**Supplemental Material for:**

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

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**Supplemental Material Section 1.**

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

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**Figure S1.1.** 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 S1.2**. 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. Nereo = *Nereocystis luetkeana*, Macro = *Macrocystis pyrifera*, None = no kelp control.

**A diagram of a flow rate

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**Figure S1.3.** 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 S1.1.** 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 S1.2.** 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 S1.3**. 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 2015, *Bolinopsis infundibulum* |
| *Mitrocoma cellularia* | 0.01 | Båmstedt 2015, *Bolinopsis infundibulum* |
| *Pleurobrachia bachei* | 0.01 | Båmstedt 2015, *Bolinopsis infundibulum* |
| *Bolinopsis infundibulum* | 0.01 | Båmstedt 2015 |
| *Evasterias troschelii* | 66.5 | O'Clair 1985 |
| *Leptasterias hexactis* | 5.5 | Menge 1975, *Leptasterias spp.* |
| *Leptasterias spp.* | 5.5 | Menge 1975, *Leptasterias spp.* |
| *Orthasterias koehleri* | 66.5 | O'Clair 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 2016 |
| *Stylasterias forreri* | 66.5 | O'Clair 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 1991, *Chlamys spp.* |
| *Crassadoma gigantea* | 0.038\*size^2.39 | MacDonald 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 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 S1.4**. 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), tide 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 S1.5**. 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), tide 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 | -34.76 | 0.00 | 0.33 |
| AA + SHD + KS + KB + T + D + AA:T + AA:KB + KB:T + RE | 13 | -34.56 | 0.2 | 0.30 |
| AA + SID + KS + KB + T + D + AA:T + AA:KB + KB:T + RE | 13 | -34.12 | 0.64 | 0.24 |
| AB + SID + KS + KB + T + D + AB:T + AB:KB + KB:T + RE | 13 | -33.01 | 1.75 | 0.14 |

**Table S1.6.** 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 S1.7.** 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 |

**Electronic Supplement Part 2.** Effect of individual families of fishes and invertebrates on meso-scale (among-site) and small-scale (within-site) variation in ammonium.

**Regional (meso-scale) variation**

We further explored the effect of animals on variation in NH₄⁺ concentration among rocky reef sites by considering only the abundance of one animal family at a time. For each of the top 15 most abundant families observed on our surveys, we constructed an GLMM identical to the top model shown in Table S4, using only the abundance of that family (NH₄⁺ regressed against family abundance, tide exchange, an interaction between family abundance and tide, Shannon diversity, survey depth, with a random effect of site and year and a gamma distribution). Here, we present the three fish families (Hexagrammidae, Gobiidae, and Sebastidae) and three invertebrate families (Muricidae, Asteriidae, and Acmaeidae) with the highest *R2* values. These six families constitute 17% of the total abundance.

We found evidence of a positive relationship between NH₄⁺ concentration and the abundance of greenlings (Hexagrammidae, GLMM, p = 0.03, Fig. S2.1), weak evidence of an interaction between greenling abundance and tide (p = 0.09), but no evidence for an effect of any other predictors (p > 0.10). We also found evidence of a positive relationship between NH₄⁺ concentration and the abundance of whitecap limpets (Acmaeidae, GLMM, p = 0.03), but no evidence of an effect of any other predictors (p > 0.40). We found no evidence of an effect of any predictors on NH₄⁺ concentration in the models for the families Sebastidae, Gobiidae, Asteriidae, or Muricidae (p > 0.10). Full model outputs are available in Table S2.1.

**A graph of different types of numbers

Description automatically generated with medium confidence**

**Figure S2.1.** Model-generated predictions of ammonium concentrations in relation to abundance across rocky reef sites for the 6 animal families with the highest *R2*.

