

Biogeochemistry from submarine groundwater discharge in Mo'orea, French Polynesia from August 2021 to March 2022

Website: <https://www.bco-dmo.org/dataset/1010349>

Data Type: Other Field Results

Version: 1

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Project

» [RUI: Collaborative Research: Defining the biogeochemical context and ecological impacts of submarine groundwater discharge on coral reefs](#) (Moorea SGD)

Contributors	Affiliation	Role
Silbiger, Nyssa	California State University Northridge (CSUN)	Principal Investigator
Newman, Sawyer	Woods Hole Oceanographic Institution (WHOI BCO-DMO)	BCO-DMO Data Manager

Abstract

The addition of terrestrial inputs to the ocean can have cascading impacts on coastal biogeochemistry by directly altering the water chemistry and indirectly changing ecosystem metabolism, which also influences water chemistry. Here, we use submarine groundwater discharge (SGD) as a model system to examine the direct geochemical and indirect biologically mediated effects of terrestrial nutrient subsidies on a fringing coral reef. We hypothesize that the addition of new solutes from SGD alters ecosystem metabolic processes including net ecosystem production and calcification, thereby changing the patterns of uptake and release of carbon by benthic organisms. SGD is a common land-sea connection that delivers terrestrially sourced nutrients, carbon dioxide, and organic matter to coastal ecosystems. Our research was conducted at two distinct coral reefs in Mo'orea, French Polynesia, characterized by contrasting flow regimes and SGD biogeochemistry. Using a Bayesian structural equation model, our research elucidates the direct geochemical and indirect biologically mediated effects of SGD on both dissolved organic and inorganic carbon pools. We reveal that SGD-derived nutrients enhance both net ecosystem production and respiration. Furthermore, the study demonstrates that SGD-induced alterations in net ecosystem production significantly influence pH dynamics, ultimately impacting net ecosystem calcification. Notably, the study underscores the context-dependent nature of these cascading direct and indirect effects resulting from SGD, with flow conditions and the composition of the terrestrial inputs playing pivotal roles. Our research provides valuable insights into the interplay between terrestrial inputs and coral reef ecosystems, advancing our understanding of coastal carbon cycling and the broader implications of allochthonous inputs on ecosystem functioning.

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Coverage

Location: Mo'orea, French Polynesia 17.515 S, 149.914 W; depth = 1-2 m

Spatial Extent: N:-17.5155 E:-149.899 S:-17.5411 W:-149.914

Temporal Extent: 2021-08-04 - 2022-03-31

Methods & Sampling

Water sample collection

Field sampling was conducted at Cabral and Varari, two fringing coral reef sites on the western coast of Mo'orea, French Polynesia, during the dry season (August 2021) and wet season (March 2022). Discrete seawater samples were collected approximately 20 cm above the benthos using acid-washed high-density polyethylene (HDPE) bottles or a Subsurface Automated Sampler (SAS) following Enochs et al. (2020). Sampling locations included reef sites, submarine groundwater discharge (SGD) seepage points, and inland groundwater sources. Geographic coordinates were recorded for each sampling location, and samples were collected across seasonal, tidal, and spatial gradients to characterize the influence of submarine groundwater discharge on reef biogeochemistry.

Samples collected for nutrient and fluorescent dissolved organic matter (fDOM) analyses were filtered through 0.22 μm Sterivex filters either in situ prior to entering acid-washed Mylar bags within the SAS or immediately after collection using sterile syringes. Nutrient samples were stored frozen (-20°C) in 50 mL Falcon tubes until analysis. fDOM samples were stored refrigerated (4°C) in amber glass bottles and analyzed within two months of collection.

Samples for total alkalinity (TA) were collected into Tedlar bags pre-fixed with 50% saturated HgCl_2 in deionized water or fixed immediately after collection. Samples were transferred to amber HDPE bottles and stored in a cool, dark environment until analysis. Groundwater and low-salinity samples (salinity <20) were collected in duplicate following Mos et al. (2021), with one sample preserved using HgCl_2 and one filtered and refrigerated. Differences between preservation methods were consistently less than $5 \mu\text{mol kg}^{-1}$, and preserved samples were used in all analyses.

