**SUPPLEMENTARY INFORMATION**

**Ocean temperature controls kelp decomposition and carbon sink potential**

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**Supplementary Table 1.** Locations of 35 study sites in each region with times of deployment (T0) and retrievals (T1 and T2).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Region** | **Site** | **Latitude** | **Longitude** | **Species** | **T0** | **T1** | **T2** |
| Gulf of Alaska | Hesketh | 59,50722 | -151,54919 |  | 30-May-18 | 9-Jul-18 | 6-Sep-18 |
| Jakolof | 59,46843 | -151,53777 | *S. latissima* | 30-May-18 | 9-Jul-18 | 6-Sep-18 |
| Herring | 59,48115 | -151,52243 |  | 30-May-18 | 9-Jul-18 | 6-Sep-18 |
| British Columbia | Fulford | 48,74803 | -123,43338 |  | 22-Jul-18 | 20-Aug-18 | 21-Sep-18 |
| Portland | 48,73232 | -123,37640 | *S. latissima* | 22-Jul-18 | 20-Aug-18 | 21-Sep-18 |
| Russell | 48,75055 | -123,40543 |  | 22-Jul-18 | 20-Aug-18 | 21-Sep-18 |
| Gulf of St. Lawrence | Site 1 | 47,70000 | -70,40000 |  | 5-Jul-18 | 9-Aug-18 | 9-Sep-18 |
| Site 2 | 47,70000 | -70,40000 | *S. latissima* | 5-Jul-18 | 9-Aug-18 | 9-Sep-18 |
| Site 3 | 47,70000 | -70,40000 |  | 5-Jul-18 | 9-Aug-18 | 9-Sep-18 |
| Nova Scotia | Paddy's Head | 44,52720 | -63,95230 | *S. latissima* | 13-Jul-18 | 2-Sep-18 | lost |
| Sandy Cove | 44,46197 | -63,70975 | *L. digitata* | 13-Jul-18 | 31-Aug-18 | 7-Oct-18 |
| The Lodge | 44,55629 | -64,06705 |  | 13-Jul-18 | 2-Sep-18 | 10-Oct-18 |
| Gulf of Maine | Baker's Island 1 | 42,53698 | -70,79248 |  | 27-Jul-18 | 20-Sep-18 | lost |
| Baker's Island 2 | 42,53413 | -70,79403 | *S. latissima* | 27-Jul-18 | 20-Sep-18 | lost |
| Baker's Island 3 | 42,53553 | -70,79445 |  | 3-Aug-18 | 20-Sep-18 | lost |
| Rhode I Sound | Fort Wetherill | 41,47732 | -71,39276 | *S. latissima* | 7-Sep-18 | 26-Oct-18 | 14-Dec-18 |
| Kings Beach | 41,45294 | -71,34464 | 7-Sep-18 | 26-Oct-18 | 14-Dec-18 |
| Skagerrak | S13 | 58,41700 | 8,76258 | *S. latissima* | 24-Aug-18 | 19-Oct-18 | 6-Nov-18 |
| S3 | 58,39596 | 8,73951 | *L. hyperborea* | 25-Aug-18 | 18-Oct-18 | 6-Nov-18 |
| S5 | 58,50281 | 8,88807 |  | 25-Aug-18 | 19-Oct-18 | 8-Nov-18 |
| Norwegian Sea | Edoya | 69,60939 | 17,90804 | *S. latissima* | 12-May-18 | lost | 10-Sep-18 |
| Lost chain | 69,61261 | 17,91701 | *L. hyperborea* | 12-May-18 | 3-Jul-18 | 10-Sep-18 |
| Morten's site | 69,63068 | 17,94419 |  | 12-May-18 | 3-Jul-18 | 10-Sep-18 |
| England | Batton Bay | 50,35472 | -4,14960 | *S. latissima*  *L. hyperborea* | 3-Jul-18 | 31-Jul-18 | 4-Sep-18 |
| Ramscliff Point | 50,36082 | -4,12942 | 3-Jul-18 | 31-Jul-18 | 4-Sep-18 |
| Breakwater | 50,33415 | -4,14538 | 3-Jul-18 | 31-Jul-18 | 4-Sep-18 |
| Scotland | Danger Reef | 56,47202 | -5,46467 | *S. latissima* | 17-Jul-18 | 29-Aug-18 | 27-Sep-18 |
| The Greggs | 56,47843 | -5,51168 | *L. hyperborea* | 17-Jul-18 | 29-Aug-18 | 27-Sep-18 |
| Goat Island | 56,52522 | -5,46093 |  | 17-Jul-18 | 29-Aug-18 | 27-Sep-18 |
| France | Roscoff 1 | 48,70889 | -3,92694 | *S. latissima*  *L. hyperborea* | 20-Jul-18 | 20-Aug-18 | 23-Oct-18 |
| Roscoff 2 | 48,70917 | -3,95333 | 20-Jul-18 | 20-Aug-18 | 23-Oct-18 |
| Roscoff 3 | 48,73250 | -3,97139 | 20-Jul-18 | 20-Aug-18 | 23-Oct-18 |
| Portugal | Matosinhos N | 41,17738 | -8,70542 | *S. latissima* | 14-Jun-18 | 16-Jul-18 | 13-Sep-18 |
| Matosinhos C | 41,17625 | -8,70268 | *L. hyperborea* | 14-Jun-18 | 16-Jul-18 | 13-Sep-18 |
| Matosinhos E | 41,17715 | -8,70029 |  | 14-Jun-18 | 16-Jul-18 | 13-Sep-18 |

