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UNDERSTANDING THE THERMAL AMELIORATION PROVIDED BY ALGAE COVER IN ROCKY SHORE HABITATS

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RESUMO

O intertidal rochoso está entre os habitats mais exigentes e dinâmicos do mundo por se encontrar na interface entre ecossistema terrestre e marinho. Neste habitat, a temperatura desempenha um papel importante na função e estrutura do ecossistema, sendo altamente influenciado pela variação espacial a diferentes escalas. À escala do micro-habitat, a cobertura de algas pode desempenhar um papel de refúgio térmico para as comunidades associadas, no entanto este aspeto só foi quantificado muito raramente. Este estudo pretende em apurar este papel de refúgio, assim como quantificar as variações térmicas entre os diferentes microhabitats intertidais. Para tal, foram instalados cerca de 144 sensores de temperatura em três regiões da costa oeste portuguesa, num total de seis praias. A temperatura foi registada a cada hora, em oito microhabitas diferentes, cada um com três pares de sensores (um sensor coberto por algas e outro em rocha nua). Foram, ainda, obtidos dados da diversidade de fauna e flora associada durante o trabalho de campo *in situ*. Os resultados mostraram maior variabilidade de temperatura nos sensores colocados em patamares superiores expostos ao sol, especialmente durante o verão. Latitudinalmente, a temperatura máxima diária aumenta para sul e, por outro lado, a diferença de temperatura entre pares de sensores aparenta diminuir. Verificou-se também uma variação interanual, registando-se no verão de 2023 uma temperatura máxima mais baixa do que o verão de 2022 na região norte. As algas que cobriram os sensores mostraram ter um efeito de proteção térmica significativo, especialmente a alga *Ascophyllum nodosum* no norte de Portugal. Durante o verão, o efeito tampão das algas variou entre 32,20% a 69,37% no patamar superior do intertidal e 3,90% a 25,20% no patamar inferior. Em relação à biodiversidade por região, o norte apresentou a menor riqueza específica entre todas, mas em contrapartida, apresentou um maior volume de cobertura algal no patamar superior do intertidal. Apesar da dificuldade em garantir a cobertura de algas nos sensores ao longo do ano, estes tipos de instrumentos *in situ* revelam-se essenciais para uma monitorização contínua e mais precisa da temperatura em habitats tão complexos como o intertidal rochoso. Além disso, compreender como certas espécies tendem a atenuar os efeitos do aumento do aquecimento global é muito importante para adotar medidas de conservação, avaliar o efeito de futuras ondas de calor, ou até prever futuras transições latitudinais nas comunidades costeiras.

Palavras-chave: intertidal - ecossistemas marinhos - algas – temperatura – stress térmico

ABSTRACT

Intertidal rocky shores are among the harsher and more variable habitats in the world as they lie in the interface between air and water. Temperature plays an important role in the function and structure of these ecosystems, and they are highly influenced by spatial variation at different scales. At the microhabitat scale, algae may act as thermal buffers for associated communities, but this has been rarely quantified. With this in mind, this study focuses on establishing the role of algae as a refuge, as well as quantifying the thermal variations between different intertidal microhabitats. Overall,144 temperature data loggers were installed in three regions along the Portuguese west coast, on a total of six sites. Temperature was registered every hour within eight different microhabitats, each one with three pairs of loggers (one logger under algae and one on bare rock). Data on the diversity of associated fauna and flora was also obtained during *in situ* fieldwork. The results showed greater temperature variability in the upper intertidal exposed to the sun, especially during the summer. Latitudinally, daily maximum temperature increases towards the south and, on the other hand, temperature difference within pairs decreases. There was also inter-annual variation, with the summer of 2023 recording a lower maximum temperature than the summer of 2022 in the northern region. All algae presented a significant effect on temperature measurements, especially *Ascophyllum nodosum*. During summer, their buffer effect varied between 32,20% to 69,37% in top levels and 3,90% to 25,20% in low level. Regarding the biodiversity of each region, the north presented the lowest species richness among all, in contrast, presented a higher volume of algae cover on the upper intertidal. Despite the difficulty in maintaining loggers covered with algae along the year *in situ* dataloggers proved to be essential to provide precise and continuous monitoring of temperature in complex habitats, such as intertidal rocky shores. Moreover, understanding how certain species tend to ameliorate the effects of increasing warming conditions is very important to carry out conservation measures, to evaluate the effect of future heat waves or to predict future latitudinal transitions in coastal communities.

Keywords: intertidal - marine ecosystem - seaweed – temperature – thermal stress

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INTRODUCTION

It's becoming more evident that climate change is a major and significant growing threat to biodiversity and ecosystems around the world, forcing them to change rapidly in response. Climatic conditions affect the long-term survival of several species and, when a habitat is no longer suitable, they shift their geographical ranges and/or perish in that area (Nunez et al., 2019; Pettorelli et al., 2021). These climate changes are rapidly modifying ecosystems, not only by the effect of temperature, but also by other major global drivers such as: changes in precipitation, ocean chemistry and the frequency and magnitude of extreme events (Malhi et al., 2020; Weiskopf et al., 2020). Moreover, loss of biodiversity and degradation of ecosystems, caused by extreme events, can lead to huge impacts on the planet's ability to store carbon, while reducing the capacity of both nature and human populations to adapt to or withstand these extreme conditions (Pettorelli et al., 2021).

Within the Ocean, climate change has significant implications that lead to the disruption of marine ecosystems, affecting marine biodiversity and fish stocks, resulting in, therefore, consequences for food security and economic activities that depend on the ocean's health and productivity (Chan, 2021). According to the IPCC panel, it is expected that the ocean will continue to absorb heat over the next several decades and, by 2100 it is highly probable that it will experience a temperature rise of 2 to 4 times greater, under low emissions scenarios, and 5 to 7 times greater, under high emissions scenarios (IPCC, 2022). The accumulation of heat in the ocean has resulted in a 4% rise in thermal stratification within the upper layers across many oceanic regions (0 to 200 m, over a 40-year period) (Hoegh-Guldberg et al., 2014). Shifts of species toward higher latitudes and changes in the seasonality of their behavior are a widespread ecological reaction to this ocean warming trend (Chust et al., 2023). Evidence suggests that species with a cold-water affinity are migrating poleward, consequently creating more available habitat for species that thrive in warmer conditions (Mieszkowska et al., 2021). Though, it is expected that this will cause an increase in abundance at the poles and a corresponding decline in abundance as one moves towards the equator (Hastings et al., 2020).

The coastal systems are subject to the same large-scale warming trends as the open ocean and, ecosystems such as rocky shores (intertidal and shallow subtidal zones), present strong environmental gradients and periodical exposure to variations of marine and atmospheric factors (IPCC, 2022). Besides that, rocky shores are considered to be one of the better-understood coastal systems. In this ecosystem, we can observe short-term fluctuations, due to tidal cycles, that create an interface between marine and terrestrial environments (Helmuth et al., 2006). Physical factors, like solar radiation, desiccation or temperature, can affect the physiology, ecology and the biogeography of intertidal organisms, being temperature one of the most impactful factors (Seabra et al., 2011). With that, the last decade showed an increase in the number of studies focused on rocky intertidal assemblages (Álvarez-Losada et al., 2020; Freitas et al., 2023; Monteiro et al., 2022) providing an important model system that allowed the understanding of its community process patterns and structure (Bertness & Leonard, 1997).

