

- BCO-DMO's standard metadata entry and text formatting steps were performed.
- Scientific names in the data were checked using World Register of Marine Species (WoRMS) Taxon Match. All scientific names in the data are valid and accepted names as of 2026-08-31.
- Adjusted location fields information from Penn Cove, Washington (38 N 122 W) to Penn Cove, Washington (48 N 122 W).
- Added citations for software listed.

ISSUES POTENTIALLY IMPACTING REUSE

- N/A

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Data Files

File	
1006705_v1_abiotic_dissolution_mytilus.csv	(Comma Separated Values (.csv), 13.82 KB) MD5:a643949f75fa215d1a71620fda719ead
Primary data file for dataset ID 1006705, version 1	

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Related Publications

Carlson, R. R., Lewis, M. A., Ninokawa, A. T., Saley, A. M., Hill, T. M., & Gaylord, B. (2025). Shell dissolution rates

differ fourfold between mussel species. Royal Society Open Science, 12(7). https://doi.org/10.1098/rsos.250664
Results

Gazeau, F., Urbini, L., Cox, T., Alliouane, S., & Gattuso, J. (2015). Comparison of the alkalinity and calcium anomaly techniques to estimate rates of net calcification. Marine Ecology Progress Series, 527, 1–12. https://doi.org/10.3354/meps11287
Methods

Lueker, T. J., Dickson, A. G., & Keeling, C. D. (2000). Ocean pCO2 calculated from dissolved inorganic carbon, alkalinity, and equations for K1 and K2: validation based on laboratory measurements of CO2 in gas and seawater at equilibrium. Marine Chemistry, 70(1-3), 105–119. doi:10.1016/s0304-4203(00)00022-0 https://doi.org/10.1016/S0304-4203(00)00022-0
Methods

Ninokawa, A. T., Saley, A. M., Shalchi, R., & Gaylord, B. (2024). Multiple carbonate system parameters independently govern shell formation in a marine mussel. Communications Earth &Amp; Environment, 5(1). https://doi.org/10.1038/s43247-024-01440-5
Methods

Orr, J., Gattuso, J.-P., Epitalon, J.-M., & Lavigne, H. (2003). seacarb: Seawater Carbonate Chemistry [Dataset]. In (Editor), CRAN: Contributed Packages. The R Foundation. https://doi.org/10.32614/cran.package.seacarb https://doi.org/10.32614/CRAN.package.seacarb
Software

R Core Team. (2025). R: A language and environment for statistical computing (Version 4.5.0) [Computer software]. R Foundation for Statistical Computing. https://www.r-project.org/
Software

Saley, A. M., Ninokawa, A. T., Doan, A., & Gaylord, B. (2025). Mussel periostracum protects against shell dissolution. PLOS One, 20(7), e0327170. https://doi.org/10.1371/journal.pone.0327170
Methods

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Related Datasets

Software

Rachel Carlson, & Mazie Lewis. (2026). *Code for: Carlson et al. (2025) abiotic mussel shell dissolution analyses* (Version v1.0.0) [Computer software]. Zenodo. https://doi.org/10.5281/ZENODO.20147511 https://doi.org/10.5281/zenodo.20147511

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Parameters

Parameter	Description	Units
shell_number	Unique ID assigned to each shell for tracking purposes	unitless
treatment	Unpainted shells were labeled as shell.trossulus or shell.californianus, depending on species. Painted shells were labeled as shell.trossulus.painted or shell.californianus.painted	unitless
species	Species of marine mussel: *Mytilus californianus* or *Mytilus trossulus*	unitless
paint_treatment	Whether the shell was painted as part of the treatment: painted or unpainted	unitless
G	Rate of abiotic dissolution	umol/hr/g
OmegaAragonite	Aragonite saturation calculated with seacarb in R	unitless
duration	Length of incubation time	hours
shell_wt	Weight of shell	g
shell_length	Length of shell	mm

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Instruments

Dataset-specific Instrument Name	856 Conductivity Module
Generic Instrument Name	Conductivity Meter
Dataset-specific Description	Total alkalinity was measured by a Metrohm 855 Robotic Titrosampler, an 800 Dosino, and an 856 Conductivity Module.
Generic Instrument Description	Conductivity Meter - An electrical conductivity meter (EC meter) measures the electrical conductivity in a solution. Commonly used in hydroponics, aquaculture and freshwater systems to monitor the amount of nutrients, salts or impurities in the water.

Dataset-specific Instrument Name	Horiba Laqua PC 1100 conductivity probe
Generic Instrument Name	Conductivity Meter
Dataset-specific Description	Oxygen and temperature were measured using a PreSens Microx 4 micro-optode; salinity with a Horiba Laqua PC 1100 conductivity probe; and pH with a Horiba Laqua PC 1100 instrument. The Horiba LAQUA PC1100 was used for routine pH measurements. Probe measurements were corrected using periodic spectrophotometric pH measurements.
Generic Instrument Description	Conductivity Meter - An electrical conductivity meter (EC meter) measures the electrical conductivity in a solution. Commonly used in hydroponics, aquaculture and freshwater systems to monitor the amount of nutrients, salts or impurities in the water.

