

# Supplementary information

## Tables and Figures

**Temporal variability of sea surface temperature affects marine macrophytes range retractions as well as gradual warming**

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**Table S1** List of variables initially used to calculate the anomalies between the resurvey period (1991-2015) and the baseline period (1982-1990) in the statistical analyses. All variables were calculated from time series of daily sea surface temperature (daily OISST v2.1 data; Huang et al 2021). (\*) Variables in which both their annual and seasonal mean values (summer, autumn, winter, spring) were calculated (5 values per variable, so that the total number of variables were 85).

| Variables of change   | Definition                                            | Unit        |
|-----------------------|-------------------------------------------------------|-------------|
| Mean_SST (*)          | Mean sea surface temperature                          | °C          |
| CV                    | Coefficient of variation                              | unitless    |
| D                     | Consecutive disparity index                           | unitless    |
| Env_col               | Colour of environmental noise                         | unitless    |
| MCSs_abs_max_int (*)  | Absolute maximum intensity of marine cold spells      | °C          |
| MCSs_freq (*)         | Annual frequency of marine cold spells                | events/year |
| MCSs_max_cum_int (*)  | Maximum cumulative intensity of marine cold spells    | °C days     |
| MCSs_mean_cum_int (*) | Mean cumulative intensity of marine cold spells       | °C days     |
| MCSs_mean_durat (*)   | Mean duration of marine cold spells                   | days        |
| MCSs_mean_int (*)     | Mean intensity of marine cold spells                  | °C          |
| MCSs_mean_max_int (*) | Mean maximum intensity of marine cold spells          | °C          |
| MHWs_abs_max_int (*)  | Absolute maximum intensity of marine heatwaves        | °C          |
| MHWs_freq (*)         | Annual frequency of marine heatwaves                  | events/year |
| MHWs_max_cum_int (*)  | Maximum cumulative intensity of marine heatwaves      | °C days     |
| MHWs_mean_cum_int (*) | Mean cumulative intensity of marine heatwaves         | °C days     |
| MHWs_mean_durat (*)   | Mean duration of marine heatwaves                     | days        |
| MHWs_mean_int (*)     | Mean intensity of marine heatwaves                    | °C          |
| MHWs_mean_max_int (*) | Mean maximum intensity of marine heatwaves            | °C          |
| Seasonality           | Predictability of seasonal trend                      | unitless    |
| Skewness              | Asymmetrical distribution of sea surface temperature  | unitless    |
| Threshold_h_elon      | Time over <i>Himanthalia elongata</i> thermal limit   | days/year   |
| Threshold_f_ser       | Time over <i>Fucus serratus</i> thermal limit         | days/year   |
| Threshold_l_hyper     | Time over <i>Laminaria hyperborea</i> thermal limit   | days/year   |
| Threshold_l_ochro     | Time over <i>Laminaria ochroleuca</i> thermal limit   | days/year   |
| Threshold_s_polys     | Time over <i>Saccorhiza polyschides</i> thermal limit | days/year   |

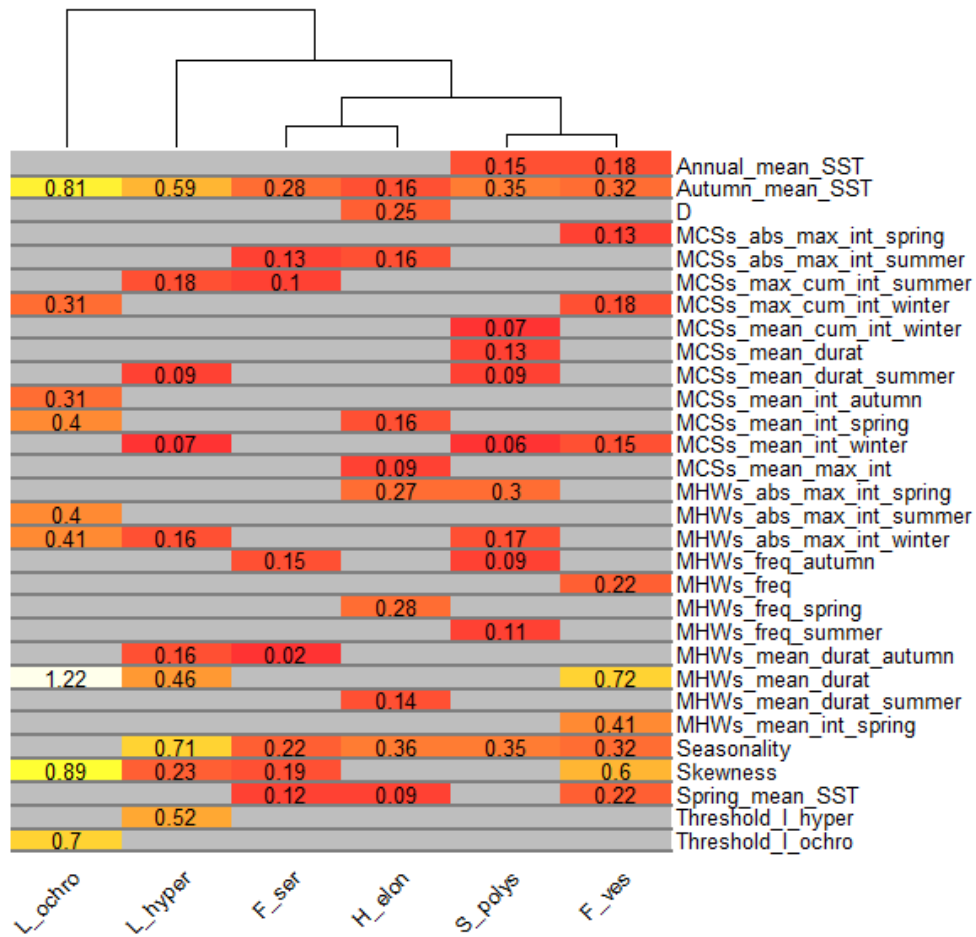
**Table S2** Correlations ( $r^2$  and  $p$ -values) and scores of environmental variables in the non-metric multidimensional scaling (NMDS). In bold are shown the variables obtaining also an independent contribution ( $I$  value) above 0.5 in the hierarchical partitioning analysis (see Fig. 2 in main text and Fig. S1 in Supporting information).