The interactions between biotic and abiotic factors, within this small spatial scale ecosystem, lead to condensed and diverse communities, that can be used as natural models to determine how physical and biological factors interact on the abundances and distribution of organisms along these types of habitats (Lima et al., 2011). Daily variations of factors, like wind speed or humidity, can also contribute to a substantial difference in temperature to witch organisms are subjected, even if they are just a few meters apart facing opposite directions (Seabra et al., 2011). Several ecological studies, mentioned in (Helmuth et al., 2011), show differences between the results of large-scale measurements of the environment and the actual temperature that organisms experience. For example, the body temperature of organisms, like invertebrates and algae, in shadow surfaces can be similar to the one in the surrounding air or rock, on the other hand when they are on a surface exposed to direct sun radiation, their body temperature is significantly different of their surroundings (Helmuth et al., 2010). According to Firth et al. (2015), there is a notable tendency for increased taxon richness and abundance on north-facing substrata relative to south-facing substrata within intertidal environments. This indicates that such habitats may be vital in offering refuge from thermal and desiccation stress as global temperatures rise. Therefore, the north-south orientation stands out as one of the most significant yet least comprehended topographic factor (Amstutz et al., 2021). The size and morphology of an organism, such color or material properties, can also strongly affect the rate of heat transfer between him and its environment (Helmuth, 2002).

The idea of ecosystem engineers has gained considerable recognition among ecologists around the world. Engineering organisms have the capacity to modify the physical structure, complexity, and heterogeneity of their surroundings, significantly impacting the communities that inhabit these environments (Sueiro et al., 2011). Within the intertidal ecosystem, biogenic habitat (i.e., macroalgal canopies or mussels beds) can also reduce heat and desiccation stress during emersion, maintaining the productivity and diversity of that specific community (Bulleri et al., 2018). As bioengineers, macroalgae are the largest organisms found in these environments, creating extensive canopies that cover large areas of the substrate. At low tide, these canopies lie flat against the substrate, mitigating thermal fluctuations and minimizing water evaporation, which in turn supports the thriving of understory species during prolonged periods of aerial exposure (Watt & Scrosati, 2013). This way, habitats formed by macroalgae may have a role as refugia or act as community “rescuers” due to their capacity to counteract global change effects, such as the increase in temperature (Wahl et al., 2020). However, there is a large knowledge gap regarding the thermal regulator effect of algae and their buffer capabilities to the underlying communities. In other words, how can algae play a role as a stressor buffer for biodiversity and how to quantify their ability to alter the strength or shape of temperature gradients that affect the resident taxa?

Research regarding the buffer effects of canopies has largely concentrated on terrestrial forests (De Lombaerde et al., 2022; Kašpar et al., 2021). On the marine side, studies are primarily directed towards the communities that inhabit macroalgal canopies, with only a few studies exploring environmental factors such as temperature (Watt & Scrosati, 2013), but not considering the different microhabitats that the complexity of the intertidal creates. However, the significant costs associated with data loggers result in limited datasets, which ultimately constrains the conclusions that can be drawn from them. The Portuguese coast has recently turned out to be a relevant area for this type of study, especially for biogeography and diversity of macroalgae and thermal changes. Characterized as a transition zone, it serves as the southern geographical boundary for numerous boreal species, as well as the northern or western boundary for subtropical and Mediterranean species (Boaventura et al., 2002; Monteiro et al., 2022). This makes it ideal for understanding how temperature can vary latitudinally and how changes in temperature can have implications for biological communities. To fill this gap, we used small and low-cost temperature data loggers, to compare temperature under algae canopy and on bare rock in various intertidal microhabitats along the Portuguese west coast. Considering the complexity of the intertidal, our main aim was to study the buffer effect of algae. Specifically, to determine how temperatures vary between low-shore and top-shore and between shaded (north-facing) and sun-exposed (south-facing) areas. Together with other *in situ* and remote sampling methods, we compared the study regions in terms of biodiversity, algae cover and temperature. In addition, an assessment of temperature variations across the various seasons was conducted, placing particular emphasis on the summer and winter months, as well as an evaluation of algae thermal amelioration. Using the biological data collected from each research site, we compare them with the temperature data. This type of small data logger has now facilitated continuous and semi-continuous *in situ* monitoring of environmental and biological data, being an important tool as climate change on a detailed microhabitat scale.

METHODS

Study sites

This study was conducted at six locations in three different coastal regions along the west coast of Portugal (Figure 1): Northern region, with Praia de Moledo (PM: 41°50'26.164" N, 8°52'31.602" W) and Praia Norte (PN: 41°41'50.006" N, 8°51'9.551" W); Central region, with Praia da Empa (PE: 38°58'44.180" N, 9°25'23.048" W) and Cabo Raso (CR: 38°42'39.064" N, 9°29'10.298" W); and Southern region, with Praia dos Alteirinhos (PA: 37°31'12.472" N, 8°47'21.185" W) and Praia de Odeceixe (PO: 37°26'43.159" N, 8°48'0.943" W). In total, 144 temperature loggers were deployed, 24 per location. They were deployed in two distinct intertidal areas (upper or “top” and lower or “low” intertidal), at two orientations (facing north or “cold” and facing south or “hot”), and covered by algae or not covered (bare rock). In each one of these combinations, three replicates were deployed. All data loggers were deployed between August and October of 2022 and their maintenance and data collection occurred every two months until April of 2024.

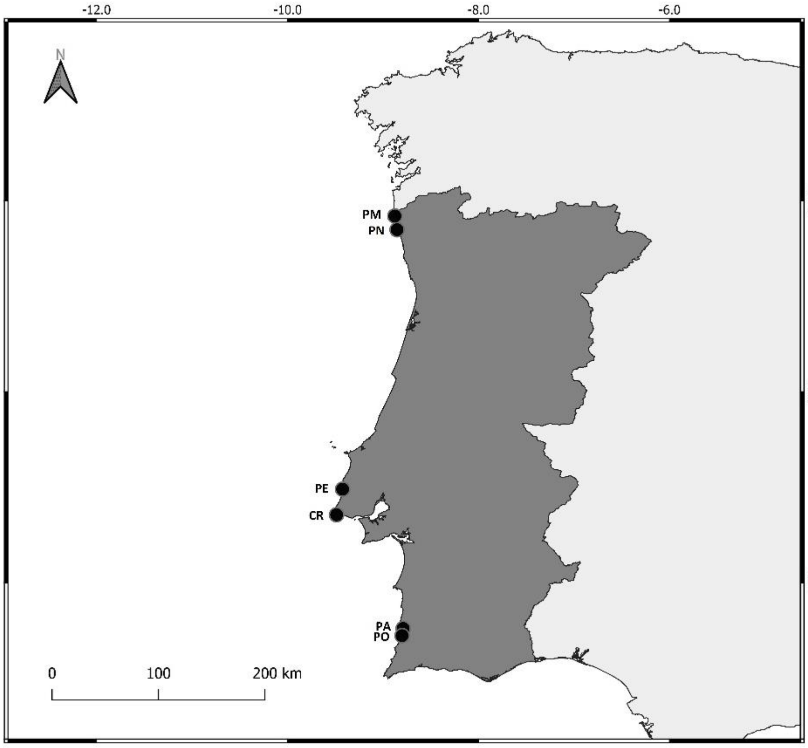


Figure 1. Study sites along the Portuguese west coast. Temperature data loggers were deployed at Praia do Moledo (PM), Praia Norte (PN), Praia da Empa (PE), Cabo Raso (CR), Praia dos Alteirinhos (PA) and Praia de Odeceixe (PO).

