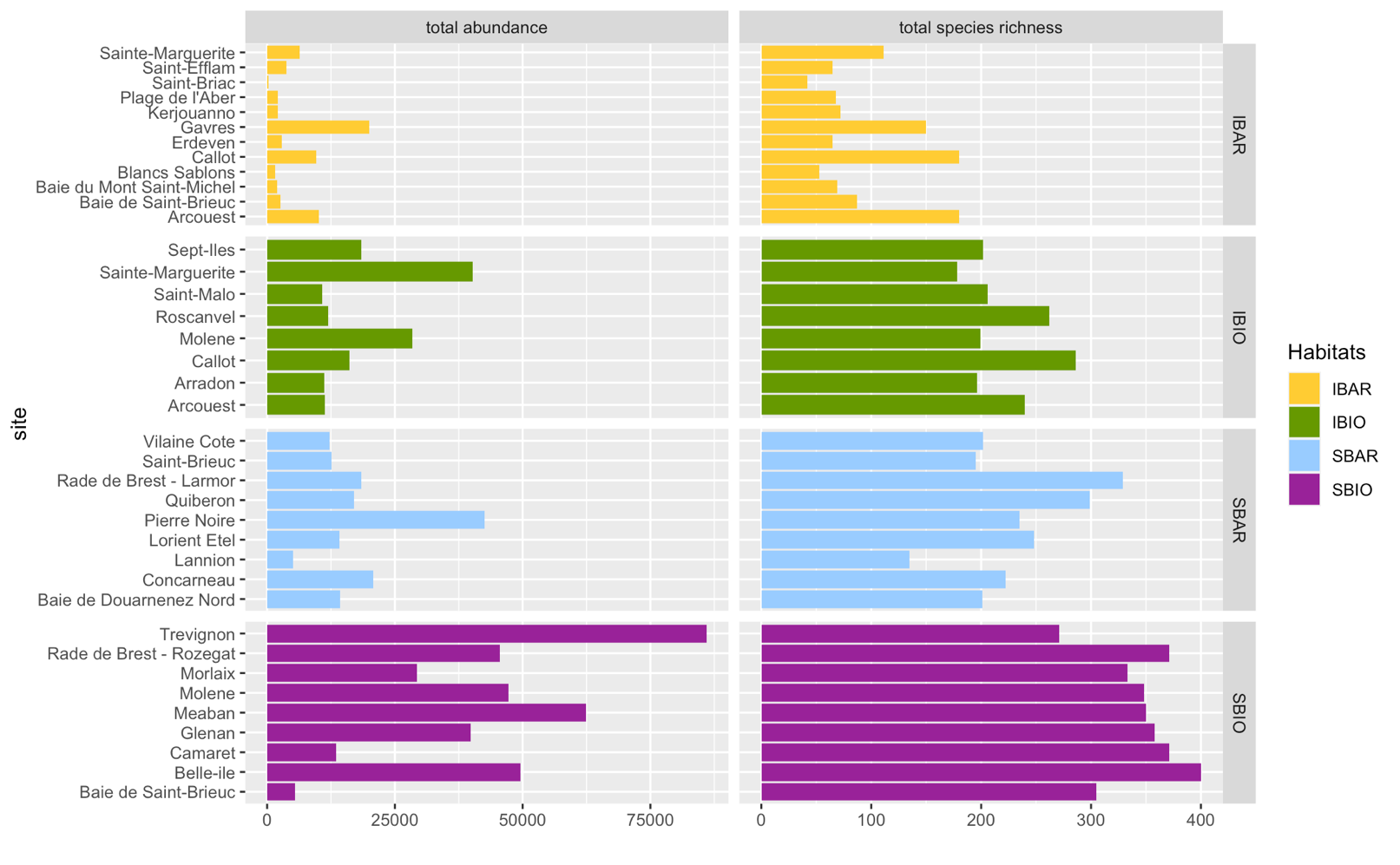
**Appendices**

**Disentangling the effect of space, time, and environmental and anthropogenic drivers on coastal macrobenthic β diversity in contrasting habitats over 15 years**

**Appendix A:** Total abundance and species richness at each site and habitat over the 15 years.

**Appendix B:** Details of protocols, numerical model products and techniques used to extract and calculate each of the explanatory variables.

