**Supplemental Material for:**

**Title:** Spatial dynamics of animal-mediated nutrients in temperate waters

**Authors:** Em G Lim1,2\*, Claire M Attridge1, Kieran D Cox1, Jasmin M Schuster2,3,4, Kiara R Kattler1§, Emily J Leedham1¶, Bridget Maher3, Andrew L Bickell1†, Francis Juanes3, Isabelle M Côté1

**Affiliations:**

1Department of Biological Sciences, Simon Fraser University, Burnaby, British Columbia, Canada

2Bamfield Marine Sciences Center, Bamfield, British Columbia, Canada

3Department of Biology, University of Victoria, Victoria, British Columbia, Canada

4Hakai Institute, Campbell River, British Columbia, Canada

§Present address: Department of Biological Sciences,University of Alberta, Edmonton, Canada

¶Present address: Institute of Marine Science, Waipapa Taumata Rau, The University of Auckland, New Zealand

†Present address: Department of Biology, University of Victoria, British Columbia, Canada

\*Corresponding author: Em Lim, [em\_lim@sfu.ca](mailto:em_lim@sfu.ca)

**A green hill with yellow dots and a black text

Description automatically generated**

**Figure S1.01.** Schematic of methods used to survey biological communities adjacent to a kelp forest, kelp forest density, and NH₄⁺ inside vs outside the forest. We first ran a 50 m Reef Life Survey transect parallel to the kelp forest (green shaded area) and counted fishes in the water column within 5 m on either side of the transect (light blue shaded areas), and cryptic fishes and macroinvertebrates within 1 m on either side of the transect (darker blue shaded area). Next, we ran four 5 m long transects into the kelp forest, 5 m apart from each other, to assess kelp density and biomass within 0.5 m on either side of the transect (four perpendicular black lines). Finally, we took NH₄⁺ samples at the beginning and end of the first three kelp transects (yellow circles) to compare NH₄⁺ inside vs outside kelp forests.

A comparison of different types of mass

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**Figure S1.02**. Relationship between Shannon diversity and (a) kelp forest biomass and (b) animal biomass in kelp forests across 16 sites (small-scale) in Barkley Sound, British Columbia, Canada. Macro = *Macrocystis pyrifera*, Nereo = *Nereocystis luetkeana*, No kelp = no kelp control.

**A diagram of a flow rate

Description automatically generated**

**Figure S1.03.** Change in ammonium in containers containing zero or four California sea cucumbers (*Apostichopus californicus*) relative to initial ammonium concentration after 24 hours in mesocosms with varying flow rates. Shaded areas indicate 95% confidence intervals, and raw data are plotted as points. While NH₄⁺ concentration remained the same across flow rates in the control mesocosms, sea cucumbers enriched NH₄⁺ concentration when flow was low. This enrichment declined as flow rate increased.

**Table S1.01.** Rocky reef sites sampled using Reef Life Survey methods, with the associated coordinates and years each site was surveyed.

|  |  |  |  |
| --- | --- | --- | --- |
| **Site code** | **Site name** | **Coordinates** | **Years sampled** |
| BMSC1 | Dodger Channel | 48.82894897, -125.1975708 | 2021, 2022, 2023 |
| BMSC2 | Kirby | 48.85039902, -125.1987686 | 2021, 2023 |
| BMSC3 | Ohiat | 48.85558319, -125.1837997 | 2021, 2022, 2023 |
| BMSC4 | Kii xin | 48.81511688, -125.1753311 | 2021, 2023 |
| BMSC5 | Taylor Rock | 48.82733154, -125.1966019 | 2021, 2022, 2023 |
| BMSC6 | Baeria Rocks South Island | 48.95023346, -125.1555481 | 2021, 2022, 2023 |
| BMSC7 | Baeria Rocks N Island Southside | 48.95464325, -125.1539917 | 2021 |
| BMSC8 | Baeria Rocks N Island Northside | 48.95508194, -125.1533737 | 2021, 2022, 2023 |
| BMSC9 | Eagle Bay | 48.83478928, -125.1470261 | 2021, 2022, 2023 |
| BMSC10 | Ross Islets Slug Island | 48.87051773, -125.160347 | 2021, 2022, 2023 |
| BMSC11 | Wizard Island South | 48.85746765, -125.1582336 | 2021, 2022, 2023 |
| BMSC12 | Wizard Island North | 48.858284, -125.1609192 | 2021, 2022, 2023 |
| BMSC13 | Effingham West | 48.8650322, -125.3137207 | 2021, 2022 |
| BMSC14 | Effingham Archipelago | 48.87908173, -125.2974014 | 2021, 2022 |
| BMSC15 | Raymond Kelp Rock | 48.88028336, -125.3128815 | 2021, 2022 |
| BMSC16 | Faber Islets | 48.89070129, -125.300499 | 2021, 2022 |
| BMSC17 | Wouwer Channel | 48.86548233, -125.3614807 | 2021, 2022 |
| BMSC18 | Eussen Rock | 48.91161728, -125.2670364 | 2021, 2022 |
| BMSC19 | Ed King SW Pyramid | 48.82860184, -125.2212982 | 2021, 2022, 2023 |
| BMSC20 | Ed King East | 48.83566666, -125.214798 | 2021, 2022, 2023 |
| BMSC21 | Dixon SW | 48.85205078, -125.1235657 | 2021, 2022, 2023 |
| BMSC22 | Dixon Inside | 48.85426712, -125.1170349 | 2021, 2022, 2023 |
| BMSC23 | Aguilar Point | 48.837589, -125.144145 | 2022, 2023 |
| BMSC24 | Swiss Boy | 48.916073, -125.131174 | 2023 |
| BMSC25 | Goby Town | 48.838595, -125.135015 | 2023 |
| BMSC26 | Hosie South | 48.9071, -125.037017 | 2023 |
| BMSC27 | San Jose North Island | 48.901183, -125.060433 | 2023 |