Sampling devices – Data loggers

Temperature was recorded by data loggers (EnvLogger version T7.3, electricblue.eu) that were embedded in the bedrock. For their fixation, a shallow, 30 mm diameter hole was drilled into the rock, the logger was inserted, and the hole sealed with an epoxy glue (Z-Spar Splashzone compound). Loggers were kept near the surface of the rock with only a thin layer of epoxy sealing them. The communication with the loggers and the data download was done via a smartphone app (EnvLogger Viewer). To do this, users used a smartphone with NFC. Data was stored in a folder on the smartphone in CSV format.

Three pairs of loggers were installed for each type of condition (shore level and surface directions). Each pair of data logger is composed of one logger covered with algae (study logger) and another one placed next to it with no algae cover (control logger). The species of the algae cover changed between locations to accommodate natural variations in species' compositions (**Appendix B**). In cases where canopy algae were selected, the logger was deployed right below the canopy next to the holdfast and immediately covered by the algae. When the loggers were deployed within turf algae (i.e., an aggregation of a variety of short algae species, mostly filamentous, foliose and/or calcareous articulated, sensu Connell et al. 2014), the drilling of the hole disturbed the algae locally, and the logger was not covered until the turf algae grew back.

Data recording had a resolution of 0.1 ºC and a precision of 0.2 ºC and was set to record every hour. Every time data was downloaded, the logger mission was restarted, and the memory cleared. Photoquadrats were taken at each logger location right before their maintenance. Control loggers were scrubbed clean on every visit. This maintenance was performed every two months to minimize algae growth and keep loggers clean of algae.

Using daily retrievals of the temperature of the ocean surface from NOAA (https://www.noaa.gov/), from the last 40 years, we compared the biological data with sea surface temperature (SST) satellite data to justify grouping data by regions.

Biological sampling

The volume of the algae covering each logger was estimated using a similar portion of the same algae collected in the surrounding area. For each one, a graduated cylinder was filled with a minimal amount of water (adjusted based on the size of the algae), after which the collected algae were added to assess the volume. This collection process occurred only once after all algae had been established covering the logger completely, when possible.

Based on the photoquadrats taken for each logger and for each sampling day, the algae cover was evaluated with a classification scale between 1 and 5, complemented with a classification scale of three letters (i.e., "lim" for limpet, "sab" for *Sabellaria* biogenic reefs, "san" for sand and "roc" for rock) due to the presence of another type of cover found during the loggers’ maintenance (Table 1). Examples of the different types of cover can be seen in **Appendix C**.

During the sampling period, each pair of study vs control loggers were evaluated as a “good pair”, “medium pair” and “bad pair”, according to the conditions being tested (e.g. a good pair would include a test logger covered with algae and a control logger with bare rock, which was not always the case during fieldwork). The pairs variability was registered in a heatmap to better select and analyse the temperature data. Based on Table 1, the “good pair” is formed by an uncovered logger with a classification (or label) of 1 or 2 and a covered logger with a classification of 4 or 5. The “medium pair” is formed by at least one logger with a classification of 3, and the “bad pair” is formed by an uncovered logger with a classification above 3, a covered logger with a classification below 3, or both.

We identified species covering the loggers on the photoquadrats using field guides. When it was not possible to reach species level identification, they were either categorized by their respective families or recorded as turf in cases where they were small (<2cm).

Table 1. Classification scale of the cover in data loggers

Label	Meaning	Observations
1	clean	without algae
2	slightly	quarter or some algae spots
3	partially	half covered with algae
4	covered	covered but with a thin layer of algae
5	fully	fully and well covered with algae
lim	limpet	logger covered with a gastropod
sab	*Sabellaria alveolata*	logger covered with a biogenic reef
san	sand	logger covered with sand
roc	rock	logger covered with a rock

To get a complete picture of biodiversity and associated fauna in each location, we complemented photoquadrat analysis described above with free roaming sampling (one 2-hour survey per site, n=3), quadrats (25x25cm, n=15) and/or transects (2x25m, n=2) taken during site visits. Given the limited biological data obtained from Praia de Moledo, it was necessary to include additional species sourced from a relevant article (J.

Pereira et al., 2021) and a monitoring study carried out at the location. (List of species available in **Appendix B**).

Data analysis

All files of temperature data were checked to ensure that errors, such as misspelled logger id name and different date format, were corrected. Some loggers were replaced due to total loss of algae coverage and files were merged based on the date from the new logger deployment. Before temperature analysis, we joined the loggers from the same pair, calculating the temperature difference for each one, and rearranged the visualization order of some variables (package *forcats*, from R-studio). “sh” (shore) was rearranged by latitudinal order and “lvl” (level of zonation) from top to low. The first two days after loggers’ deployment were removed from the analysis.

To analyse the temperature measured in each site we used a scatter plot (function *ggscatter* from package *ggpubr*) with Pearson correlation method for exposure versus shore level comparison. For a better comparison, the same kind of scatter plot was used to see the differences in the temperature registered in each type of exposure by overlaying them. The maximum, minimum and mean daily temperature recorded for each location were calculated, as well as the highest temperature difference between pairs of loggers (see supplementary Material **Appendix D – 1.1 and 1.2**). To visualize that temperature difference for each site and level, we used a *ggplot* function with *geom_hline* (package *ggplot2*), overlaying the two types of exposure.

Next, we assessed how the temperature varied across seasons. To obtain distinct seasonal patterns, we selected a “all-year” good pair from Praia Norte and compared the temperature data within it. We used the *ggline* function (package *ggpubr*) to create a multi-line plot for each type of exposure (hot and cold) and plotted labels for the different seasons for better visualization on seasonality patterns. Additionally to the plot, we calculated the maximum, minimum and temperature difference exclusive for this pair. By applying subsets in the data, we create new datasets to just include the summer (2022 and 2023) and winter seasons (2022-2023 and 2023-2024). From there, we were able to compare and corroborate the temperature tendency within and between these four events, as well between regions.