**Table S2.1.** Model summaries from the meso-scale (among-site) models including only the biomass of one family (indicated in the top left cell) for each model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sebastidae** (*R2* = 0.67) | **Estimate** | **Std. error** | **z-value** | **p-value** |
| Intercept | 0.13 | 1.23 | 0.11 | 0.91 |
| Abundance | 1.98 | 3.22 | 0.61 | 0.54 |
| Tide exchange | -0.53 | 1.00 | -0.53 | 0.60 |
| Biodiversity | -0.10 | 0.13 | -0.75 | 0.45 |
| Depth | -0.02 | 0.13 | -0.18 | 0.86 |
| Abundance:Tide | -1.79 | 2.82 | -0.63 | 0.53 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Muricidae** (*R2* = 0.54) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.43 | 0.33 | -1.30 | 0.19 |
| Abundance | 0.79 | 0.51 | 1.55 | 0.12 |
| Tide exchange | 0.05 | 0.12 | 0.44 | 0.66 |
| Biodiversity | 0.00 | 0.10 | -0.04 | 0.97 |
| Depth | 0.04 | 0.09 | 0.43 | 0.67 |
| Abundance:Tide | 0.12 | 0.55 | 0.22 | 0.83 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Asterinidae** (*R2* = 0.651) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.58 | 0.26 | -2.28 | 0.02 |
| Abundance | 0.21 | 0.26 | 0.80 | 0.42 |
| Tide exchange | 0.12 | 0.07 | 1.80 | 0.07 |
| Biodiversity | -0.12 | 0.09 | -1.29 | 0.20 |
| Depth | 0.06 | 0.09 | 0.62 | 0.54 |
| Abundance:Tide | 0.07 | 0.27 | 0.26 | 0.80 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Hexagrammidae** (*R2* = 0.47) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 4.96 | 2.54 | 1.95 | 0.05 |
| Abundance | 14.67 | 6.69 | 2.19 | 0.03 |
| Tide exchange | -3.35 | 2.01 | -1.67 | 0.10 |
| Biodiversity | 0.01 | 0.09 | 0.11 | 0.91 |
| Depth | 0.02 | 0.09 | 0.25 | 0.81 |
| Abundance:Tide | -9.01 | 5.35 | -1.68 | 0.09 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Acmaeidae** (*R2* = 0.46) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.19 | 0.33 | -0.59 | 0.56 |
| Abundance | 1.42 | 0.67 | 2.13 | 0.03 |
| Tide exchange | 0.03 | 0.16 | 0.21 | 0.84 |
| Biodiversity | -0.01 | 0.09 | -0.09 | 0.93 |
| Depth | 0.00 | 0.09 | 0.05 | 0.96 |
| Abundance:Tide | -0.16 | 0.58 | -0.28 | 0.78 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Gobiidae** (*R2* = 0.44) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.64 | 0.29 | -2.19 | 0.03 |
| Abundance | 0.17 | 0.23 | 0.75 | 0.45 |
| Tide exchange | 0.04 | 0.07 | 0.52 | 0.61 |
| Biodiversity | -0.01 | 0.10 | -0.11 | 0.91 |
| Depth | -0.06 | 0.11 | -0.55 | 0.58 |
| Abundance:Tide | 0.13 | 0.17 | 0.80 | 0.43 |

**Within-site (small-scale) variation**

As above, we further explored the effect of animals on ∆NH₄⁺ – the difference in NH₄⁺ concentration between inside and outside kelp forests – by rerunning the top LMM in Table S5 with the biomass of only one animal family at a time. We ran models for the 15 most abundant families, but only present the three fish families (Gobiidae, Cottidae, and Embiotocidae) and three invertebrate families (Echinasteridae, Strongylocentrotidae, and Asteriidae) with the highest *R2* values. These six families contribute almost half (48%) of the total biomass observed on the surveys.

We found a negative relationship between ∆NH₄⁺ and the biomass of gobies (Gobiidae) and evidence of positive kelp:goby biomass and tide:goby biomass interactions (GLM, p < 0.003, Fig. S2.2). ∆NH₄⁺ was positively correlated with the biomass of sculpins (Cottidae; p = 0.046) and surfperches (Embiotocidae; p < 0.001), but no interactions with biomass were significant (p > 0.06). Sea stars in the family Echinasteridae displayed a positive relationship with ∆NH₄⁺, a negative kelp:sea star biomass interaction, and a positive tide:sea star biomass interaction (p < 0.001). We found evidence for a smaller but still positive relationship between the biomass of urchins in the family Strongylocentrotidae and sea stars in the family Asteropseidae and ∆NH₄⁺ (p < 0.005), but no interactions with biomass were significant (p > 0.17). Full model outputs are available in Table S2.2.

A graph of different types of growth

Description automatically generated with medium confidence

**Figure S2.2.** Model-generated predictions of difference in ammonium concentrations between inside and outside kelp forests in relation to animal biomass for the 6 animal families with the highest *R2*.