**Table S1.02.** Kelp forest site names, coordinates, survey dates and dominant kelp forest species. Macro = giant kelp (*Macrocystis pyrifera*), Nereo = bull kelp (*Nereocystis luetkeana*).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Site code** | **Site name** | **Coordinates** | **Date** | **Kelp** |
| KCCA1 | Ross Islet Slug Island | 48.87039, -125.1599 | 2022-07-04 | Macro |
| KCCA2 | Between Scott & Brady | 48.83287, -125.1493 | 2022-07-05 | Macro |
| KCCA3 | Dodger Channel 1 | 48.83072, -125.19439 | 2022-07-06 | Macro |
| KCCA4 | Flemming 112 | 48.87868, -125.1434 | 2022-07-07 | Macro |
| KCCA6 | Less Dangerous Bay | 48.87535, -125.0915 | 2022-07-24 | None |
| KCCA7 | Ed King East Inside | 48.83608, -125.2131 | 2022-07-25 | Macro |
| KCCA9 | Wizard Islet South | 48.85728, -125.1595 | 2022-07-27 | Macro |
| KCCA12 | North Helby Rock | 48.85831, -125.1649 | 2022-08-03 | Macro |
| KCCA14 | Danvers Danger Rock | 48.877, -125.0923 | 2022-08-06 | Macro |
| KCCA15 | Cable Beach | 48.82484, -125.16067 | 2022-08-07 | Nereo |
| KCCA16 | Tzartus 116 | 48.90084, -125.0811 | 2022-08-18 | Macro |
| KCCA17 | Turf Island 2 | 48.884864, -125.146937 | 2022-08-20 | Macro |
| KCCA18 | Second Beach | 48.815969, -125.174 | 2022-08-21 | Nereo |
| KCCA19 | Wizard Islet North | 48.85916, -125.15908 | 2022-08-22 | None |
| KCCA21 | Bordelais Island | 48.81822, -125.2294516 | 2022-09-01 | Nereo |
| KCCA22 | Taylor Rock | 48.82721, -125.19717 | 2022-09-05 | Macro |

**Table S1.03**. Wet weight estimates for each invertebrate species used to calculate total biomass for Reef Life Survey data. We used shell-free wet weight for species with large shells (e.g., hermit crabs, snails). When weight information was unavailable for a species, we used estimates from the closest relative or most similarly sized species available. For the three species we sized in situ (*Pycnopodia helianthoides*, *Crassadoma gigantea*, and *Haliotis kamtschatkana*), we used published length-weight relationships to calculate wet weight from size.