For the role of algae coverage, we used a density plot (*ggplot* function with *geom_density*) to compare temperature under the algae and exposed to sun (hot) x temperature in bare rock and in shaded surface (cold). Here we also selected a good pair from Praia Norte. In addition, we calculated the density and temperature for the peaks, as well as a Welch Two Sample t-test (Xu et al., 2017)(see **Appendix D - 2**) to confirm the significance of the measurements. To account for temporal autocorrelations, the degrees of freedom (d.f.) were adjusted using the Quenouille procedure for two independent samples (n_1 + n_2 - 2). After, the data were filtered according to the mean of coverage of each pair, recorded during the months of summer'23. We excluded from the dataset all pairs that presented a mean coverage below 2,6 and above 5. We analysed the ranges of temperature recorded under each species of algae, between levels of shore, using a boxplot (*ggplot* function with *geom_boxplot*) divided by shore level and type of exposure. Furthermore, we did a descriptive statistics analysis and estimated the mean, sd, median, trimmed, mad, min, max, range, skew, kurtosis and se for the boxplot (see **Appendix D - 3**). Next, we fitted a generalized linear model (GLM), using the *glm* function (Gamma family, link = "log"), to predict the response variable, 95th percentil of daily maximum temperature, based on several predictor variables (cover, species, exposure and sites), including an interaction between cover and species. We excluded the tidal levels due to collinearity in the model. The best model was selected based on the Akaike Information Criterion (AIC) and supported by normality in the residuals (Q-Q plot). The mean reduction in daily temperature variability (or buffer effect) was calculated with the formula: $\frac{mean\ (daily\ sd\ of\ study\ logger)}{mean\ (daily\ sd\ of\ control\ logger)} \times 100\%$, for each pair of loggers, during summer and winter seasons. We only considered the buffer effect from "good" and "medium" pairs and excluded those who had missing values (see table in **Appendix D - 4**).

Finally, for the biological data, we used a non-metric Multi-dimensional Scaling (nMDS), *metaMDS* function from the *vegan* package, to analyse quantitative data on species' presence between all sampling sites. For that was used the Raup-Crick dissimilarity index, ideal for presence/absence data. To support the delimitation by region and to compare temperature data with biological data, we used another nMDS with Sea Surface Temperature (SST) from the last 40 years. This SST data, obtained from NOAA, contain a considerable amount of data that make this analysis more robust, not possible with the amount of data collected during the study. A non-parametric test was made to perform an analysis of similarities (ANOSIM) between sites, as well the similarity percentage (SIMPER). The species richness and the average algae volume from each region were verified using Microsoft® Excel®. We also created a heat map by site, tidal level and type of exposure to visualize the variability in the pair' coverage along the sampling period. To complement, we selected some pairs with the most noticeable cover variance along the sampling period and created a "composed image" with a temperature interactive time series plot, using the *dygraphs* package, and the photoquadrats imagens from each logger of the pair, every time maintenance was carried out.

All data analysis was calculated using R-studio (version 2024.09.0+375) and Microsoft® Excel® (version 2409 Build 16. 0. 18025. 20160, 64-bit). Complete results of the statistical analyses are present in **Appendix D**.

RESULTS

Temperature data

A. Difference between variables

For each microhabitat per site, there is a strong positive correlation (r between 0.9 and 1.0) between the temperature on bare rock and under algae (figure 2). However, for most combinations tidal level and microhabitats the temperature in bare rock tends to be higher than under algae. This means that a temperature plateau is reached below the algae though it still continues to rise over bare rock. Two exceptions were found in the top cold microhabitat in Praia da Empa "emp" and Cabo Raso "cbr", where when the temperature rises, a pronounced change can be seen in the middle range of temperatures, where temperature under algae is slightly higher than on bare rock. This can be seen through the inclination of the regression line for the top cold level of the two sites.

When analysing the “good pairs” at top hot level in Praia Norte “vcn”, it showed a strong correlation (R=0.79, p<2.2e-16), although weaker when compared with the other plots. In this particular microhabitat (top hot), the relationship between the temperature conditions has a higher variability. Observing the regression line (in blue – figure 2), it deviates more significantly from the red line, particularly at lower and higher temperature extremes.

Despite the difficulty in obtaining good pairs, the same general pattern emerges in all. The “low” loggers present less temperature variation, opposed to the “top” ones that show a higher temperature variation, both in “cold” and “hot” microhabitats. A higher amplitude of the data dispersion indicates a strongest temperature amplitude, detected in the exposed top tidal level of each site. The maximum temperatures registered in this microhabitat from north to south are as follows: 43,3 ºC (north), 44,1 ºC (centre) and 46,1 ºC (south). On the other hand, the minimum temperatures registered were 3,3 ºC (north), 4,4 ºC (centre) and 2,9 ºC (south).

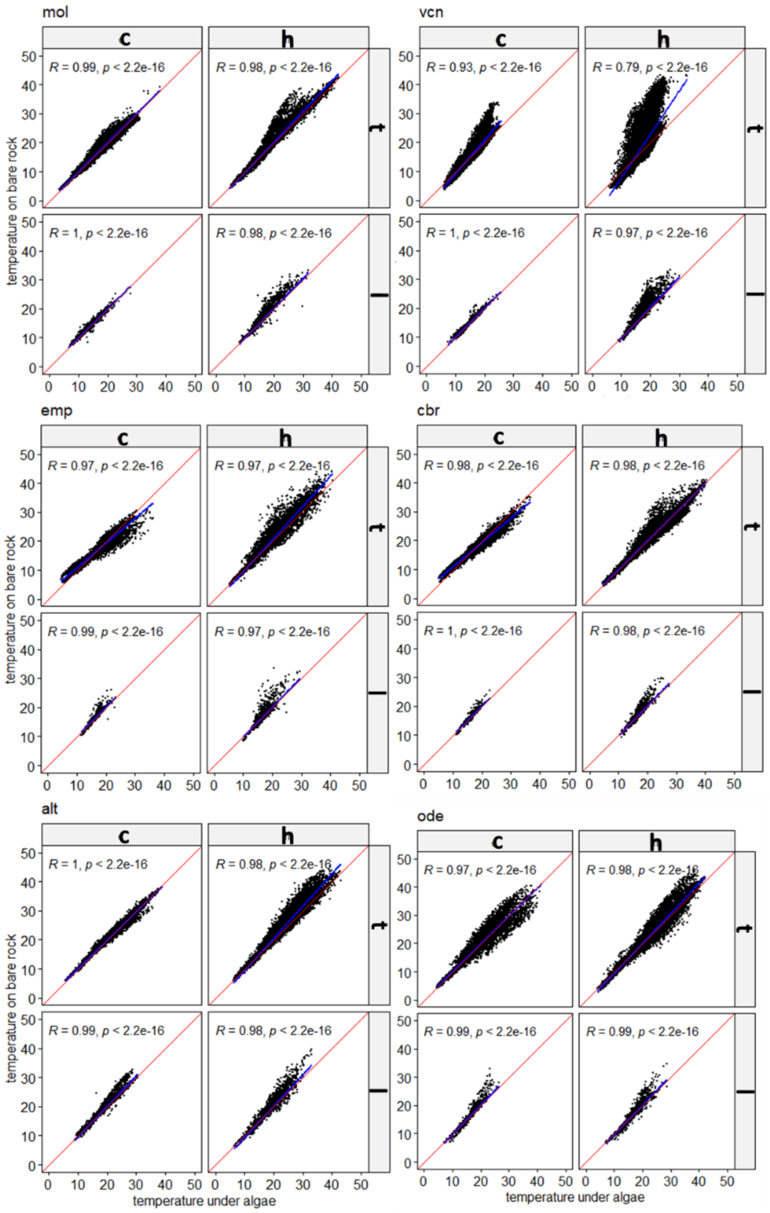


Figure 2. Scartterplot of all pairs of loggers by level and exposure for each site. Pearson test of temperature. Blue line - confidence interval for the regression line. Sites: "mol" - Praia do Moledo, "vcn" - Praia Norte, "emp" - Praia da Empa, "cbr" - Cabo Raso, "alt" - Praia dos Alteirinhos, and "ode" - Praia de Odeceixes. Level and Exposure: "l" - Low level, "t" - Top level; "h" - Hot, "c" - Cold.