**Supplementary Table 2.** Summary of generalized linear mixed-effects models (GLMM) relating the decomposition (% d-1) of kelp detritus to environmental conditions and tissue properties at 12 regions of the northern hemisphere. Temperature (average and range) is temperature at the seafloor over the duration of the experiment. Light is average light (Lux) over the first 2 weeks of the experiment. The % carbon is the initial carbon content in the kelp detritus, and water movement is average g forces within the cages over the experiment. GLMMs are with gamma distribution and identity link function. Model 1 uses the full dataset (n = 12 regions) with predictors temperature (range, average), light and species, and model 2 uses a subset of the data (n = 9 regions) with additional predictors % carbon content and water movement, because these variables were not obtained at all 12 regions. Site and region represent random effects.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model 1.** | **Estimate** | **SE** | **t** | **p** |
| (Intercept) | 1,307 | 0,400 | 3,271 | **0.001** |
| Average temperature | 0,051 | 0,019 | 2,753 | **0.006** |
| Temperature range | -0,003 | 0,019 | -0,142 | 0.887 |
| Light | -0,014 | 0,024 | -0,577 | 0.564 |
| Species | 0,122 | 0,047 | 2,589 | **0.010** |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Model 2.** | | | | | |
|  |  | **Estimate** | **SE** | **t** | **p** |
| (Intercept) |  | 2,296 | 1,520 | 1,510 | 0,131 |
| Average temperature |  | 0,058 | 0,018 | 3,196 | **0,001** |
| Temperature range |  | -0,020 | 0,021 | -0,954 | 0,340 |
| % Carbon |  | -0,055 | 0,021 | -2,589 | **0,010** |
| Light |  | -0,015 | 0,023 | -0,661 | 0,509 |
| Water movement |  | 0,136 | 0,041 | 3,277 | **0,001** |
| Species |  | 0,057 | 0,116 | 0,488 | 0,626 |

**Supplementary Table 3.** ANOVA and *t*-tests of nitrogen enrichment (%N content) for kelp species in each region over the duration of experiment. Tukey’s post-hoc tests are performed to compare between initial and final sampling time in each region.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| ***S. latissima*** |  |  |  |  |  |
|  | **Df** | **SS** | **MSS** | **F** | **p** |
| Region | 11 | 79,41 | 7,22 | 79,40 | <0.001 |
| Time | 2 | 6,58 | 3,29 | 36,16 | <0.001 |
| Region x Time | 20 | 14,94 | 0,75 | 8,22 | <0.001 |
| Residuals | 285 | 25,91 | 0,09 |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
| **Tukey's results** |  |  |  |  |  |
| **Region** | **Comparison** | **Est** | **P** |  |  |
| Norwegian Sea | T2,T0 | -0.004 | 1 |  |  |
| Skagerrak | T2,T0 | 0.376 | 0.655 |  |  |
| Scotland | T2,T0 | 0.517 | 0.074 |  |  |
| England | T2,T0 | 0.198 | 1 |  |  |
| France | T2,T0 | 0.942 | **<0.001** |  |  |
| British Columbia | T2,T0 | -0.235 | 1 |  |  |
| Gulf of St. Lawrence | T2,T0 | 0.008 | 1 |  |  |
| Nova Scotia | T2,T0 | 0.437 | 0.635 |  |  |
| Gulf of Maine | T1,T0 | 0.349 | 0.856 |  |  |
| Rhode I Sound | T1:T0 | 1.300 | **<0.001** |  |  |
| Portugal | T1:T0 | 0.382 | 0.829 |  |  |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| ***L. hyperborea*** | |  |  |  |  |
|  | **Df** | **SS** | **MS** | **F** | **p** |
| Region | 5 | 5.23 | 1.05 | 13.07 | **<0.001** |
| Time | 2 | 2.50 | 1.25 | 15.62 | **<0.001** |
| Region x Time | 8 | 1.46 | 0.18 | 2.27 | **0.026** |
| Residuals | 143 | 11.44 | 0.08 |  |  |
|  |  |  |  |  |  |
| **Tukey's results** | |  |  |  |  |
| **Region** | **Comparison** | **Est** | **P** |  |  |
| Norwegian Sea | T2,T0 | 0.472 | 0.747 |  |  |
| Skagerrak | T2,T0 | 0.090 | 0.998 |  |  |
| Scotland | T2,T0 | 0.551 | **0.004** |  |  |
| England | T2,T0 | 0.181 | 0.995 |  |  |
| France | T2,T0 | 0.507 | 0.015 |  |  |