Salinity and pH were measured immediately after collection. pH was measured on the total hydrogen ion concentration scale (pHT) using a Tris-calibrated glass electrode following Dickson Standard Operating Procedure (SOP) 6a. In situ temperature was measured using conductivity-temperature loggers deployed at each study site, and in situ pH was subsequently back-calculated using the seacarb package in R. Salinity was measured immediately after collection using a conductivity electrode. All sample containers and analytical vials were acid washed and rinsed three times with sample water prior to use.

Laboratory analyses

Dissolved inorganic nutrients (NO_x , NH_4^+ , SiO_3^{2-} , and PO_4^{3-}) were analyzed using a Seal Analytical AA3 nutrient autoanalyzer at the University of Hawai'i School of Ocean and Earth Science and Technology (SOEST) Laboratory for Analytical Biogeochemistry. Analytical precision (coefficient of variation) was approximately 0.3% for NO_x , 1.3% for NH_4^+ , 0.5% for SiO_3^{2-} , and 0.2% for PO_4^{3-} .

Fluorescent dissolved organic matter (fDOM) was analyzed on 0.22 μm filtered seawater using a HORIBA Aqualog three-dimensional scanning fluorometer following Nelson et al. (2015). Fluorescence excitation-emission matrices (EEMs) were processed to quantify individual fluorescence components. For statistical analyses, fluorescence peaks were grouped into Humics (Marine Humic-Like and Visible Humic-Like fluorescence) and Proteinaceous (Tryptophan-Like and Tyrosine-Like fluorescence) following Coble et al. (2014).

Total alkalinity was measured using a Mettler-Toledo T5 automatic titrator following Dickson SOP 3b. Instrument accuracy was verified daily using Certified Reference Material supplied by the A. G. Dickson laboratory at Scripps Institution of Oceanography, with analytical accuracy better than $5 \mu\text{mol kg}^{-1}$.

Data Processing Description

This data and code package available at Zenodo supports the results publication (Silbiger et al., 2025, Ecological Monographs). The repository contains R scripts for data processing, Bayesian structural equation modeling, and figure generation, along with associated output files. The dry and wet season discrete water-sample datasets in the repository are derived from the biogeochemical observations in this BCO-DMO dataset. See the references of this dataset to find a link to this Zenodo software holding.

BCO-DMO Curation Notes

Curation Actions Performed on Data File

- "NA" treated as missing data values and converted to blank values in the data file.
- Converted Date from %m/%d/%Y to %Y-%m-%d.
- Created ISO_DateTime.UTC by combining Date and Time, interpreting the values as Pacific/Tahiti local time, converting them to UTC, and formatting the result as %Y-%m-%dT%H:%M:%SZ.
- Renamed Date to Date_Local and Time to Time_Local.
- Set column types: string for Location, LocationID, Plate_Seep, Tide, and Season; number for Lat, Long, Salinity, Temperature, TA_umol_kg, pH_t, Phosphate_umolL, Silicate_umolL, NN_umolL, Ammonia_umolL, MarineHumic_Like, VisibleHumic_Like, Tryptophan_Like, and Tyrosine_Like; date for Date_Local; time for Time_Local; and datetime for ISO_DateTime.UTC.
- Updated metadata for all columns, including descriptions, standard name IDs, and supplied units.
- Marked ISO_DateTime.UTC, Lat, and Long as primary parameters.
- Saved the final table as 1010349_v1_submarine_groundwater_discharge_biogeochemistry_data.csv.

Problem Description

Missing values in the data file indicate missing samples or sample contamination.