As expected, when overlaying the type of exposure (hot and cold), it can be seen more clearly that the temperature range of the pairs in a hot surface is higher than in a cold surface (Figure 3). These differences are more detectable in top levels, when habitats get exposed to terrestrial environment during low tide. (complementary graphics in **Appendix D – 5.1 and 5.2**).

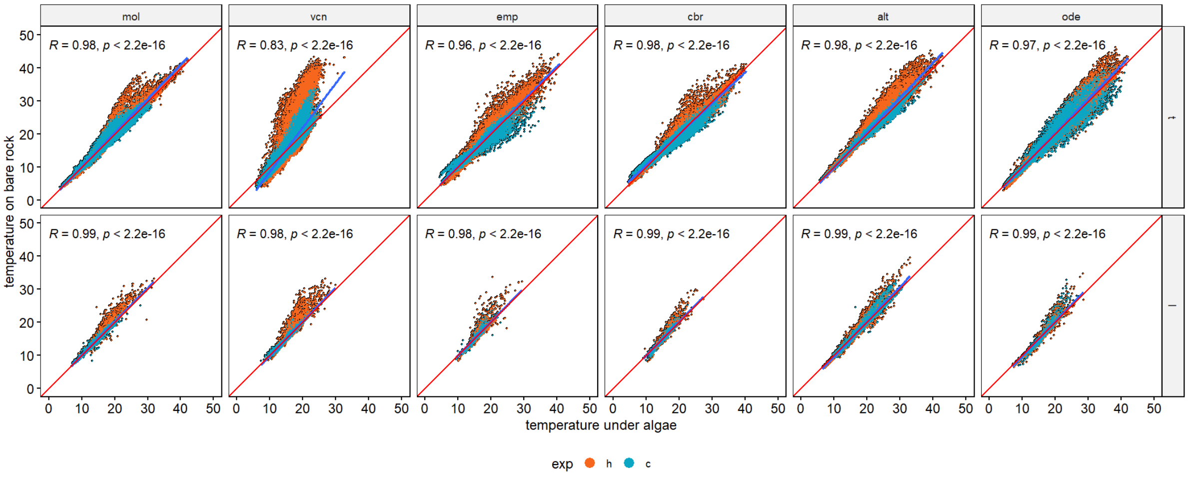


Figure 3. Scartterplot of shore pairs combined, divided by level and subdivided by exposure. "l" - Low level, "t" - Top level. Exposure ("exp"): "h" - Hot in orange, "c" - Cold in blue. Pearson test. Blue line - confidence interval for the regression line. Sites: "mol" - Praia do Moledo, "vcn" - Praia Norte, "emp" - Praia da Empa, "cbr" - Cabo Raso, "alt" - Praia dos Alteirinhos, and "ode" - Praia de Odeceixes.

During the sampling period, fluctuations in the temperature registered within pairs of loggers (bare rock – under algae) were found in all sites (figure 4). The site Praia Norte ("vcn") exhibited higher amplitude when compared with the other sites, with a temperature difference within pairs spanning from 20 ºC to -5.4 ºC for the upper shore and from 10.4 ºC to -3.2 ºC for the lower shore. In all the remaining sites, the difference between bare rock and under algae was less pronounced. The higher temperature difference was detected during the midseason (late spring and the beginning of summer) and on the top level loggers.

Observations of the tidal levels indicate that the temperature data exhibits notable clustering, characterized by a pronounced amplitude at the upper level, which implies that there are regular changes occurring within this dataset. On the lower shore, the temperature values appear in a thinner form, showing peaks only during low tides, when the datalogger remains emerged from water. During the warmer periods of the day, when in low tide and exposed to sun, the major temperature difference registered by a pair was as follows, **20 ºC** in the North, **13,3 ºC** in the Center **12,2 ºC** in the South (Table in **Appendix D**).

Figure 4. Temperature difference between pairs of loggers (bare rock and under algae) for each site and level ("l" - Low level, "t" - Top level) and color division by exposure ("c" – cold: blue 95%; "h" – hot: orange). The division of the graph according to exposure can be found in ***Appendix D – 6.1 and 6.2****.*

B. Seasonality

Distinct seasonal trends are evident throughout the sampling period, especially when choosing a good pair of loggers from Praia Norte that will be subject to further analysis (Figure 5). For both hot and cold exposures, the transition between seasons are gradual, with spring and autumn serving as a transitional period and with higher temperatures registered in the summer and lower temperatures registered during winter. Throughout the winter of 2022/23, we registered the lowest temperature by a "hot" control logger, 4.1 ºC, with a -2.7 ºC difference from the covered logger (fig.5B). At the other extreme, in "cold" (fig.5A), the lowest temperature logged was 4.8 ºC in a control sample, with a -2.3 ºC difference from the covered logger. This shows that a buffer effect can also be obtained for lower temperatures. Regarding the winter of 2023/24, in the "hot" microhabitat (fig.5B), the minimum temperature registered was 6.0 ºC by the control logger, with a -2.7 ºC difference of the covered logger, and 6.8 ºC for the "cold", with -2.6 ºC difference by the control logger.

Analysing the summer seasons, in 2022, the hottest day in the "hot" microhabitat (fig.5B) registered a temperature of 41.4 ºC in the control logger, with +14.8 ºC difference from the covered logger. In the "cold (fig.5A) microhabitat the maximum temperature registered was 33.4 ºC, with a +11.1 ºC difference from the covered logger. These examples can also provide evidence for a buffer effect, in this case, for higher temperatures. When examining the pair from the “hot” microhabitat (fig.5B), this showed, in 2023, a warmer summer registering a maximum of 42.0 ºC in the hottest day by the control logger, and 24.5 ºC registered in the covered logger, providing a difference of 17.5 ºC between them in the same hour. On the other hand, in the “cold” microhabitat (fig.5A) the summer of 2023 was cooler, registering a maximum of 32.3 ºC in the control logger, with a difference of +9.5 ºC from the covered logger.