* Distance between sites

Distances among sites were calculated as the shortest paths along the coast using the “gdistance” R package (Etten 2017). This calculation relied on a transition layer that was built on a 100 m resolution raster constructed from polygon layer made available by OpenStreetMap (<http://openstreetmapdata.com/data/land-polygons>). Land polygons were modified to correct for invalid polygons using the “rgeos” R package (Bivand et al. 2021).

* Grain-size distribution

In each habitat, an additional sediment core was collected at each point for grain size distribution and organic matter content assessment. Sediment samples were dried in an oven (48h at 60°C), weighed, rinsed on a 63 μm sieve, dried (48h at 60°C) and weighed again, then passed through sieve columns. This protocol allowed to separate the sediment into 15 fractions (<63 μm, 63-80, 80-100, 100-125, 125-160, 160-200, 200-315, 315-500, 500-800, 800-1250, 1250-2000, 2000-3150, 3150-5000, 5000-10000 and >10000 μm) whose masses were measured. Since the protocols have evolved during the time series (fractions were not the same as those described above in SBAR before 2015 and in IBAR and IBIO in 2004 and 2005), we decided to merge some fractions in order to homogenize the data as much as possible to allow a comparison between habitats. As a result, the following fractions were used for the calculation of granulometric indices: < 63 μm, 63-125, 125-500, 500-2000, > 2000 μm.

These data were used to calculate the following summary indices using the R package “G2Sd” (Fournier et al. 2014):

* Mean of the grain-size distribution (logarithmic Folk and Ward method, μm scale)
* Median of the grain-size distribution (logarithmic Folk and Ward method, μm scale)
* Trask or Sorting index defined as with D25 the 25th percentile and D75 the 75th percentile of the grain-size distribution
* Kurtosis of the grain-size distribution (logarithmic Folk and Ward method, μm scale).

Lastly, fractions were grouped into percentages of gravels (> 2 mm), sand (63 μm to 2 mm) and mud (< 63 μm) (Fournier et al. 2014).

Finally, the percentage of organic matter was estimated by mass loss after combustion at 450°C for 5 fours.

Values at the site level were estimated by averaging data from the three points within each site.

Overall, 8 % of observations contained missing values in the intertidal habitats in total and 10 % in the subtidal habitats in total. Missing values were imputed using k-Nearest neighbor imputation with the median value of the 5 closest neighbors based on Gower distance computed on the matrix containing: the remaining sedimentary variables (i.e., grain-size distribution data), hydrodynamics data (current velocity, fetch and depth, the latter only for the subtidal habitats), as well as two variables containing the identity of site and year of the samples. This imputation procedure was performed for the two tidal zones separately. This procedure was done using the *kNN* function of the “VIM” R package (Kowarik and Templ 2016).

* *Zostera marina* morphological and structural traits

In IBIO, at each of the 3 points, all *Zostera marina* shoots in two 0.05 m2 quadrats (except in 2016 and 2017 where two 0.1 m2 quadrats were used, without visible impacts on the time series) were collected to measure densities (shoot.m-2), leaves (precisely leaves and sheaths) and roots (rhizomes) biomasses (g.m-2), and describe each shoot’s morphology with measures of sheath height (mm), leaves length (mm) and width (mm), as well as the number of leaves per shoot and broken leaves.

Sheath height was measured from the first node to the separation mark of the leaves. The length of each leaf was measured from the first node to the apex. The number of broken leaves was counted and expressed as a percentage of the total number of leaves found in each quadrat. One leaf of median length was used to estimate the leaf width for each shoot. Leaves and roots biomasses were estimated as dry weight after 48 hours desiccation at 60°C for each quadrat. The detailed protocol of the biometric measurements can be found in Auby et al. (2018).