|                                 | $r^2$ | $p$   | NMDS1 | NMDS2 |
|---------------------------------|-------|-------|-------|-------|
| <b>Annual_mean_SST</b>          | 0.37  | 0.001 | 0.5   | 0.35  |
| <b>Autumn_mean_SST</b>          | 0.58  | 0.001 | 0.76  | -0.09 |
| <b>Seasonality</b>              | 0.87  | 0.001 | 0.92  | 0.12  |
| <b>Skewness</b>                 | 0.37  | 0.001 | -0.6  | -0.12 |
| <b>Spring_mean_SST</b>          | 0.26  | 0.001 | -0.5  | -0.11 |
| MCSSs_abs_max_int_spring        | 0.07  | 0.001 | 0.26  | 0.08  |
| MCSSs_max_cum_int_winter        | 0.15  | 0.001 | -0.2  | -0.32 |
| MCSSs_mean_int_winter           | 0.14  | 0.001 | 0.1   | 0.36  |
| <b>MHWs_freq</b>                | 0.25  | 0.001 | 0.05  | 0.49  |
| <b>MHWs_mean_durat</b>          | 0.67  | 0.001 | -0.69 | -0.45 |
| <b>MHWs_mean_int_spring</b>     | 0.16  | 0.001 | -0.33 | -0.23 |
| <b>MCSSs_abs_max_int_summer</b> | 0.24  | 0.001 | 0.46  | -0.17 |
| MCSSs_max_cum_int_summer        | 0.24  | 0.001 | 0.3   | -0.39 |
| <b>MHWs_freq_autumn</b>         | 0.51  | 0.001 | 0.45  | 0.55  |
| MHWs_mean_durat_autumn          | 0.92  | 0.001 | 0.4   | -0.87 |
| <b>Threshold_I_hyper</b>        | 0.96  | 0.001 | 0.89  | 0.4   |
| MCSSs_mean_durat_summer         | 0.12  | 0.001 | 0.16  | 0.31  |
| <b>MHWs_abs_max_int_winter</b>  | 0.37  | 0.001 | -0.61 | 0.06  |
| <b>Threshold_I_ochro</b>        | 0.02  | 0.029 | 0.11  | 0.11  |
| MCSSs_mean_int_autumn           | 0.17  | 0.001 | -0.12 | -0.4  |
| <b>MCSSs_mean_int_spring</b>    | 0.49  | 0.001 | 0.49  | 0.5   |
| MHWs_abs_max_int_summer         | 0.05  | 0.002 | 0.1   | 0.19  |
| <b>D</b>                        | 0.25  | 0.001 | -0.47 | -0.15 |
| MCSSs_mean_max_int              | 0.23  | 0.001 | 0.46  | -0.13 |
| <b>MHWs_abs_max_int_spring</b>  | 0.73  | 0.001 | -0.81 | -0.26 |
| <b>MHWs_freq_spring</b>         | 0.74  | 0.001 | -0.85 | -0.1  |
| MHWs_mean_durat_summer          | 0.62  | 0.001 | -0.78 | 0.09  |
| MCSSs_mean_cum_int_winter       | 0.24  | 0.001 | 0.48  | 0.05  |
| <b>MCSSs_mean_durat</b>         | 0.14  | 0.001 | 0.13  | 0.34  |
| MHWs_freq_summer                | 0.01  | 0.165 | 0.1   | 0.06  |

**Table S3** Overall anomalies at the surveyed persistent and extirpated populations of macroalgae. Anomalies were calculated as the difference between the resurvey period (1991-2015) and the baseline period (1982-1990) for all variables.