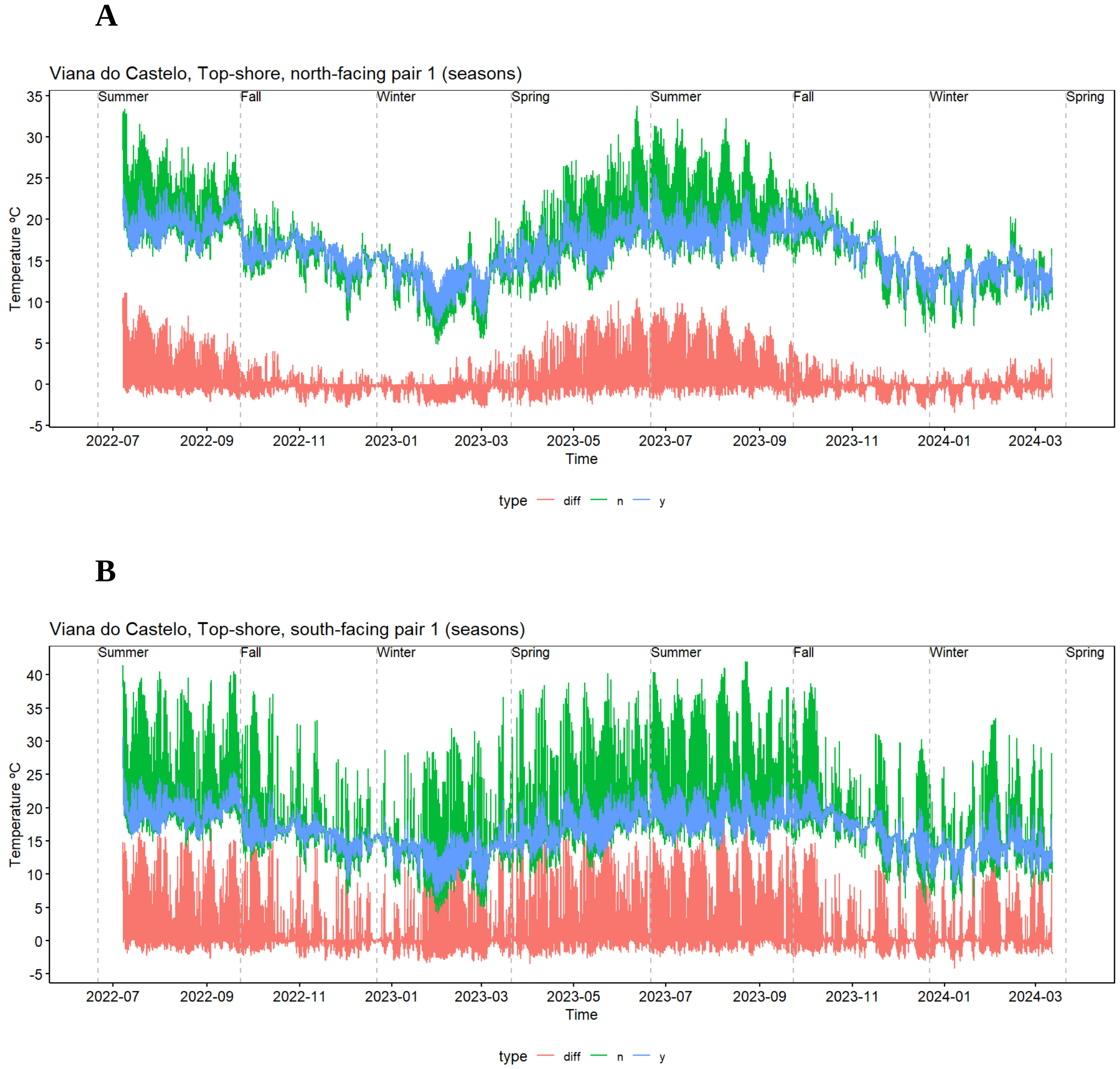


Figure 5. Temperature differences within a good pair for loggers between seasons. Loggers from Praia Norte, in top level and (A) hot or south-facing and (B)cold or north-facing. Green line represents the not covered logger, the blue line represents the algae covered logger, and the red line represents the difference between the two loggers.

These seasonal variations can be observed in all sites and sustained by the average of the daily maximum and minimum temperatures for “hot” and “cold” microhabitats of the top level (measured with the control loggers). These are the examples where we can find a higher temperature variability. An observable pattern in both winter and summer seasons is that the average temperatures (minimum and maximum, respectively) tend to rise as we descend latitudinally along the coast (see tables 1.1 and 1.2 of **Appendix D**). Regarding the winter, all sites registered an increase of the minimum average temperature from 2022/23 to 2023/24. The maximum mean temperature in the north region decreased slightly from 2022 to 2023 during summer, with Praia do Moledo and Praia Norte registering 20.1ºC and 20.6ºC, respectively, in 2022, and 19.6ºC and 19.8ºC, respectively, in 2023.

C. Algae cover and its buffer effect

To better understand the role of algae cover, we analysed the differences in temperature recorded in the top level between a logger in the ‘hot’ microhabitat under algae (logger 1 or hot) and a logger in the ‘cold’ microhabitat without algae (logger 2 or cold), from a pair of Praia Norte (figure 6). The overall distribution of both loggers appears to be unimodal, with a single prominent peak right skewed. The “logger hot” shows a higher and narrower peak, reaching a maximum density of 0.226 at 18.42 ºC. Yet, the “logger cold” appears to have a lower and broader peak, with a maximum density of 0.169 at 18.37 ºC. It maintains higher density values at higher temperatures (above 22 ºC) compared to “logger hot”. Analysing more closely the skewness of the density curve for both loggers, we see that the mean is greater than the median. The median temperature in “logger hot” (18.50) is slightly lower than in “logger cold” (18.70), but in both loggers, the mean is higher than the median (18.65 and 19.50 respectively).

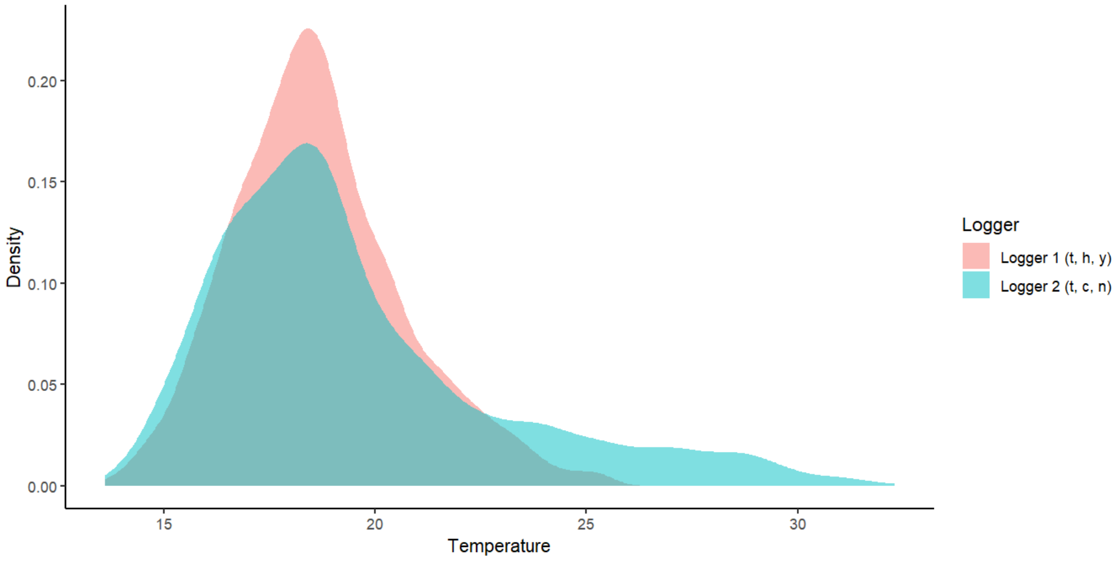


Figure 6. Density plots between a top level, "hot" exposure and covered logger and a top level, "cold" exposure and not covered logger in Praia Norte, during summer'23. Welch Two Sample T-Test in ***Appendix D - 2****.*

The Welch Two Sample t-test between the two distinct loggers' microhabitats, confirm, with the negative t-value (t = -9.9178), that the mean of the "logger 1" is significantly lower than the "logger 2". The extremely low p-value (< 2.2e-16) indicates a statistically significance difference in temperature measurements between the two loggers.