Total *Zostera marina* leaves and roots biomasses and densities were scaled up and expressed per square meter for the two quadrats. Data were estimated at the point level by averaging the data from the two quadrats. Values were estimated at the site level by averaging the data from the three points within each site.

Overall, between 2 and 4 values were missing depending on the variable. They were imputed by k-Nearest neighbor imputation using the median value of the 5 closest neighbors based on Gower distance. This imputation procedure was performed using the matrix containing the identity of the site and year of the samples along with the remaining biometric data. This procedure was done using the *kNN* function of the “VIM” R package (Kowarik and Templ 2016)

* Hydrology

Daily mean bottom temperature (°C), current velocity (m.s-1) and salinity (psu) were extracted and computed from the ocean physic Multi-Year product IBI\_REANALYSIS\_PHYS\_005\_002 (Sotillo et al. 2015), downloaded from the E.U. Copernicus Marine Service platform (<https://marine.copernicus.eu/>) in September 2020 (note that products are regularly updated, see product improvements pages <http://marine.copernicus.eu/services-portfolio/product-improvements>). This product is defined on a standard grid at 1/12° (~ 6-9 km), 50 vertical levels for mean daily and monthly values and only surface levels for hourly values.

The data were extracted and averaged in a buffer of radius equivalent to the resolution of the model around each point. For points where no model cell intersected the buffer, the radius of the buffer was changed to a radius equivalent to the resolution of the model plus the minimum distance of the point to the closest model cell.

Bottom temperature (°C) is the daily mean seafloor potential temperature (only defined on one layer). Salinity (psu) was computed from the daily mean salinity averaged on all the vertical levels of the model (i.e., over the entire water column). Current velocity (m.s-1) was extracted from the hourly model (with the same spatial resolution) in order to properly account for tidal currents. However, those were only available for the surface layer. Thus, current velocity was computed using the hourly eastward (uo) and northward (vo) velocities at the surface level: hourly current velocities were obtained using the formula , then daily mean current velocity was obtained by averaging hourly current velocities of the day considered.

Data values were estimated at the site level by averaging the data from the points at each site.

* Meteorology

For the intertidal habitats, daily mean air temperature (°C) and wind velocity (m.s-1), daily total rainfall (mm), minimum daily air temperature (°C), maximum daily air temperature (°C), and daily air temperature range (°C) were extracted and computed from the SIM2 model of Météo-France (Le Moigne et al. 2020). This product is defined at an 8 km grid resolution.

Data were extracted and averaged in a buffer of radius equivalent to the resolution of the model around each point. For points where no model cell intersected the buffer, the radius of the buffer was changed to a radius equivalent to the resolution of the model plus the minimum distance of the point to the closest model cell.

Daily air temperature range (°C) was computed by subtracting the minimum daily air temperature to the maximum daily air temperature.

Values were estimated at the site level by averaging the data from the three points within each site.

It should be noted that when the minimum, average, maximum and standard deviation values of the variables were calculated from the sampling date back to the previous 1st November, the minimum of daily total rainfall was always equal to 0 and therefore removed from the analyses.

* Fetch

Fetch was calculated using land polygon data made available by OpenStreetMap (<http://openstreetmapdata.com/data/land-polygons>) and an archive of the “fetchR” package (because it is no longer available on CRAN) downloaded at <https://cran.r-project.org/src/contrib/Archive/fetchR/fetchR_2.1-1.tar.gz>. Land polygons were modified to correct for invalid polygons using the “rgeos” package (Bivand et al. 2021). The average wind fetch, referred to as ‘fetch’, was calculated in kilometers as the average length of nine radiating fetch segments (one every 10 degrees) with a maximum distance for any fetch segment set to 300 km. Values were estimated at the site level by averaging the values from the three points within each site.