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Related Publications

Coble, P. G., Lead, J., Baker, A., Reynolds, D. M., & Spencer, R. G. M. (Eds.). (2014). Aquatic Organic Matter Fluorescence. <https://doi.org/10.1017/cbo9781139045452> <https://doi.org/10.1017/CBO9781139045452>
Methods

Dickson, A.G., Sabine, C.L. and Christian, J.R. (Eds.) 2007. Guide to best practices for ocean CO₂ measurements. PICES Special Publication 3, 191 pp. https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/Handbook_2007.html
Methods

Enochs, I. C., Formel, N., Shea, L., Chomiak, L., Piggot, A., Kirkland, A., & Manzello, D. (2020). Subsurface automated samplers (SAS) for ocean acidification research. *Bulletin of Marine Science*, 96(4), 735–752. <https://doi.org/10.5343/bms.2020.0018>
Methods

Mos, B., Holloway, C., Kelaher, B. P., Santos, I. R., & Dworjanyn, S. A. (2021). Alkalinity of diverse water samples can be altered by mercury preservation and borosilicate vial storage. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-89110-w>
Methods

Nelson, C. E., Donahue, M. J., Dulaiova, H., Goldberg, S. J., La Valle, F. F., Lubarsky, K., ... Thomas, F. I. M. (2015). Fluorescent dissolved organic matter as a multivariate biogeochemical tracer of submarine groundwater discharge in coral reef ecosystems. *Marine Chemistry*, 177, 232–243. doi:[10.1016/j.marchem.2015.06.026](https://doi.org/10.1016/j.marchem.2015.06.026)
Methods

Silbiger, N. J., Donahue, M. J., Hagedorn, B., Barnas, D. M., Jorissen, H., Kerlin, J. R., McClintock, R., Nixon, E., Sparagon, W. J., Zeff, M., & Nelson, C. E. (2025). Terrestrial nutrient inputs restructure coral reef dissolved carbon fluxes via direct and indirect effects. *Ecological Monographs*, 95(2). Portico. <https://doi.org/10.1002/ecm.70020>

Related Datasets

Software

Dr. Nyssa Silbiger. (2025). njsilbiger/BiogeochemicalCascades_SGD: V1.1 (Version SGD_EcoMetab) [Computer software]. Zenodo. <https://doi.org/10.5281/ZENODO.15104032> <https://doi.org/10.5281/zenodo.15104032>

Parameters

Parameter	Description	Units
Location	Name of the Mo'orea sampling site. Values identify the primary field site associated with the sample (Cabral or Varari).	unitless
Lat	Latitude of the sampling location in decimal degrees; negative values indicate degrees south.	decimal degrees
Long	Longitude of the sampling location in decimal degrees; negative values indicate degrees west.	decimal degrees
LocationID	Unique alphanumeric identifier for the individual reef plate location, seepage point, spring, beach pit, or other sampled location within a site.	unitless
Plate_Seep	Sampling-location category indicating whether the sample was collected at an experimental reef plate location, submarine groundwater discharge seep, spring, beach pit, offshore/reference location, or another location type represented in the data.	unitless
Date_Local	Calendar date on which the water sample was collected in local time (TAHT (Tahiti Time)).	yyyy-mm-dd
Time_Local	Local time of water-sample collection in Mo'orea, French Polynesia (TAHT (Tahiti Time)).	HH:MM:SS
ISO_DateTime_UTC	Datetime of water-sample collection in UTC. This column was created from the Date_Local and Time_Local columns, and values were converted from Tahiti Local Time to UTC.	unitless
Tide	Tidal category at the time of sample collection. Values are High or Low; NA is used when a tidal category was not applicable or unavailable.	unitless