**Supplementary Table 4**. Decomposition rates (average ± SD) and residence times reported for different types of marine detritus.

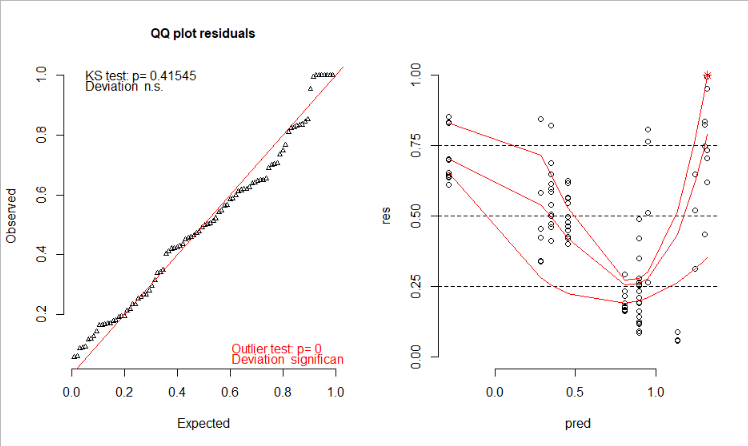
|  |  |  |  |
| --- | --- | --- | --- |
| **Organic carbon sources** | **Decomposition**  **% d-1** | **Residence time**  **d to 50%** | **Source** |
| *S. latissima* | 0.74 ± 0.71|| | 68|| | This study |
| *L. hyperborea* | 0.76 ± 1.1 | 66 | This study |
| Seagrass (*Posidonia*) | 0.58 ± 0.13 | 88 | 1 |
| Seagrass (*Thalassia*) | 1.6 | 57 | 2 |
| Seagrass (*Haladule*) | 0.37 ± 0.14 | 136 | 3 |
| Seagrass (*Halophila*) | 5.1 | 9.7 | 4 |
| Seagrass (*Cymodocea*) | 0.41 | 120 | 5 |
| Seaweed (*Caulerpa*) | 7.1 | 7 | 6 |
| Seaweed (*Fucus*) | 3.5 | 14 | 7 |
| Seaweed (*Piliayella*) | 1.5 | 34.3 | 8 |
| Seaweed (*Cladophora*) | 1.4 | 35.7 | 8 |
| Seaweed (*Ulva*) | 0.4 ± 0.1 | 125 | 9 |
| Mangrove (*Avcennia*) |  | 15 | 10 |
| Mangrove (*Rhizophora*) |  | 57 | 10 |
| Mangrove (*Ceriops*) |  | 77 | 10 |
| POM (marine snow)\*X | 11.9 ± 1 | 4 ± 1 | 11 |
| POM (diatoms & flagellates) | 10 | 5 | 12 |
| POM (ascidian) |  | 3.5 | 13 |
| POM (*Acartia tonsa* carcasses) | 3.9 | 12.9 | 14 |
| POM (*Acartia tonsa* feces) | 1.4 | 34.7 | 14 |
| POM (copepod feces) | 30.2 | 1.7 | 15 |
| POM (zooplankton feces)¥ | 19 | 2.67 | 16 |
| DOM (marine snow) | 25 ± 4.3 | 2 | 13 |
| DOM (bacteria) X | 2.8 | 18 | 17 |
| DOM (diatoms refractory) | 0.08 ± 0.007 | 606 | 18 |
| DOM (diatoms labile) | 1.6 ± 0.6 | 30 | 18 |
| DOM (labile DOC) |  | 10 ± 15 | 19 |
| DOM (labile DOC) |  | 1.0 ± 1.5 | 19 |
| DOM (DOC)# | 0.12 | 387 | 20 |