* Depth

For the subtidal habitats, bathymetric data were retrieved from the EMODnet Digital Terrain Model (DTM) with a grid resolution of 1/16 1/16 arc minutes (circa 115 115 meters) (EMODnet Bathymetry Consortium 2018). Data were extracted and averaged in a buffer of radius equivalent to the resolution of the model around each point. Values were estimated at the site level by averaging the values from the three points within each site.

* Population

For the intertidal habitats, the number of inhabitants in buffers of 2 km radius around each point were estimated using a shapefile layer of the administrative division of French communes made available by OpenStreetmap at <https://www.data.gouv.fr/fr/datasets/decoupage-administratif-communal-francais-issu-d-openstreetmap/>, merged with population density (inhabitants/km2) of these communes retrieved from the Insee (Institut national de la statistique et des études économiques) censuses of 2007, 2012 and 2017 downloaded from l’Observatoire des territoires (<https://www.observatoire-des-territoires.gouv.fr/>). The radius value of 2 km was set arbitrarily and chosen to take into account the effect of the local population without overestimating this value for islands for example, where larger buffers could have intercepted communes from the nearest continental land. Likewise, as Sept-Iles is uninhabited, the value for the number of inhabitants was set to 0.

Data were downloaded in September 2020 and the 2020 communes’ nomenclature was used. Because the number of inhabitants changed very little between the 3 selected years, the choice was made to keep only the average of the number of inhabitants of these three years to characterize the points.

Values were estimated at the site level by averaging the data from the three points within each site and they were then log-transformed to make the data distribution more symmetrical. Values for subtidal sites were inferred to be the same as those from the nearest intertidal site.

* Land use

For the intertidal habitats, we computed the surfaces (km2) covered by artificial surfaces and agricultural areas in 10 km radius buffers around points and in watersheds in the vicinity of points. This 10 km radius value was set arbitrarily and chosen so that buffers can intercept adjacent watersheds. Land use data came from the CORINE Land Cover (CLC) database available at <https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0>. The shapefiles were downloaded in September 2020, the CLC database was available for the years 1990, 2000, 2006 and 2012. We used the 2006 and 2012 data as they are those covered by our time series. We focused on the artificial surfaces and agricultural areas according to the CLC level 1 nomenclature. We downloaded a shapefile layer of Brittany divided into watersheds available at <https://www.data.gouv.fr/fr/datasets/bassins-versants-de-bretagne/>. Finally, we used raster files from the BD ALTI® DTM which is a gridded digital terrain model that describes the shape and normal altitude of the ground surface. We used the 75 m resolution grid. Files were made available by the Institut national de l'information géographique et forestière (IGN-F) (<http://www.ign.fr/>).

The assumption was that watersheds with the lowest elevation points falling within the 10 km buffers around the points could discharge near them. We calculated the surface (km2) covered by artificial surfaces and agricultural areas in the buffers and if the lowest elevation point of a watershed was falling within the buffer, the surfaces covered by artificial surfaces and agricultural areas in the watershed were added. Since the computed surfaces were relatively stable between 2006 and 2012, the choice was made to keep only the average of the values between these two years to characterize the points. Values for subtidal sites were inferred to be the same as those from the nearest intertidal site.

* Fishing pressure

Fishing pressure was characterized by expert opinion for each site in a semi-quantitative way (‘No’, ‘Low’, ‘High’) according to the intensity of fishing carried out in each of the habitats (recreational and professional fishing in IBAR, recreational fishing in IBIO, professional fishing in SBAR and dredging in SBIO). Recreational fishing pressure in IBAR corresponds to sediment scraping for clam fishing. Recreational fishing pressure in IBIO corresponds to trampling for crab and scallop fishing and sometimes to sediment scraping for clam or cockle fishing. Variations between sites are based on their level of use. Professional fishing in intertidal sites correspond to fishing for *Donax spp.*. In subtidal sites, otter or beam trawls are mainly used to catch plaice and red mullet in SBAR while dredging is used to catch scallops and clams in SBIO.