Dataset-specific Instrument Name	oven
Generic Instrument Name	Drying Oven
Dataset-specific Description	Remaining organic materials (byssal threads, epibionts) were removed by drying shells in an oven for 24 h at 60°C.
Generic Instrument Description	a heated chamber for drying

Dataset-specific Instrument Name	800 Dosino
Generic Instrument Name	Metrohm 800 Dosino dosing drive
Dataset-specific Description	Total alkalinity was measured by a Metrohm 855 Robotic Titrosampler, an 800 Dosino, and an 856 Conductivity Module.
Generic Instrument Description	A dosing drive which can be used with a number of different Metrohm dosing devices or Metrohm titrators for simple dosing, titrations, complex automation and liquid handling tasks such as sample transfers or pipetting. This instrument uses a push rod to deliver liquid, via cylinders of variable sizes, to the attached dosing unit. The 800 Dosino can be used with cylinder sizes: 2 mL, 5 mL, 10 mL, 20 mL, or 50 mL.

Dataset-specific Instrument Name	PreSens Microx 4 micro-optode
Generic Instrument Name	Optode
Dataset-specific Description	Oxygen and temperature were measured using a PreSens Microx 4 micro-optode; salinity with a Horiba Laqua PC 1100 conductivity probe; and pH with a Horiba Laqua PC 1100 instrument.
Generic Instrument Description	An optode or optrode is an optical sensor device that optically measures a specific substance usually with the aid of a chemical transducer.

Dataset-specific Instrument Name	Shimadzu Spectrophotometer
Generic Instrument Name	Spectrophotometer
Dataset-specific Description	The Shimadzu spectrophotometer was used for ammonia analyses and for periodic spectrophotometric pH measurements using m-cresol purple dye. Spectrophotometric pH was measured at incubation temperature and used to correct routine pH probe measurements.
Generic Instrument Description	An instrument used to measure the relative absorption of electromagnetic radiation of different wavelengths in the near infra-red, visible and ultraviolet wavebands by samples.

Dataset-specific Instrument Name	Metrohm 855 Robotic Titrosampler
Generic Instrument Name	Titrator
Dataset-specific Description	Total alkalinity was measured by a Metrohm 855 Robotic Titrosampler, an 800 Dosino, and an 856 Conductivity Module.
Generic Instrument Description	Titrators are instruments that incrementally add quantified aliquots of a reagent to a sample until the end-point of a chemical reaction is reached.

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Project Information

Invertebrate calcification and behavior in seawater of decoupled carbonate chemistry (OA decoupling)

Coverage: California coast, USA

NSF Award Abstract:
This research is exploring the capacity of coastal organisms to cope with alterations in seawater chemistry driven by both freshwater inputs and absorption of carbon dioxide into the world's oceans (ocean acidification). The project focuses on calcification responses and behavioral impairments of shoreline animals under altered seawater chemistry, and forefronts a common mussel species (the California mussel), and a common snail (the black turban snail), each abundant on rocky shores along the west coast of North America. The target species operate as exemplar organisms for characterizing the responses of marine invertebrates more generally. Methods involve experimental decoupling of multiple components of the carbonate system of seawater to isolate drivers that are difficult to separate otherwise. Broader impacts include transfer of scientific information to policy-makers, including legislators, as well as training and skill-set development of future generations of scientists and citizens. One Ph.D. student is supported, as are UC Davis undergraduates conducting mentored research. The project also provides research internships for undergraduates from a local community college (Santa Rosa Junior College), many of whom are from underrepresented groups. The latter project component substantially bolsters an ongoing program at Bodega Marine Laboratory that includes efforts in diversity, equity, and inclusion. Data and interpretations from the project are feeding into an existing educational program that links to local K-12 schools and reaches ~10,000 members of the public each year.

Overall, the research of the project is dissecting drivers of calcification and behavioral disruption in key shoreline invertebrates, across present-day and future carbonate system conditions appropriate to coastal marine environments. Efforts are exploring the extent to which calcification depends on one versus multiple parameters of the seawater carbonate system. In particular, existing conceptual models emphasize the importance of calcium carbonate saturation state (Ω) and/or the ratio of bicarbonate to hydrogen ion concentrations ([HCO3-]/[H+]), and the project is examining these mechanisms as well as the possibility that more than one driver acts simultaneously. It is doing so both in bivalves and in gastropods to test for

generality across mollusks. The project is additionally examining whether pH is the only carbonate system factor contributing to known patterns of behavioral impairment in marine invertebrates. Leading explanations for debilitating behaviors induced by ocean acidification involve altered ion channel function, but discussion in the literature continues, and studies that explicitly decouple the carbonate system are necessary.

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.

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Funding

Funding Source	Award
NSF Division of Ocean Sciences (NSF OCE)	OCE-2129942

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