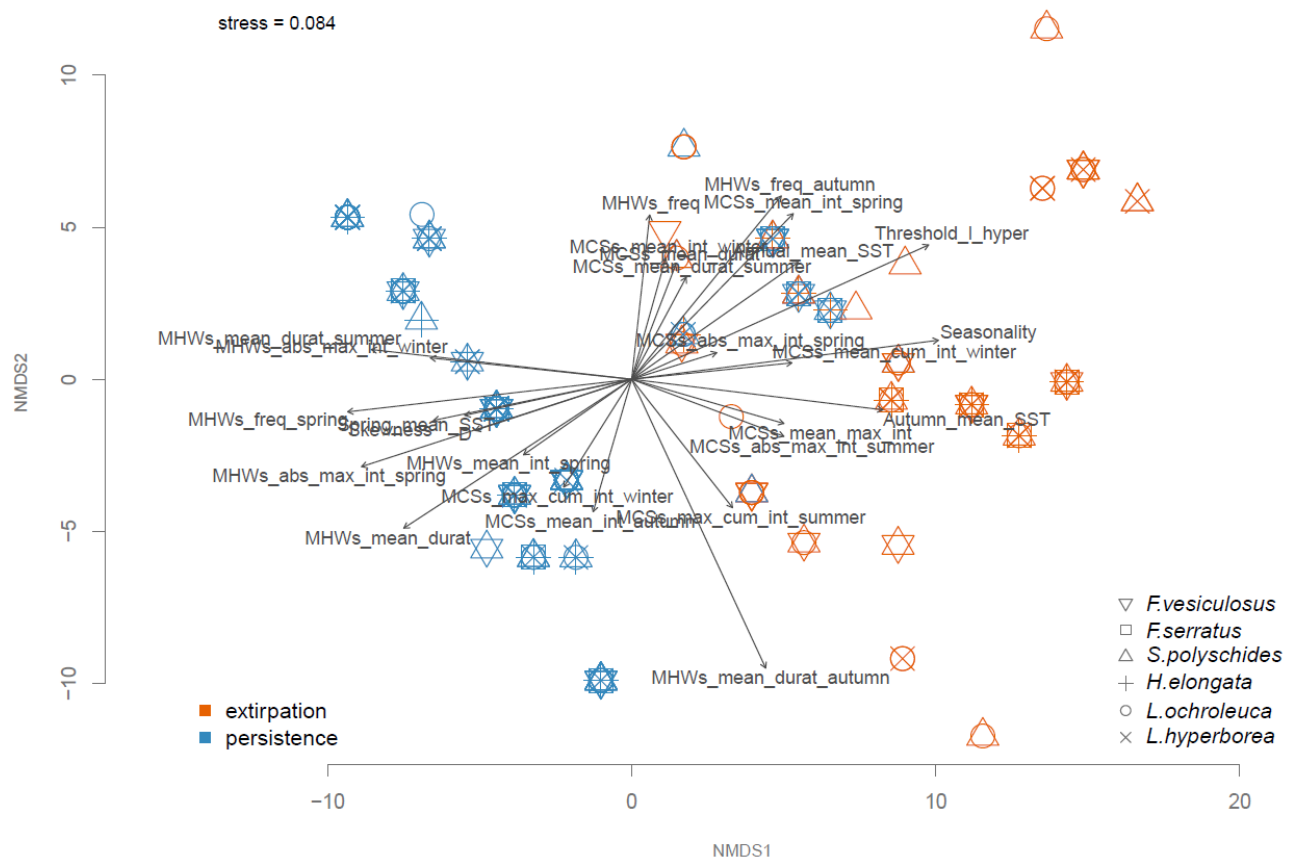
|                       | Persistence          |       |      | Extirpation |      |      |
|-----------------------|----------------------|-------|------|-------------|------|------|
|                       | Mean SST Autumn (°C) |       |      |             |      |      |
|                       | Min.                 | Mean  | Max. | Min.        | Mean | Max. |
| <i>S. polyschides</i> | 0.11                 | 0.24  | 0.36 | 0.27        | 0.36 | 0.39 |
| <i>L. ochroleuca</i>  | 0.11                 | 0.22  | 0.35 | 0.27        | 0.35 | 0.39 |
| <i>L. hyperborea</i>  | 0.11                 | 0.2   | 0.35 | 0.34        | 0.38 | 0.39 |
| <i>H. elongata</i>    | 0.11                 | 0.23  | 0.35 | 0.25        | 0.33 | 0.39 |
| <i>F. vesiculosus</i> | 0.11                 | 0.23  | 0.35 | 0.28        | 0.35 | 0.39 |
| <i>F. serratus</i>    | 0.11                 | 0.29  | 0.39 | 0.35        | 0.37 | 0.39 |
|                       | Seasonality          |       |      |             |      |      |
|                       | Min.                 | Mean  | Max. | Min.        | Mean | Max. |
| <i>S. polyschides</i> | -1.12                | -0.21 | 1.51 | 0.01        | 1.35 | 2.58 |
| <i>L. ochroleuca</i>  | -1.12                | -0.43 | 0.85 | 0.08        | 1.25 | 2.62 |
| <i>L. hyperborea</i>  | -1.12                | -0.53 | 0.85 | 1.14        | 1.92 | 2.62 |
| <i>H. elongata</i>    | -1.12                | -0.45 | 0.06 | -0.01       | 0.92 | 2.31 |
| <i>F. vesiculosus</i> | -1.06                | -0.31 | 0.85 | 0.14        | 1.32 | 2.58 |
| <i>F. serratus</i>    | -0.95                | 0.18  | 1.9  | 0.07        | 1.6  | 2.31 |
|                       | Skewness             |       |      |             |      |      |
|                       | Min.                 | Mean  | Max. | Min.        | Mean | Max. |
| <i>S. polyschides</i> | -0.03                | 0.06  | 0.11 | -0.03       | 0.02 | 0.05 |
| <i>L. ochroleuca</i>  | 0.03                 | 0.07  | 0.09 | -0.03       | 0    | 0.05 |
| <i>L. hyperborea</i>  | 0.03                 | 0.07  | 0.09 | -0.01       | 0.03 | 0.05 |
| <i>H. elongata</i>    | 0.03                 | 0.07  | 0.09 | 0.03        | 0.04 | 0.05 |
| <i>F. vesiculosus</i> | 0.03                 | 0.07  | 0.11 | -0.03       | 0.01 | 0.04 |
| <i>F. serratus</i>    | 0.03                 | 0.06  | 0.09 | 0.03        | 0.04 | 0.05 |