Extraction, formatting and analysis of environmental and anthropogenic variables were conducted with the R programming language versions 4.0.1 and 4.1.2 (R Core Team 2021, 2022). Spatial analyses were conducted with the R packages “raster” (Hijmans et al. 2022), “sf” (Pebesma 2018), “sp” (Pebesma and Bivand 2005; Bivand et al. 2013), “maptools” (Bivand et al. 2022) or on the QGIS 3.14 software (QGIS Development Team 2022).‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬‬**Appendix C:** Table listing the mean values +/- their standard deviation for each variable in Table 1 and indicating whether or not these variables had been selected by the VIF. See Table 1 for abbreviations and descriptions of variables.

| **Data** | **Variable**  **abbreviations** | **Selected after VIF** | **Mean +/-**  **standard deviation** | | | |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | IBAR | IBIO | SBAR | SBIO |
| Sediments | mud (%)  OM (%)  So  gravel (%)  D50 (μm)  mean.grain (μm)  kurtosis (μm)  sand (%) | YES  YES  YES  NO  YES  YES  YES  NO | 4.05 +/-  6.63  1.16 +/-  0.73  1.63 +/-  0.70  7.72 +/-  7.39  177.77 +/- 94.65  179.68 +/-  199.18  3.21 +/-  1.82  88.22 +/-  10.52 | 9.25 +/-  10.54  1.96 +/-  1.29  2.51 +/-  1.75  15.20 +/-  14.68  299.29 +/-  339.05  630.36 +/-  2558.18  2.54 +/-  1.66  75.50 +/-  19.55 | 19.02 +/-  15.92  2.31 +/-  1.10  2.19 +/-  1.59  5.78 +/-  7.23  139.39 +/-  147.90  291.59 +/-  1836.83  3.40 +/-  3.02  75.13 +/-  18.54 | 7.53 +/-  8.43  3.34 +/-  1.43  3.05 +/-  1.88  56.59 +/-  16.43  1466.38 +/- 641.72  11915.13 +/-  12460.81  2.52 +/-  2.97  35.74 +/-  18.04 |
| *Zostera*  *marina*  morphological  and structural  traits | broken (%)  leaf.width (mm)  sheath.height (mm)  leaf.length (mm)  leaf.biom (g.m2)  leaves/shoot  density (shoot.m2)  root.biom (g.m2) | YES  YES  NO  YES  YES  YES  YES  YES |  | 21.01 +/-  9.84  4.16 +/-  1.07  79.24 +/-  27.97  261.80 +/-  99.79  51.15 +/-  32.98  3.48 +/-  0.53  359.32 +/-  190.58  129.50 +/-  113.71 |  |  |
| Hydrology &  Hydrodynamics  Hydrology &  Hydrodynamics | s.d.bottomT (°C)  max.bottomT (°C)  mean.bottomT (°C)  min.bottomT (°C)  s.d.sal (psu)  max.sal (psu)  mean.sal (psu)  min.sal (psu)  s.d.current ( m.s-1)  max.current (m.s-1)  mean.current (m.s-1)  min.current (m.s-1) | YES  YES  YES  YES  YES  YES  NO  NO  YES  NO  NO  YES | 1.82 +/-  0.43  14.85 +/-  1.16  10.61 +/-  0.91  8.01 +/-  1.35  0.50 +/-  0.63  34.97 +/-  