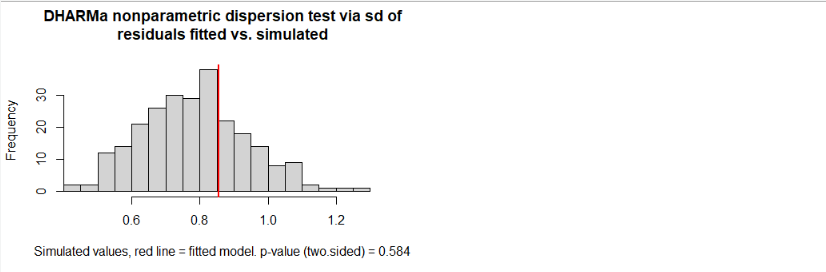
|| averaged across regions. \* Aggregates that include bacteria, plankton, flagellates, and detritus. ¥Fecal pellets of *Acartia*, *Evadne*, *Podon*, and calanoid copepods. #50 m depth collection. X Surface ocean.

**Supplementary Information 1**

**Additional model and model fit assessments.**

Model fit assessments for GLMM, showing relationship between decomposition and temperature, species, temperature range and light. Residuals are visualized using DHARMa package 21.





**Decomposition vs. latitude.** Linear mixed model fit by maximum likelihood.

Formula: WWperday ~ Latitude + (1 | Region/Site). *F* tests use Satterthwaite’s method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model 1**  **Fixed effects** | **DF** | **MS** | **F** | **p** |
| All parameters |  |  |  |  |
| Latitude | 12 | 0.8009 | 7.70 | **0.0164** |
| **Random effects** | **N** | **Variance** | **SD** |  |
| (1 | Site:Region) | 34 | 0.004 | 0.066 |  |
| (1 | Region) | 12 | 0.327 | 0.572 |  |
| Residual |  | 0.104 | 0.0.32 |  |

**Nitrogen enrichments vs. environmental variables.** Linear mixed model fit by maximum likelihood

showing relationship between percent increase of nitrogen and environmental variables.

Formula: Nitrogen rate ~ Mean Temperature+Species+Exposure+(1|Region/Site). *F* tests use

Satterthwaite’s method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model 1**  **Fixed effects** | **DF** | **MS** | **F** | **p** |
| All parameters |  |  |  |  |
| Average temperature | 36.5 | 24.840 | 1.27 | 0.267 |
| Light | 36.3 | 31.164 | 1.59 | 0.215 |
| Species | 40.7 | 0.268 | 0.013 | 0.907 |
| Water movement | 45.0 | 0.0003 | 0.000 | 0.997 |
| **Random effects** | **N** | **Variance** | **SD** |  |
| (1 | Site:Region) | 22 | 0.00 | 0.000 |  |
| (1 | Region) | 8 | 24.53 | 4.953 |  |
| Residual |  | 18.64 | 4.318 |  |

**Carbon loss vs. environmental variables.** Linear mixed model fit by maximum likelihood showing relationship between percent loss of carbon and environmental variables. Formula: Carbon loss rate ~ Mean Temperature+Species+Exposure+(1|Region/Site). *F*  tests use Satterthwaite’s method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model 1**  **Fixed effects** | **DF** | **MS** | **F** | **p** |
| All parameters |  |  |  |  |
| Average temperature | 15.7 | 55.8 | 0.039 | 0.845 |
| Light | 23.0 | 330.3 | 0.233 | 0.634 |
| Species | 42.9 | 151.2 | 0.107 | 0.746 |
| Water movement | 41.6 | 792.7 | 0.559 | 0.459 |
| **Random effects** | **N** | **Variance** | **SD** |  |
| (1 | Site:Region) | 22 | 0.00 | 0.000 |  |
| (1 | Region) | 8 | 24.53 | 4.953 |  |
| Residual |  | 18.64 | 4.318 |  |

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