|  |  |  |
| --- | --- | --- |
| **Species** | **Weight (g)** | **Source, proxy species if applicable** |
| *Cancer productus* | 200 | E.G. Lim, unpubl. |
| *Glebocarcinus oregonensis* | 3 | Hines 1982, small crabs |
| *Romaleon antennarium* | 3 | Hines 1982, small crabs |
| *Chorilia longipes* | 1.235 | Hines 1982, *Pugettia richii* |
| *Pugettia foliata* | 1.235 | Hines 1982, *Pugettia richii* |
| *Pugettia gracilis* | 1.235 | Hines 1982, *Pugettia richii* |
| *Pugettia producta* | 46 | Hines 1982 |
| *Pugettia richii* | 1.235 | Hines 1982 |
| *Scyra acutifrons* | 2 | Hines 1982 |
| *Scyra* spp*.* | 1.235 | Hines 1982 |
| *Cryptolithodes sitchensis* | 3 | Hines 1982, small crabs |
| *Cryptolithodes typicus* | 3 | Hines 1982, small crabs |
| *Hapalogaster mertensii* | 65 | Stewart et al. 2015, *Phyllolithodes papillosus* |
| *Lopholithodes mandtii* | 65 | Stewart et al. 2015, *Phyllolithodes papillosus* |
| *Phyllolithodes papillosus* | 65 | Stewart et al. 2015 |
| *Oregonia gracilis* | 3 | Hines 1982, small crabs |
| *Paguroidea* spp*.* | 0.43 | McKinney et al. 2004, Paguroidea |
| *Pagurus beringanus* | 0.43 | McKinney et al. 2004, Paguroidea |
| *Pagurus hemphilli* | 0.43 | McKinney et al. 2004, Paguroidea |
| *Pandalus danae* | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| *Pandalus gurneyi* | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| *Pandalus* spp*.* | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| *Pandulus spp.* | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| *Lophopanopeus bellus* | 3 | Hines 1982, small crabs |
| *Pachycheles pubescens* | 4.25 | Stillman and Somero 1996, *Petrolisthes* spp*.* |
| *Petrolisthes eriomerus* | 4.25 | Stillman and Somero 1996, *Petrolisthes* spp*.* |
| *Heptacarpus stylus* | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| Brachyura spp. | 3 | Hines 1982, small crabs |
| Unidentified shrimp | 0.11 | McKinney et al. 2004, *Palaemonetes pugio* |
| *Polyorchis penicillatus* | 0.01 | Båmstedt and Martinussen 2015, *Bolinopsis infundibulum* |
| *Mitrocoma cellularia* | 0.01 | Båmstedt and Martinussen 2015, *Bolinopsis infundibulum* |
| *Pleurobrachia bachei* | 0.01 | Båmstedt and Martinussen 2015, *Bolinopsis infundibulum* |
| *Bolinopsis infundibulum* | 0.01 | Båmstedt and Martinussen 2015 |
| *Evasterias troschelii* | 66.5 | O’Clair and Rice 1985 |
| *Leptasterias hexactis* | 5.5 | Menge 1975, *Leptasterias* spp*.* |
| *Leptasterias* spp*.* | 5.5 | Menge 1975, *Leptasterias* spp*.* |
| *Orthasterias koehleri* | 66.5 | O’Clair and Rice 1985, *Evasterias troschelii* |
| *Pisaster brevispinus* | 146.18 | Peters et al. 2019, *Pisaster giganteus* |
| *Pisaster ochraceus* | 128 | Sanford 2002 |
| *Pycnopodia helianthoides* | 0.018\*size^3.13 | Lee et al. 2016 |
| *Stylasterias forreri* | 66.5 | O’Clair and Rice 1985, *Evasterias troschelii* |
| *Patiria miniata* | 26.97 | Peters et al. 2019 |
| *Henricia pumila* | 10 | Menge 1975, *Henricia* spp. |
| *Henricia* spp*.* | 10 | Menge 1975 |
| *Dermasterias imbricata* | 92 | Montgomery 2014 |
| *Mediaster aequalis* | 10 | Menge 1975, *Henricia spp*. |
| *Solaster dawsoni* | 486 | Montgomery 2014, *Solaster stimpsoni* |
| *Solaster stimpsoni* | 486 | Montgomery 2014 |
| *Pteraster tesselatus* | 10 | Menge 1975, *Henricia* spp*.* |