0.46  34.24 +/-  1.19  33.00 +/-  2.83  0.04 +/-  0.03  0.25 +/-  0.18  0.18 +/-  0.14  0.09 +/-  0.08 | 1.68 +/-  0.38  14.70 +/-  1.03  10.91 +/-  0.97  8.59 +/-  1.30  0.39 +/-  0.66  35.12 +/-  0.44  34.53 +/-  1.29  33.55 +/-  3.05  0.08 +/-  0.05  0.56 +/-  0.31  0.41 +/-  0.23  0.21 +/-  0.13 | 1.77 +/-  0.35  14.74 +/-  1.13  10.68 +/-  0.86  8.21 +/-  1.12  0.73 +/-  0.86  34.53 +/-  1.57  33.49 +/-  2.65  31.67 +/-  4.60  0.04 +/-  0.03  0.27 +/-  0.17  0.18 +/-  0.12  0.09 +/-  0.06 | 1.72 +/-  0.38  14.88 +/-  1.14  11.02 +/-  0.89  8.62 +/-  1.17  0.49 +/-  0.55  35.11 +/-  0.40  34.41 +/-  1.06  33.17 +/-  2.54  0.05 +/-  0.03  0.38 +/-  0.22  0.27 +/-  0.18  0.14 +/-  0.11 |
| Meteorology  Meteorology | min.drangeT (°C)  max.drangeT (°C)  s.d.drangeT (°C)  mean.drangeT (°C)  s.d.minT (°C)  s.d.T (°C)  s.d.maxT (°C)  max.maxT (°C)  max.T (°C)  max.minT (°C)  mean.maxT (°C)  mean.T (°C)  mean.minT (°C)  min.minT (°C)  min.T (°C)  min.maxT (°C)  max.rain (mm)  s.d.rain (mm)  mean.rain (mm)  max.wind (m.s-1)  s.d.wind (m.s-1)  mean.wind (m.s-1)  min.wind (m.s-1) | YES  YES  NO  NO  YES  NO  YES  YES  YES  YES  YES  NO  YES  YES  NO  YES  YES  YES  YES  YES  YES  NO  YES | 0.42 +/-  0.21  12.11 +/-  2.14  2.52 +/-  0.43  4.50 +/-  0.64  3.45 +/-  0.48  3.12 +/-  0.53  3.20 +/-  0.67  19.41 +/-  3.28  15.45 +/-  1.93  13.59 +/-  1.40  10.72 +/-  0.96  8.34 +/-  0.98  6.22 +/-  1.02  -2.66 +/-  2.33  0.34 +/-  2.15  2.35 +/-  1.95  25.95 +/-  7.12  4.52 +/-  0.90  3.00 +/-  0.91  11.46 +/-  2.09  2.20 +/-  0.38  4.94 +/-  0.92  1.07 +/-  0.38 | 0.42 +/-  0.21  12.06 +/-  2.28  2.49 +/-  0.44  4.43 +/-  0.69  3.45 +/-  0.52  3.06 +/-  0.51  3.07 +/-  0.56  18.41 +/-  2.73  14.99 +/-  1.53  13.33 +/-  1.10  10.50 +/-  0.98  8.17 +/-  1.03  6.08 +/-  1.11  -2.75 +/-  2.45  0.34 +/-  2.20  2.39 +/-  2.01  25.69 +/-  7.20  4.59 +/-  0.95  3.17 +/-  0.97  11.42 +/-  2.30  2.22 +/-  0.40  4.86 +/-  1.02  1.03 +/-  0.43 |  |  |
| Fetch | fetch (km) |  | 34.97 +/- 23.61 | 31.87 +/- 25.08 | 49.65 +/- 29.00 | 49.75 +/-  33.06 |
| Depth | Depth (m) |  |  |  | -12.39 +/-  5.47 | -9.84 +/-  5.60 |
| Population | hab (log) |  | 6.10 +/-  2.11 | 5.83 +/-  2.24 | 6.04 +/- 0.71 | 6.12 +/-  0.60 |
| Land use | artificial surface (km2)  agricultural area (km2) |  | 241.45 +/-  683.89  1477.12 +/-  4057.27 | 43.04 +/-  31.82  189.32 +/-  207.68 | 312.77 +/-  780.44  1867.32 +/-  4641.34 | 25.11 +/-  24.97  125.33 +/-  205.70 |