Salinity	Salinity measured immediately after sample collection using a DuraProbe 4-cell conductivity electrode connected to a Thermo Scientific Orion Star multimeter.	PSU
Temperature	In situ water temperature measured with an Onset HOBO U24-002-C conductivity/temperature logger.	degrees Celsius
TA_umol_kg	Total alkalinity of the water sample. Samples were analyzed using a Mettler-Toledo T5 automatic titrator following Dickson SOP 3b; accuracy was verified daily with Dickson certified reference material and was better than 5 micromoles per kilogram.	micromoles per kilogram
pH_t	Seawater pH on the total hydrogen ion concentration scale. pH was measured with a Tris-calibrated Thermo Scientific Orion ROSS Ultra pH/ATC Triode following Dickson SOP 6a and adjusted to in situ temperature using the seacarb R package.	unitless
Phosphate_umolL	Concentration of dissolved inorganic phosphate (PO_4^{3-}) in 0.22-micrometer-filtered water, measured with a Seal Analytical AA3 nutrient autoanalyzer.	micromoles per liter
Silicate_umolL	Concentration of dissolved silicate (reported as SiO_3^{2-}) in 0.22-micrometer-filtered water, measured with a Seal Analytical AA3 nutrient autoanalyzer.	micromoles per liter
NN_umolL	Concentration of nitrate plus nitrite (NO_x) in 0.22-micrometer-filtered water, measured with a Seal Analytical AA3 nutrient autoanalyzer.	micromoles per liter
Ammonia_umolL	Concentration of Ammonia (NH_4^+) in 0.22-micrometer-filtered water, measured with a Seal Analytical AA3 nutrient autoanalyzer.	micromoles per liter
MarineHumic_Like	Marine humic-like fluorescent dissolved organic matter component measured from excitation-emission matrices of 0.22-micrometer-filtered water using a HORIBA Aqualog 3-D scanning fluorometer.	Raman units
VisibleHumidic_Like	Visible humic-like fluorescent dissolved organic matter component measured from excitation-emission matrices of 0.22-micrometer-filtered water using a HORIBA Aqualog 3-D scanning fluorometer.	Raman units
Tryptophan_Like	Tryptophan-like, proteinaceous fluorescent dissolved organic matter component measured from excitation-emission matrices of 0.22-micrometer-filtered water using a HORIBA Aqualog 3-D scanning fluorometer.	Raman units

Tyrosine_Like	Tyrosine-like, proteinaceous fluorescent dissolved organic matter component measured from excitation-emission matrices of 0.22-micrometer-filtered water using a HORIBA Aqualog 3-D scanning fluorometer.	Raman units
Season	Seasonal sampling period. Dry-season sampling occurred in August 2021 and wet-season sampling occurred in March 2022.	unitless

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Instruments

Dataset-specific Instrument Name	Seal Analytical AA3 Nutrient Autoanalyzer
Generic Instrument Name	Bran+Luebbe / SEAL Analytical AutoAnalyzer 3 (AA3) continuous-flow analyzer
Dataset-specific Description	Manufacturer: Seal Analytical Model: AA3 Continuous Flow AutoAnalyzer Purpose: Determination of nitrate + nitrite (NO _x), ammonium (NH ₄ ⁺), phosphate (PO ₄ ³⁻), and silicate (SiO ₃ ²⁻). Calibration: Multi-point calibration using certified nutrient standards. Analytical precision was approximately 0.3% (NO _x), 1.3% (NH ₄ ⁺), 0.5% (SiO ₃ ²⁻), and 0.2% (PO ₄ ³⁻).
Generic Instrument Description	The AutoAnalyzer 3 (AA3) is a segmented continuous-flow analyzer (continuous flow analyzer, CFA) used for automated colorimetric analysis of dissolved nutrients and other analytes in environmental, seawater, freshwater, wastewater, soil, and agricultural samples. The AA3 was originally manufactured by Bran+Luebbe and, following acquisition of the product line in 2006, has continued to be manufactured and supported by SEAL Analytical. The AA3 is the third-generation instrument in the Technicon AutoAnalyzer family and is widely used for determination of nitrate, nitrite, ammonium, phosphate, silicate, and other dissolved nutrients. See the description from the manufacturer.