| *Mesocentrotus franciscanus* | 29.51 | Schuster and Bates 2023 |
| *Strongylocentrotus droebachiensis* | 20 | Stewart et al. 2015, *Strongylocentrotus polyacanthus* |
| *Strongylocentrotus purpuratus* | 20 | Stewart et al. 2015, *Strongylocentrotus polyacanthus* |
| *Apostichopus californicus* | 319.31 | Peters et al. 2019, *Apostichopus parvimensis* |
| *Chlamys hastata* | 2.5 | MacDonald et al. 1991, *Chlamys* spp*.* |
| *Crassadoma gigantea* | 0.038\*size^2.39 | MacDonald et al. 1991 |
| *Enteroctopus dofleini* | 137.5 | Osborn 1995, *Octopus rubescens* |
| *Octopus rubescens* | 80 | Osborn 1995 |
| *Opalia wroblewskyi* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Diodora aspera* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Megathura crenulata* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Haliotis kamtschatkana* | 0.00058\*size^3.2 | Zhang et al. 2007 |
| *Neverita lewisii* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Ceratostoma foliatum* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Nucella lamellosa* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Armina californica* | 0.54 | McKinney et al. 2004, gastropods |
| *Cadlina luteomarginata* | 0.54 | McKinney et al. 2004, gastropods |
| *Cadlina modesta* | 0.54 | McKinney et al. 2004, gastropods |
| *Cadlina sylviaearleae* | 0.54 | McKinney et al. 2004, gastropods |
| *Coryphella verrucosa* | 0.54 | McKinney et al. 2004, gastropods |
| *Dendronotus iris* | 0.54 | McKinney et al. 2004, gastropods |
| *Dirona albolineata* | 0.54 | McKinney et al. 2004, gastropods |
| *Dirona pellucida* | 0.54 | McKinney et al. 2004, gastropods |
| *Diaulula odonoghuei* | 0.54 | McKinney et al. 2004, gastropods |
| *Diaulula sandiegensis* | 0.54 | McKinney et al. 2004, gastropods |
| *Peltodoris nobilis* | 0.54 | McKinney et al. 2004, gastropods |
| *Doris montereyensis* | 0.54 | McKinney et al. 2004, gastropods |
| *Doris odhneri* | 0.54 | McKinney et al. 2004, gastropods |
| *Antiopella fusca* | 0.54 | McKinney et al. 2004, gastropods |
| *Hermissenda crassicornis* | 0.54 | McKinney et al. 2004, gastropods |
| *Acanthodoris hudsoni* | 0.54 | McKinney et al. 2004, gastropods |
| *Acanthodoris nanaimoensis* | 0.54 | McKinney et al. 2004, gastropods |
| *Onchidoris bilamellata* | 0.54 | McKinney et al. 2004, gastropods |
| *Limacia cockerelli* | 0.54 | McKinney et al. 2004, gastropods |
| *Polycera tricolor* | 0.54 | McKinney et al. 2004, gastropods |
| *Triopha catalinae* | 0.54 | McKinney et al. 2004, gastropods |
| *Triopha modesta* | 0.54 | McKinney et al. 2004, gastropods |
| *Triopha* spp*.* | 0.54 | McKinney et al. 2004, gastropods |
| *Melibe leonina* | 0.54 | McKinney et al. 2004, gastropods |
| *Tritonia festiva* | 0.54 | McKinney et al. 2004, gastropods |
| *Acmaea mitra* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Lottia scutum* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Berthella chacei* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Calliostoma ligatum* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Tegula funebralis* | 0.91 | Palmer 1982, *Nucella* spp*.* |
| *Pomaulax gibberosus* | 31 | Schuster and Bates 2023 |
| *Eurylepta leoparda* | 0.54 | McKinney et al. 2004, gastropods |