Analysing the temperature recorded under each species of algae, we notice differences within the same level (top or low) (figure 7). At the top level, the species found in the northern region (*Ascophyllum* and *Pelvetia*) registered, below them, a lower temperature range, especially Ascophyllum. At the low level, *Mastocarpus* and Sargassaceae have a lower temperature range than Turf. Between levels, *Fucus* and turf exhibit a notable temperature differences between shaded ("cold") and sun-exposed ("hot") conditions and, together with *Pelvetia*, recorded higher temperatures than the rest. Also, *Fucus* (hot sd=4.82 and cold sd=3.66) and *Pelvetia* (sd=3.52) shows a higher variability than the rest (sd < 1.97). As expected, and already seen, the top level had a higher temperature and higher variability than the low level.

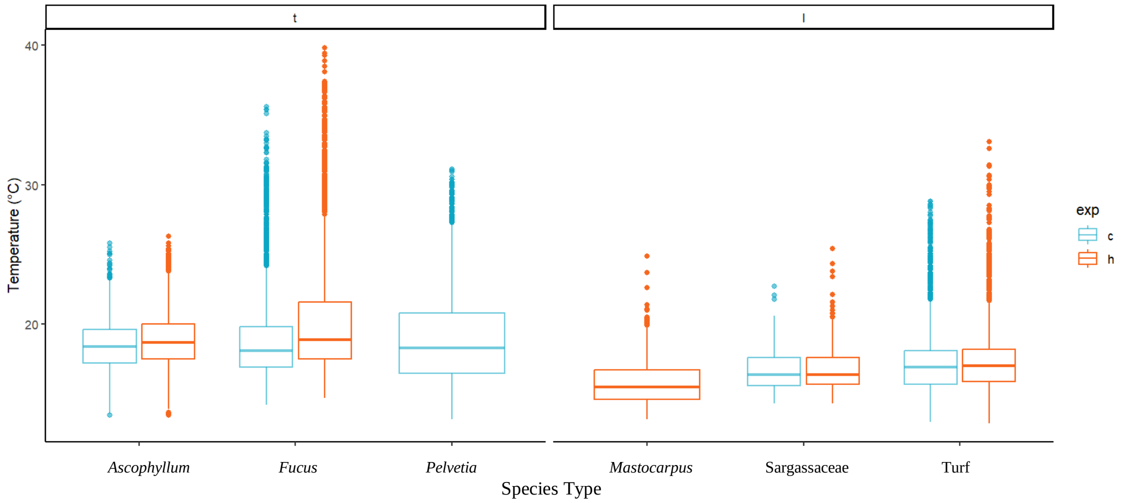


Figure 7. Temperature under different algae species, by level (top and low) and exposure (hot and cold). Category of cover selected (3-5) for the study loggers. Data from summer '23. Boxplot extra data information in ***Appendix D - 3.***

Through the analysis of the predictors (GLM results in **Appendix D - 7**), all algae appear to have significant effects on temperature ($p < 0.05$), as well as the type of algae cover category ($p<3.56e-06$). Regarding the species effect when taking into account the level of cover (compared to baseline species *Ascophyllum*), only *Mastocarpus stellatuus* present statistically significant ($p < 0.001$), with Sargassaceaea in the limit ($p=0.057$), *Fucus* without significance ($p=0.188$), and *Pelvetia canaliculate* and Turf with singularities (NA values). However, this analysis must be made under the scope that different species of algae are only present in specific regions (e.g. *Ascophyllum* at Praia Norte, one of the northern sampling sites) which in turn are subjected to different temperature regimes. Regarding the algae's buffer effect (**Appendix D - 4**), it is more evident in top levels (32,20% to 69,37%) than in low levels (3,90% to 25,20%) during summer. Winter presents the same tendency, with the top level (3,70% to 59,97%) having a higher percentage of buffer effect than the low level (2,23% to 14,90%), although there is an overlap of values. In the level of exposure, for both summer and winter, the tendency is also for a higher percentage of buffer effect for "hot" than in "cold".

Biological data

Analysing the SST temperature data from the last 40 years of each region using an nMDS, it becomes clear that the different regions (North, Centre and South) aggregate in terms of biodiversity and temperature forming separate clusters (Figure 8).

The distance between Praia do Moledo (PM) and Praia Norte (PN), observed in fig. 8A, may be supported by the type of algae found in each, such as *Ascophyllum nodosum*, which is only found in one place along the Portuguese coast, in this case Praia Norte (ANOSIM statistic R: 0.6389; Significance: 0.066667; Nº of permutations: 719). The resemblance (Bray Curtis similarity) of each region, according to their species richness, ranges from 49,77% in the north, 73% in the center and 60,36% in the south.

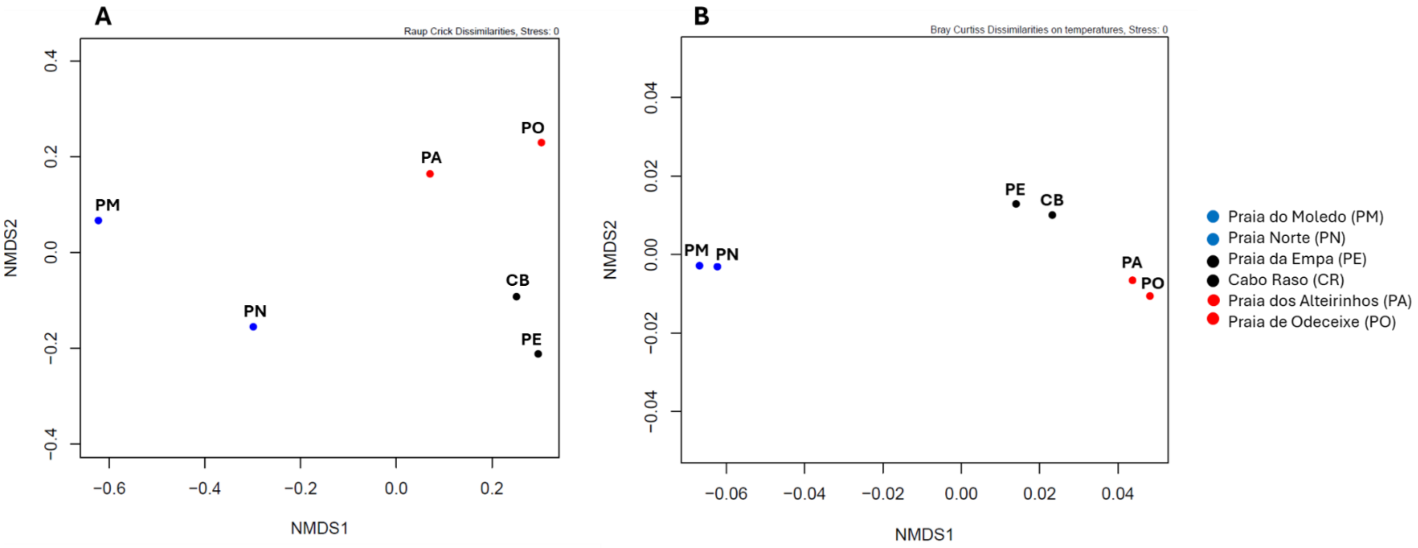


Figure 8. Non-metric multidimensional scaling (nMDS) of the biological data from all the study points (A) and the nMDS of SST temperature data from the last 40 years for the study sites (B).