Dataset-specific Instrument Name	Orion Star Multimeter with DuraProbe Conductivity Electrode
Generic Instrument Name	Conductivity Meter
Dataset-specific Description	Manufacturer: Thermo Fisher Scientific Model: Orion Star Meter with DuraProbe 4-cell Conductivity Probe Purpose: Measurement of seawater salinity immediately following sample collection. Calibration: Conductivity probe calibrated according to manufacturer recommendations prior to field sampling. Measurement specifications: Conductivity accuracy $\pm 0.5\%$ of reading (± 1 digit); conductivity resolution 0.001 $\mu\text{S cm}^{-1}$ (minimum, auto-ranging); salinity resolution 0.01 PSU; salinity accuracy $\pm 0.5\%$ of reading (± 1 digit); temperature accuracy $\pm 0.1^\circ\text{C}$.
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	Traceable Digital Thermometer
Generic Instrument Name	digital thermometer
Dataset-specific Description	Manufacturer: Control Company Model: 5-077-8 Accuracy: ± 0.05 °C Resolution: 0.001 °C Purpose: Temperature measurement during pH analyses.
Generic Instrument Description	An instrument that measures temperature digitally.

Dataset-specific Instrument Name	Subsurface Automated Sampler (Custom Build)
Generic Instrument Name	Discrete water sampler
Dataset-specific Description	Manufacturer: Custom-built instrument described by Enochs et al. (2020) Model: Subsurface Automated Sampler (SAS) Purpose: Used to collect discrete seawater samples underwater during selected sampling periods. Calibration: Sampling system; no sensor calibration required.
Generic Instrument Description	A device that collects an in-situ discrete water sample from any depth and returns it to the surface without contamination by the waters through which it passes, such as a water bottle.

Dataset-specific Instrument Name	HORIBA Aqualog 3-D Scanning Fluorometer
Generic Instrument Name	Fluorometer
Dataset-specific Description	Manufacturer: HORIBA Scientific Model: Aqualog® 3-D Scanning Fluorometer Purpose: Collection of excitation-emission matrices (EEMs) and quantification of Marine Humic-Like, Visible Humic-Like, Tryptophan-Like, and Tyrosine-Like fluorescence. Calibration: Instrument-specific excitation and emission corrections, Raman normalization, and blank subtraction were applied according to laboratory protocols.
Generic Instrument Description	A fluorometer or fluorimeter is a device used to measure parameters of fluorescence: its intensity and wavelength distribution of emission spectrum after excitation by a certain spectrum of light. The instrument is designed to measure the amount of stimulated electromagnetic radiation produced by pulses of electromagnetic radiation emitted into a water sample or in situ.

Dataset-specific Instrument Name	HOBO Conductivity/Temperature Logger
Generic Instrument Name	Onset HOBO Saltwater Conductivity/Salinity data logger U24-002-C
Dataset-specific Description	Manufacturer: Onset Computer Corporation Model: U24-002-C Conductivity accuracy: $\pm 3\%$ of reading or $50 \mu\text{S/cm}$ (low range), $\pm 5\%$ of reading within $\pm 3,000 \mu\text{S/cm}$ of the calibration point (high range); conductivity resolution (precision): $2 \mu\text{S/cm}$; temperature accuracy: $\pm 0.1^\circ\text{C}$; and resolution: 0.01°C Purpose: In situ temperature measurements used to calculate carbonate chemistry.
Generic Instrument Description	HOBO Salt Water Conductivity/Salinity Data Logger is a cost-effective data logger for measuring cost-effective data logger for measuring salinity, conductivity, and temperature in saltwater environments with relatively small changes in salinity ($\pm 5,000 \mu\text{S/cm}$) such as saltwater bays, or to detect salinity events such as upwelling, rainstorm, and discharge events.

Dataset-specific Instrument Name	Thermo Scientific Orion ROSS Ultra pH/ATC Triode
Generic Instrument Name	pH Sensor
Dataset-specific Description	Manufacturer: Thermo Fisher Scientific Model: Orion™ ROSS Ultra pH/ATC Triode Purpose: Measurement of seawater pH on the total hydrogen ion concentration scale (pHT). Calibration: Tris-buffer calibration following Dickson SOP 6a Measurement specifications: mV range ± 2000.0 mV; mV resolution 0.1 mV; mV accuracy ± 0.2 mV or $\pm 0.05\%$ of reading (whichever is greater). The meter provides pH accuracy of ± 0.002 pH with a resolution of up to 0.001 pH.
Generic Instrument Description	An instrument that measures the hydrogen ion activity in solutions. The overall concentration of hydrogen ions is inversely related to its pH. The pH scale ranges from 0 to 14 and indicates whether acidic (more H^+) or basic (less H^+).