**Table S1.04**. Akaike’s Information Criterion (AIC) values calculated for each model of ammonium concentration in relation to animal abundance (AA) or animal biomass (AB), Shannon diversity (SHD) or Simpson diversity (SID), tidal exchange rate (T), depth (D), and an interaction term. RE = random effect of both site and year. k is the number of parameters in the model. The model with the lowest AIC score is the “best” model; ΔAIC is the difference in AIC score between a given model and the “best” model; AIC weight represents the probability that a model is the best model, given the data and the set of candidate models.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Predictors** | **k** | **AIC** | **ΔAIC** | **AIC weight** |
| AA + SHD + T + D + AA:T + RE | 9 | 45.60 | 0.00 | 0.50 |
| AA + SID + T + D + AA:T + RE | 9 | 46.09 | 0.50 | 0.39 |
| AB + SHD + T + D + AB:T + RE | 9 | 49.70 | 4.10 | 0.06 |
| AB + SID + T + D + AB:T + RE | 9 | 49.98 | 4.38 | 0.06 |

**Table S1.05**. Akaike’s Information Criterion (AIC) values calculated for each model of delta ammonium concentration in vs outside kelp forests in relation to animal abundance (AA) or animal biomass (AB), Shannon diversity (SHD) or Simpson diversity (SID), kelp species (KS), kelp biomass (KB), tidal exchange rate (T), depth (D), and three interaction terms. RE = random effect of site. k is the number of parameters in the model. The model with the lowest AIC score is the “best” model; ΔAIC is the difference in AIC score between a given model and the “best” model; AIC weight represents the probability that a model is the best model, given the data and the set of candidate models.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Predictors** | **k** | **AIC** | **ΔAIC** | **AIC weight** |
| AB + SHD + KS + KB + T + D + AB :T + AB :KB + KB:T + RE | 13 | -33.16 | 0.00 | 0.30 |
| AA + SHD + KS + KB + T + D + AA:T + AA:KB + KB:T + RE | 13 | -32.89 | 0.27 | 0.26 |
| AA + SID + KS + KB + T + D + AA:T + AA:KB + KB:T + RE | 13 | -32.80 | 0.36 | 0.25 |
| AB + SID + KS + KB + T + D + AB:T + AB:KB + KB:T + RE | 13 | -32.38 | 0.78 | 0.20 |

**Table S1.06.** Excretion rate model to determine log transformed NH₄⁺ excretion rate (uM/hour/L) for California sea cucumbers (*Apostichopus californicus*) based on size index: sqrt(length\*girth). Adjusted R-squared for this model is 0.39.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **t value** | **p value** |
| Intercept | 1.40 | 0.22 | 6.23 | < 0.001 |
| Size index | 0.05 | 0.009 | 5.52 | < 0.001 |

**Table S1.07.** Excretion rate model to determine log transformed NH₄⁺ excretion rate (uM/hour/L) for red rock crabs (*Cancer productus*) based on carapace width (mm). Adjusted R-squared for this model is 0.82.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **t value** | **p value** |
| Intercept | 1.22 | 0.32 | 3.76 | 0.002 |
| Carapace | 0.02 | 0.003 | 8.73 | < 0.001 |

**Table S1.08.** Meso-scale linear mixed-effect model describing drivers of among-site variability in ammonium concentration. The model was constructed with a gamma distribution (link = ‘log’), so coefficients are presented in log space. Continuous predictors were centred and scaled to compare effect sizes between predictors with varying units.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.61 | 0.25 | -2.48 | 0.01 |
| Abundance | -0.07 | 0.12 | -0.55 | 0.58 |
| Tidal exchange | 0.00 | 0.08 | 0.00 | 1.00 |
| Biodiversity | -0.10 | 0.12 | -0.80 | 0.42 |
| Depth | 0.05 | 0.09 | 0.51 | 0.61 |
| Abundance:tide | -0.25 | 0.10 | -2.54 | 0.01 |

**Table S1.09**. Small-scale linear mixed effect model describing drivers of ammonium concentration inside – outside kelp forests. Continuous predictors were centred and scaled. Kelp species is a categorical predictor with three levels: macro = *Macrocystis pyrifera* (intercept level), nereo = *Nereocystis luetkeana*, none = no kelp control.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 0.16 | 0.03 | 5.91 | < 0.001 |
| Kelp nereo | 0.24 | 0.07 | 3.64 | < 0.001 |
| Kelp none | -0.40 | 0.10 | -4.13 | < 0.001 |
| Kelp biomass | 0.29 | 0.05 | 5.95 | < 0.001 |
| Tidal exchange | 0.06 | 0.02 | 2.25 | 0.02 |
| Animal biomass | 0.05 | 0.03 | 1.64 | 0.10 |
| Biodiversity | -0.03 | 0.02 | -1.20 | 0.23 |
| Depth | 0.04 | 0.03 | 1.31 | 0.19 |
| Kelp:tide | 0.29 | 0.08 | 3.85 | < 0.001 |
| Kelp:animals | -0.05 | 0.02 | -2.08 | 0.04 |
| Tide:animals | -0.13 | 0.04 | -3.19 | 0.001 |

**Table S1.10**. Fine-scale linear model describing ammonium variation between cages with 0, 1, or 2 California sea cucumbers (*Apostichopus californicus)*.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 0.91 | 0.07 | 12.43 | < 0.001 |
| Cukes - one | 0.03 | 0.10 | 0.31 | 0.76 |
| Cukes - two | 0.00 | 0.10 | 0.01 | 0.99 |
| Depth | 0.38 | 0.05 | 8.07 | < 0.001 |

**Table S1.11.** Fine-scale model describing ammonium variation between cages with zero, medium, or large red rock crabs (*Cancer productus*). The model was constructed with a gamma distribution (link = ‘log’), so coefficients are presented in log space.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -1.78 | 0.25 | -7.25 | < 0.001 |
| Crabs - medium | 2.20 | 0.26 | 8.48 | < 0.001 |
| Crabs - large | 2.61 | 0.27 | 9.83 | < 0.001 |

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