Independent contribution (I value) in the hierarchical partitioning analysis of variables discriminating between persistence and extirpation populations for each macroalgae species. Dendrogram at top shows clustering of species whose extirpation/persistence patterns can be explained by the same factors. See Table S1 in Supporting information for a description of the variables. SST: sea surface temperature.



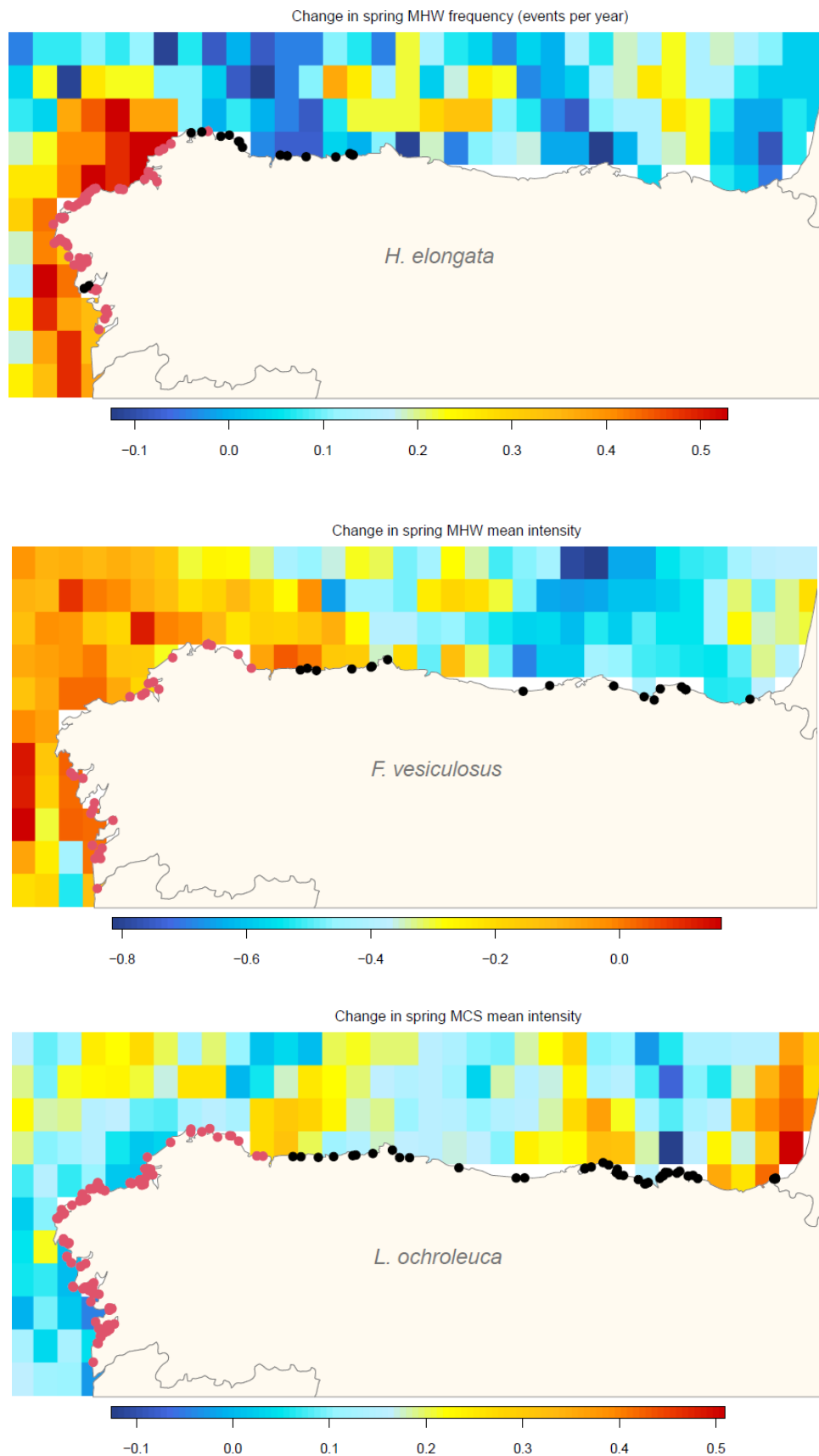
**Figure S2**

Non-metric multidimensional scaling (NMDS) ordination of the sites where extirpation or persistence has occurred over the baseline and resurvey periods in the Northern Spanish coast. The change in autumn mean sea surface temperature, seasonality and skewness showed a gradient direction able to explain the extirpation-persistence distribution (e.g. extirpated