Dataset-specific Instrument Name	Mettler-Toledo Automatic Titrator
Generic Instrument Name	Titrator
Dataset-specific Description	Manufacturer: Mettler-Toledo Model: T5 Automatic Titrator Purpose: Determination of total alkalinity. Calibration: Daily calibration and validation using Certified Reference Materials (CRM) from the A. G. Dickson Laboratory (Scripps Institution of Oceanography). Analytical accuracy was better than $5 \mu\text{mol kg}^{-1}$.
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

RUI: Collaborative Research: Defining the biogeochemical context and ecological impacts of submarine groundwater discharge on coral reefs (Moorea SGD)

Coverage: Mo'orea, French Polynesia

NSF Award Abstract:

Submarine groundwater discharge (SGD) is the flow of water from land through the coastal seafloor into the nearby ocean. Approximately 13,000 cubic kilometers of groundwater is discharged into coastal environments every year, yet the effects of this fresh and often nutrient rich SGD are still poorly understood for coral reefs. This SGD input is driven by changes in precipitation, human land use, sea-level rise, tidal amplitude, and groundwater usage, many of which are rapidly changing with climate and human impacts. This project improves our understanding of SGD effects on coral reefs to better predict how both natural and human-induced changes will affect coastal ecosystem functioning in the future. Working in one of the most comprehensively studied coral reef ecosystems in the Pacific (Mo'orea, French Polynesia, home of the Mo'orea Coral Reef Ecosystem LTER); this project tests the influence of SGD on individual, community, and ecosystem-scale coral reef processes. Using mensurative studies, caging experiments, and a synthetic model, the investigators: 1) characterize SGD gradients and relate it to high resolution coral reef cover data, 2) determine how individual to ecosystem processes are influenced by SGD, and 3) develop a synthetic model to show how changes in SGD fluxes will alter reef ecosystem functioning. As SGD is a common feature on nearshore coral reefs worldwide, the results of this study have global implications for understanding the performance of coral reefs, which are essential economic, cultural, and scientific resources. This project is structured to provide training across multiple career levels, linking 13 undergraduate students, 2 graduate students, 2 senior personnel, 1 postdoctoral researcher, 1 female beginning lead investigator, and 2 senior co-investigators, with a focus on encouraging participation from underrepresented groups (e.g., through the Alaska Native and Native Hawaiian, Asian American and Native American Pacific Islander, and Hispanic-Serving Institutions of California State University Northridge, the University of Hawai'i at Mānoa, and California State University Long Beach). The investigators work with local K-12 students and teachers in Mo'orea and collaborate with an artist-in-residence to communicate science to the broader public through interactive and immersive art experiences in Mo'orea, Miami, and Los Angeles.

SGD is a natural and understudied feature of many nearshore coral reef ecosystems, which can contribute substantial changes to marine biogeochemistry, with impacts for coastal organisms such as reef-building corals, macroalgae, and bioeroders. SGD may play a key role in coral reef ecosystem functioning because it alters key physicochemical parameters (e.g., temperature, salinity, and nutrient and carbonate chemistry) that substantially affect both biotic and abiotic processes on coral reefs. This project (i) characterizes the spatial extent and biogeochemical signal of SGD in Mo'orea, French Polynesia, (ii) identifies how SGD influences microbial processes, benthic organism growth rates and physiology, species interactions between corals, macroalgae, and herbivores, and net ecosystem calcification and production rates, and (iii) quantitatively assesses how changes in SGD fluxes will alter reef biogeochemistry and ecosystem functioning through an integrative modelling effort. Specifically, the hydrogeological, biogeochemical, and ecological data collected in this study are synthesized in a Bayesian structural equation model. This project characterizes and quantifies how SGD directly and indirectly affects ecosystem functioning via changes in biogeochemistry and altered individual to ecosystem responses, thereby providing a better capacity to track and predict alterations in reef ecosystem function.

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-1924281

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