**Appendix D**: Significance of the individual contribution of each fraction (i.e., explanatory matrix) in hierarchical partitioning of Figure 5.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Explanatory matrix** | | | | |
| **Habitat** | Prox.anthro | Environment | Sp.dbMEMs | Sp.linear | Tp.dbMEMs |
| IBAR | *p =* 0.001  \*\*\* | *p =* 0.001  \*\*\* | *p =* 0.001  \*\*\* | *p =* 0.001  \*\*\* | *p =* 0.041  \* |
| IBIO | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.043  \* |
| SBAR | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.029  \* |
| SBIO | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.001  \*\*\* | *p* = 0.011  \* |

**Appendix E**: Adjusted R2 and p-value of the simple (without all other variables as conditions) or partial (with all other variables as conditions) RDA models for each matrix of descriptors within each habitat (IBAR = intertidal bare habitat, IBIO = intertidal biogenic habitat, SBAR = subtidal bare habitat, SBIO = subtidal biogenic habitat). “Space” represents the spatial dbMEMs and the spatial linear trend taken together. Env. = natural environmental variables. Prox.anthro = proxies of anthropogenic pressures.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Habitat** | **Simple RDA** | | | | **Partial RDA** | | | |
| Time | Space | Env. | Prox.anthro | Time | Space | Env. | Prox.anthro |
| IBAR | *R*2 = 0.003  *p* = 0.298 | *R*2 = 0.129  *p* = 0.001  \*\*\* | *R*2 = 0.331  *p* = 0.001  \*\*\* | *R*2 = 0.338  *p* = 0.001  \*\*\* | *R*2 = 0.009  *p* = 0.001  \*\*\* | *R*2 = 0.025  *p* = 0.001  \*\*\* | *R*2 = 0.044  *p* = 0.001  \*\*\* | *R*2 = 0.109  *p* = 0.001  \*\*\* |
| IBIO | *R*2 = 0.000  *p* = 0.500 | *R*2 = 0.317  *p* = 0.001  \*\*\* | *R*2 = 0.530  *p* = 0.001  \*\*\* | *R*2 = 0.488  *p* = 0.001  \*\*\* | *R*2 = 0.020  *p* = 0.001  \*\*\* | *R*2 = 0.003  *p* = 0.001  \*\*\* | *R*2 = 0.013  *p* = 0.001  \*\*\* | *R*2 = 0.030  *p* = 0.001  \*\*\* |
| SBAR | *R*2 = 0.000  *p* = 0.513 | *R*2 = 0.228  *p* = 0.001  \*\*\* | *R*2 = 0.435  *p* = 0.001  \*\*\* | *R*2 = 0.271  *p* = 0.001  \*\*\* | *R*2 = 0.021  *p* =0.001 \*\*\* | *R*2 = 0.014  *p* = 0.001  \*\*\* | *R*2 = 0.070  *p* = 0.001  \*\*\* | *R*2 = 0.063  *p* = 0.001  \*\*\* |
| SBIO | *R*2 = 0.007  *p* = 0.167 | *R*2 = 0.200  *p* = 0.001  \*\*\* | *R*2 = 0.462  *p* = 0.001  \*\*\* | *R*2 = 0.296  *p* = 0.001  \*\*\* | *R*2 = 0.023  *p* = 0.001  \*\*\* | *R*2 = 0.002  *p* = 0.035  \* | *R*2 = 0.011  *p* = 0.003  \*\* | *R*2 = 0.017  *p* = 0.001  \*\*\* |



**Appendix F**: Representation of the two first distance based Moran’s Eigen Vector Maps (dbMEM) representing positive spatial correlation in each habitat (IBAR: A, B; SBIO: C,D; SBAR: E,F; SBIO: G,H). Black circles correspond to positive values in each eigenvector while white circles correspond to negative values. The size of the circles is proportional to the absolute value of their position along each eigenvector. IBAR = intertidal bare habitat, IBIO = intertidal biogenic habitat, SBAR = subtidal bare habitat, SBIO = subtidal biogenic habitat.

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