populations tend to increase when the seasonality anomaly increases over time). Longer arrows show stronger associations ( $r^2$ ). Macroalgae populations studied are *Fucus serratus*, *F. vesiculosus*, *Himanthalia elongata*, *Laminaria hyperborea*, *L. ochroleuca* and *Saccorhiza polyschides*. See Supporting information for a description of the variables (Table S1), and the NMDS scores (Table S2). SST: sea surface temperature.



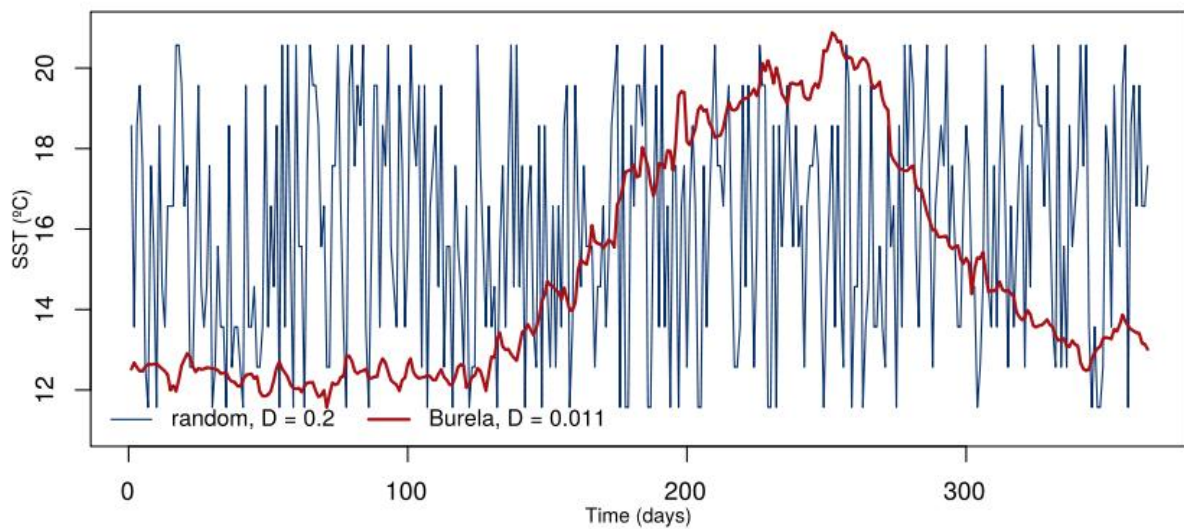
### Figure S3

Examples of anomalies in variables related to marine heatwaves (MHWs) and marine cold spells (MCSs) at extirpated and persistent populations of macroalgae (black and red dots respectively). Anomalies were calculated as the difference between the resurvey period (1991-2015) and the baseline period (1982-1990) for all variables.