**Table S2.2.** Model summaries from the small scale (within-site) models including only the biomass of one family (indicated in the top left cell) for each model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Echinasteridae** (*R2* = 0.97) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 3.22 | 0.71 | 4.56 | < 0.01 |
| Kelp nereo | 0.23 | 0.03 | 6.79 | < 0.01 |
| Kelp none | -0.09 | 0.07 | -1.33 | 0.18 |
| Kelp biomass | -2.82 | 0.89 | -3.17 | < 0.01 |
| Tide exchange | 3.02 | 0.76 | 3.99 | < 0.01 |
| Animal biomass | 7.36 | 1.68 | 4.39 | < 0.01 |
| Biodiversity | -0.13 | 0.02 | -5.96 | < 0.01 |
| Depth | 0.04 | 0.02 | 2.19 | 0.03 |
| Kelp:tide | 0.20 | 0.04 | 5.39 | < 0.01 |
| Kelp:animals | -7.66 | 2.14 | -3.58 | < 0.01 |
| Tide:animals | 6.87 | 1.78 | 3.86 | < 0.01 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Gobiidae** (*R2* = 0.92) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | -0.56 | 0.24 | -2.35 | 0.02 |
| Kelp none | 0.89 | 0.34 | 2.61 | 0.01 |
| Kelp biomass | 1.06 | 0.38 | 2.81 | < 0.01 |
| Tide exchange | 4.79 | 0.98 | 4.89 | < 0.01 |
| Animal biomass | -1.71 | 0.57 | -3.01 | < 0.01 |
| Biodiversity | 0.14 | 0.04 | 3.55 | < 0.01 |
| Depth | 0.00 | 0.03 | -0.10 | 0.92 |
| Kelp:tide | 0.11 | 0.08 | 1.35 | 0.18 |
| Kelp:animals | 2.65 | 0.98 | 2.69 | 0.01 |
| Tide:animals | 12.22 | 2.48 | 4.93 | < 0.01 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cottidae** (*R2* = 0.92) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 1.23 | 0.56 | 2.20 | 0.03 |
| Kelp nereo | 0.12 | 0.07 | 1.63 | 0.10 |
| Kelp none | -0.43 | 0.09 | -4.66 | < 0.01 |
| Kelp biomass | -0.35 | 0.37 | -0.96 | 0.34 |
| Tide exchange | -0.68 | 1.14 | -0.60 | 0.55 |
| Animal biomass | 2.56 | 1.28 | 2.00 | 0.05 |
| Biodiversity | -0.16 | 0.04 | -4.40 | < 0.01 |
| Depth | 0.11 | 0.03 | 3.82 | < 0.01 |
| Kelp:tide | 0.17 | 0.08 | 2.13 | 0.03 |
| Kelp:animals | -1.59 | 0.86 | -1.85 | 0.06 |
| Tide:animals | -1.88 | 2.68 | -0.70 | 0.48 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Strongylocentrotidae** (*R2* = 0.87) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 0.00 | 0.06 | 0.01 | 0.99 |
| Kelp nereo | 0.07 | 0.08 | 0.83 | 0.41 |
| Kelp none | -0.67 | 0.12 | -5.40 | < 0.01 |
| Kelp biomass | 0.20 | 0.06 | 3.42 | < 0.01 |
| Tide exchange | 0.07 | 0.07 | 0.99 | 0.32 |
| Animal biomass | 0.08 | 0.03 | 3.21 | < 0.01 |
| Biodiversity | 0.04 | 0.03 | 1.14 | 0.25 |
| Depth | 0.10 | 0.03 | 3.21 | < 0.01 |
| Kelp:tide | 0.15 | 0.06 | 2.43 | 0.01 |
| Kelp:animals | -0.02 | 0.02 | -1.12 | 0.26 |
| Tide:animals | -0.02 | 0.02 | -1.06 | 0.29 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Embiotocidae** (*R2* = 0.88) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 0.27 | 0.04 | 6.32 | < 0.01 |
| Kelp nereo | -0.03 | 0.08 | -0.45 | 0.66 |
| Kelp none | -0.28 | 0.13 | -2.11 | 0.03 |
| Kelp biomass | 0.25 | 0.05 | 5.31 | < 0.01 |
| Tide exchange | 0.15 | 0.04 | 3.74 | < 0.01 |
| Animal biomass | 0.55 | 0.12 | 4.60 | < 0.01 |
| Biodiversity | -0.09 | 0.03 | -2.85 | < 0.01 |
| Depth | 0.07 | 0.03 | 2.39 | 0.02 |
| Kelp:tide | 0.18 | 0.07 | 2.61 | 0.01 |
| Kelp:animals | -0.05 | 0.11 | -0.48 | 0.63 |
| Tide:animals | 0.31 | 0.20 | 1.59 | 0.11 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Asteriidae** (*R2* = 0.88) | **Estimate** | **Std. error** | **z value** | **p value** |
| Intercept | 0.06 | 0.04 | 1.34 | 0.18 |
| Kelp nereo | 0.05 | 0.09 | 0.52 | 0.61 |
| Kelp none | -0.24 | 0.11 | -2.18 | 0.03 |
| Kelp biomass | 0.23 | 0.07 | 3.14 | < 0.01 |
| Tide exchange | -0.02 | 0.08 | -0.23 | 0.82 |
| Animal biomass | 0.13 | 0.05 | 2.76 | 0.01 |
| Biodiversity | -0.10 | 0.03 | -3.09 | < 0.01 |
| Depth | 0.05 | 0.03 | 1.56 | 0.12 |
| Kelp:tide | 0.12 | 0.08 | 1.52 | 0.13 |
| Kelp:animals | 0.00 | 0.03 | 0.16 | 0.87 |
| Tide:animals | 0.13 | 0.10 | 1.32 | 0.19 |