**Figure S4**

Performance of the consecutive disparity index (D; Fernández-Martínez et al 2018), a measure of **temporal variability**. Here we provide a comparison of a real sequence of sea surface temperature (SST) and a randomly generated time series with similar longitude, minimum and maximum values. The real data (in red) is a one-year time sample sequence SST from Burela (Galicia), where local extirpation of *Himanthalia elongata* occurred. D is higher in the random series due to its lack of autocorrelation between consecutive data (greater fluctuations) in comparison with the real SST time series.



**Figure S5**

Anomalies in the frequency of days above the specific thermal threshold of each macroalgae species at extirpated and persistent populations (black and red dots respectively). Anomalies were calculated as the difference between the resurvey period (1991-2015) and the baseline period (1982-1990). The anomalies for *Fucus vesiculosus* are not shown since its thermal threshold was above the maximum SST registered in the time series.

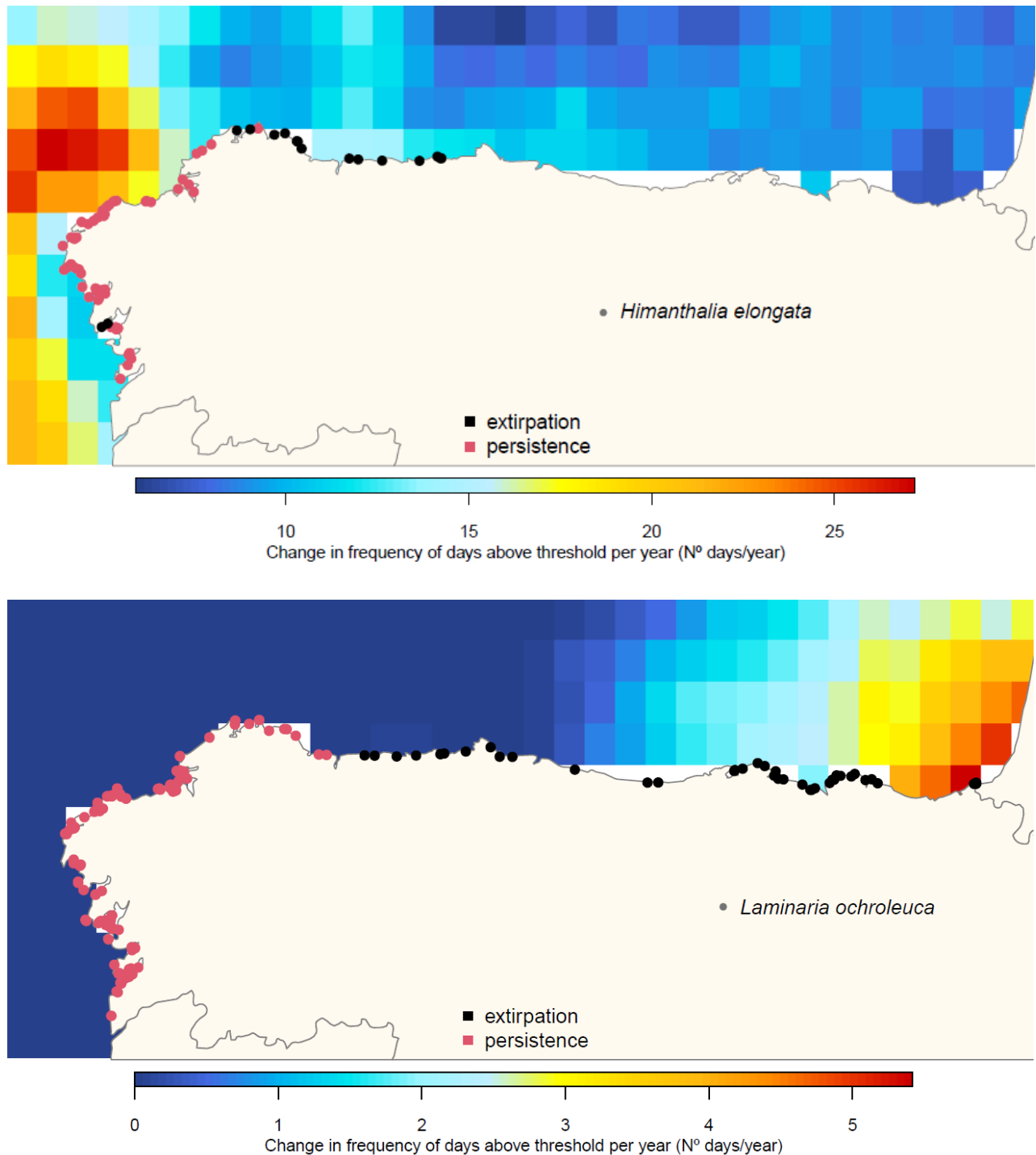


Figure S5 (cont.)

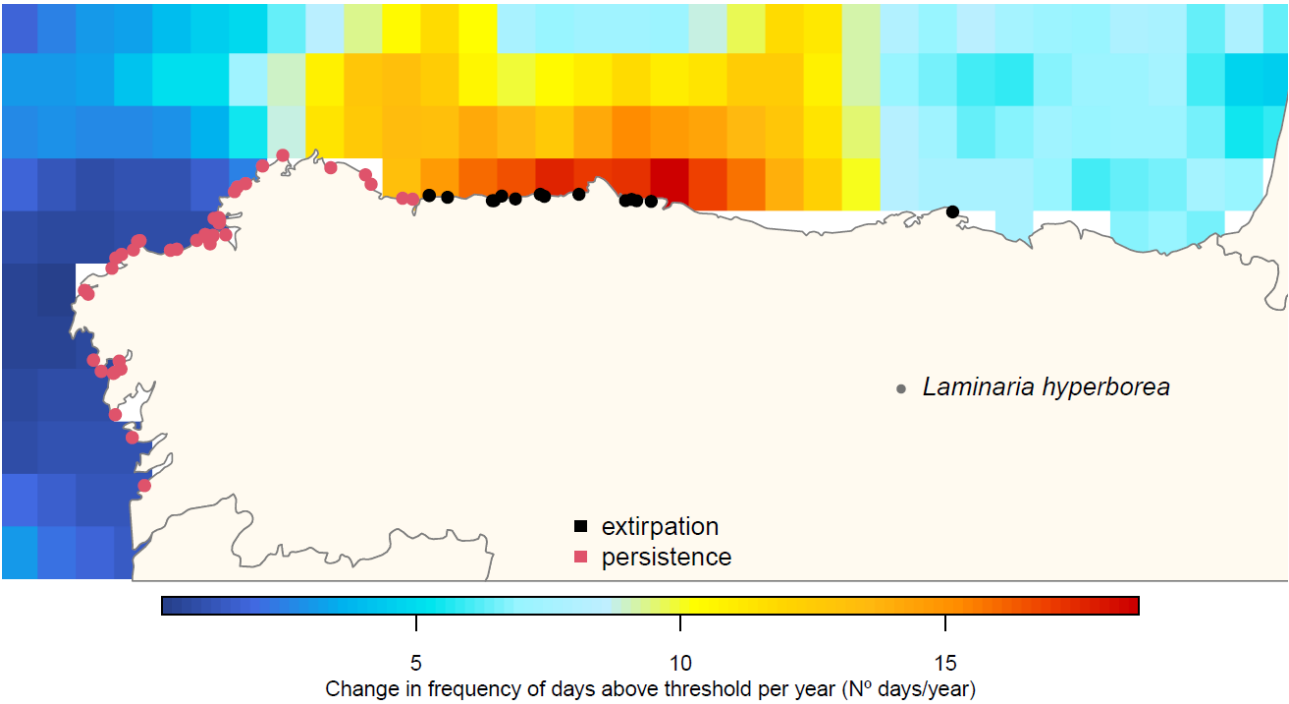
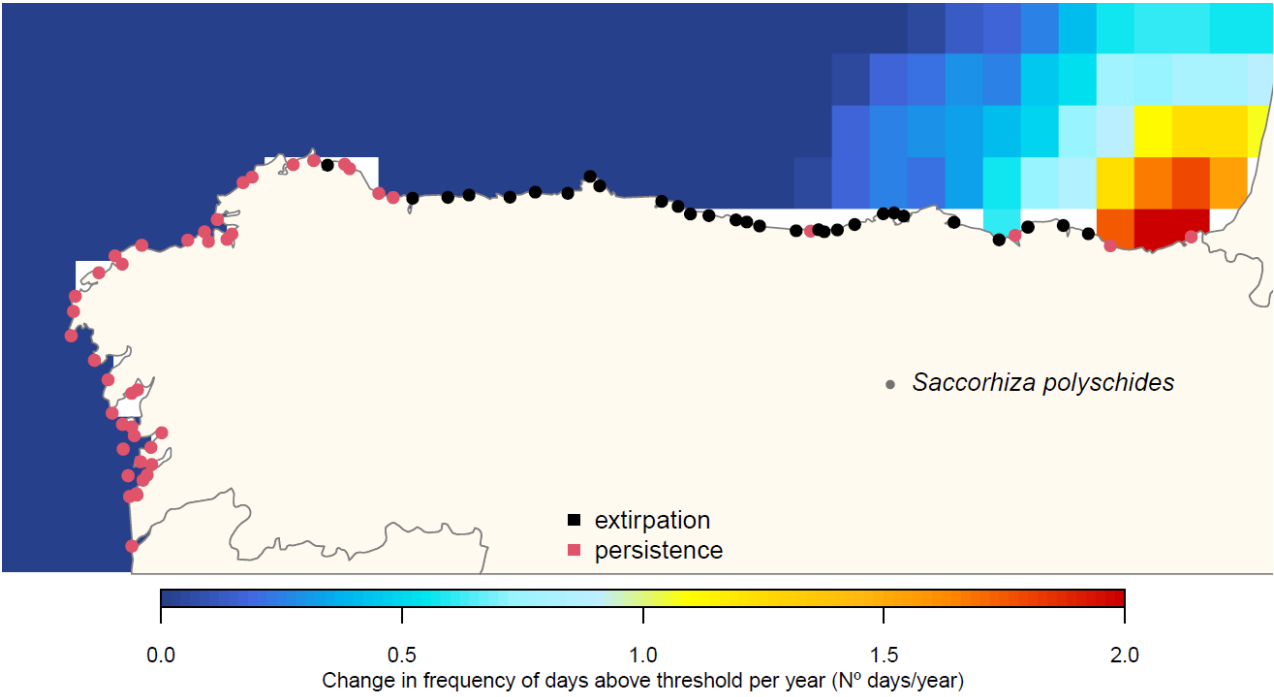
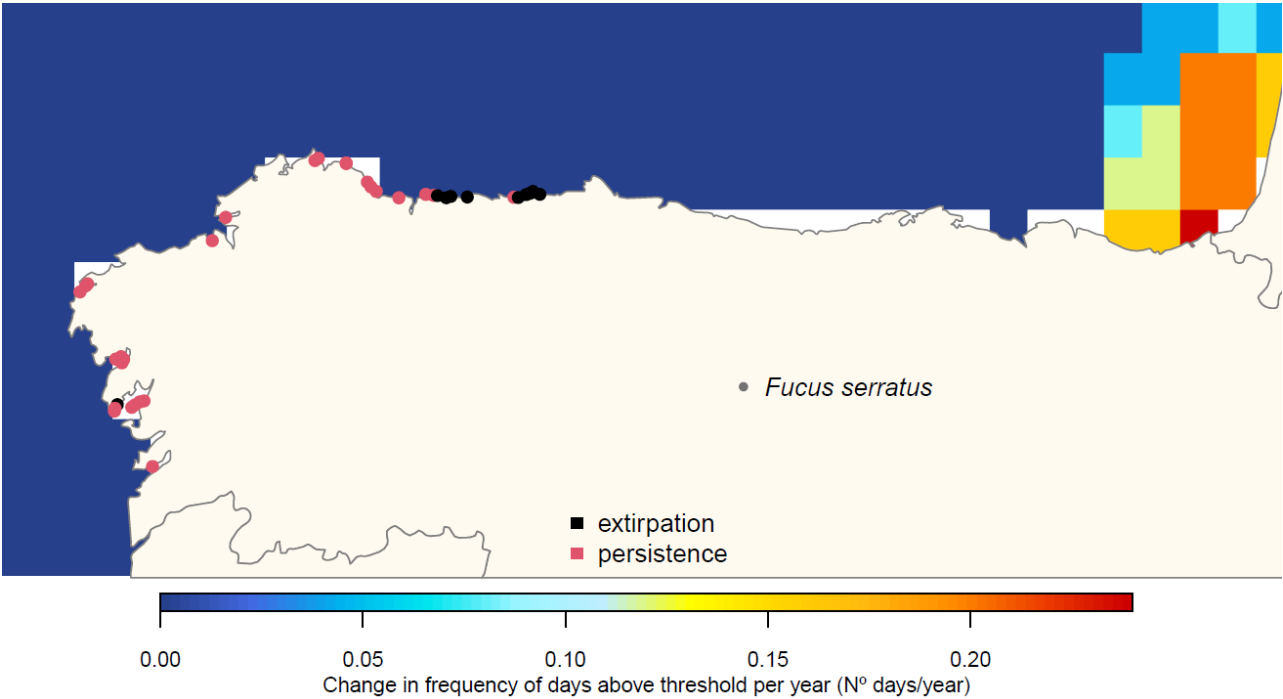


Figure S5 (cont.)



**Figure S6**

Mean, maximum and minimum SST from January 1982 to December 2015 (encompassing baseline and resurvey periods) at the study area in the Northern Spanish coast. Data were obtained from the NOAA 1/4° daily Optimum Interpolation SST data (daily OISST v2.1 data; Huang et al., 2021). Locally extinct (extirpated) and persistent populations of six macroalgae species were studied (*Fucus serratus*, *F. vesiculosus*, *Himanthalia elongata*, *Laminaria hyperborea*, *L. ochroleuca* and *Saccorhiza polyschides*). SST: sea surface temperature.