The algae associated fauna was not consistent amongst regions, especially in the northern region. Regarding species richness (fig.9), the northern region has the lowest, with 165 species where more than 60% is represented by algae (41% of Rhodophyta, 18% of Ochrophyta and 5% of Chlorophyta, n=104). The central region stands with the highest number of species richness, 279, followed by the southern region, with 205 (species list present in **Appendix C**). Looking at these two last regions (central and southern), only 39% (n=89) and 34% (n=70), respectively, of the species richness are algae.

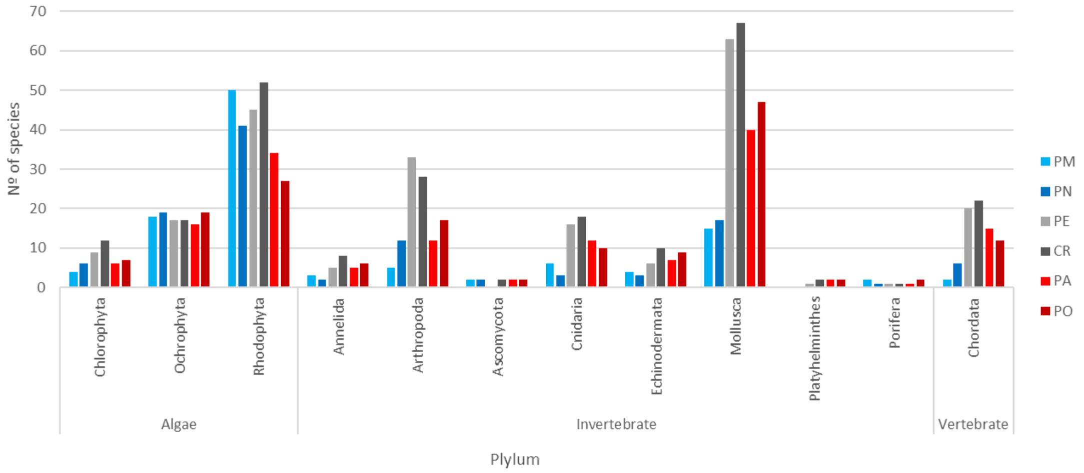


Figure 9. Representation of species richness from each study region, grouped by phylum. Northen region: Praia de Moledo and Praia Norte; Central region: Praia da Empa and Cabo Raso; Southern region: Praia dos Alteirinhos and Praia de Odeceixe.

The type of algae present in each site are, in some cases, unique. In the low level we have canopies of *Mastocarpus stellatus* and Corallinaceae in the northern region; Sargassaceae in the central region; and Turf (assemblages of different small-sized algae) is present in all the sites. The top level has *Pelvetia canaliculata* in Moledo (north), *Ascophyllum nodosum* in Praia Norte and in the central and southern regions, are represented by *Fucus sp*.

The Northern region, mainly the site Praia Norte ("PN") with *Ascophyllum nodosum*, is characterized by a high volume of algae cover in the top level, while, on the other hand, the Central region has a higher volume of algae cover in the lower shore (Table 2).

Table 2. Average algae volume (ml³) covering the loggers in each site, in the beginning of the study. PM – Praia do Moledo; PN – Praia Norte; PE – Praia da Empa; CR – Cabo Raso; PA – Praia dos Alteirinhos; PO – Praia de Odeceixe.

		North		**Center**		**South**	
	Algae	**PM**	**PN**	**PE**	**CR**	**PA**	**PO**
Top	*A. nudosum*		83,33				
	Fucus sp.			7,33	1,23	4	5,08
	P. canaliculata	9					
Low	*C. acicularis*	2	2				
	C. crispus		4				
	Corallina sp.		6				
	G. pulchellum	8					
	M. stellatus		8				
	O. pinnatifida	2					
	Sargassaceae			27,6	21,5		
	Turf			0,2	3,5	1,13	1,63

During all the sampling period, the algae coverage oscillated between seasons and in all regions (Fig.10). With spring, a small increase in algae coverage are notable in almost all sites until the end of summer, the hottest and harsher periods. In Praia Norte, the coverage for the top level remained almost all the time unaltered. In loggers deployed with low or no algae coverage, it was difficult to improve the level of coverage during autumn, a time of year when nutrients and light are lower. For loggers with initial algae cover, there is a general decrease over winter.

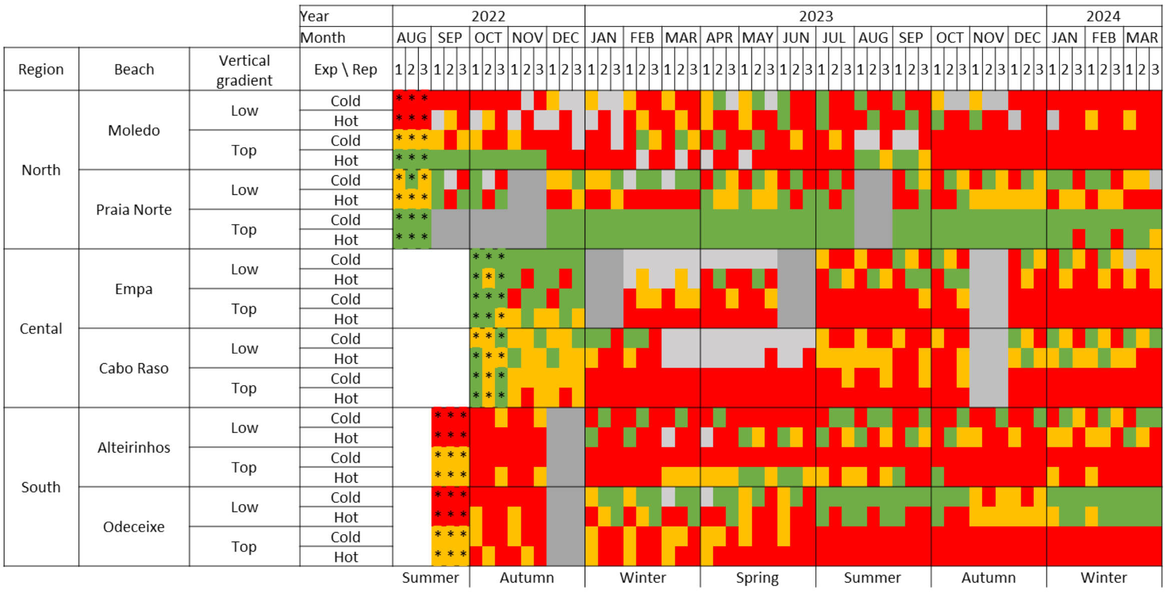


Figure 10. Heatmap of all pairs of loggers during sampling period, for all sites and microhabitats. Green – good pair; Yellow – medium pair; Red – bad pair; Grey – information gap; "" – logger deployed.*

The analysis of the photoquadrats allows us to establish a timeline of algae coverage variation along the sampling period. The abundance shifts found, follow the range of temperature variation registered with the loggers and, therefore an increase or decrease in the temperature experienced in each microhabitat (observed in figure 11 – More examples in the **Appendix D – 8.1 to 8.3**). It is commonly noted that algae tend to experience a decline or diminishment in their coverage during the late summer and early autumn periods, with a subsequent recovery or increase in growth occurring in early spring.

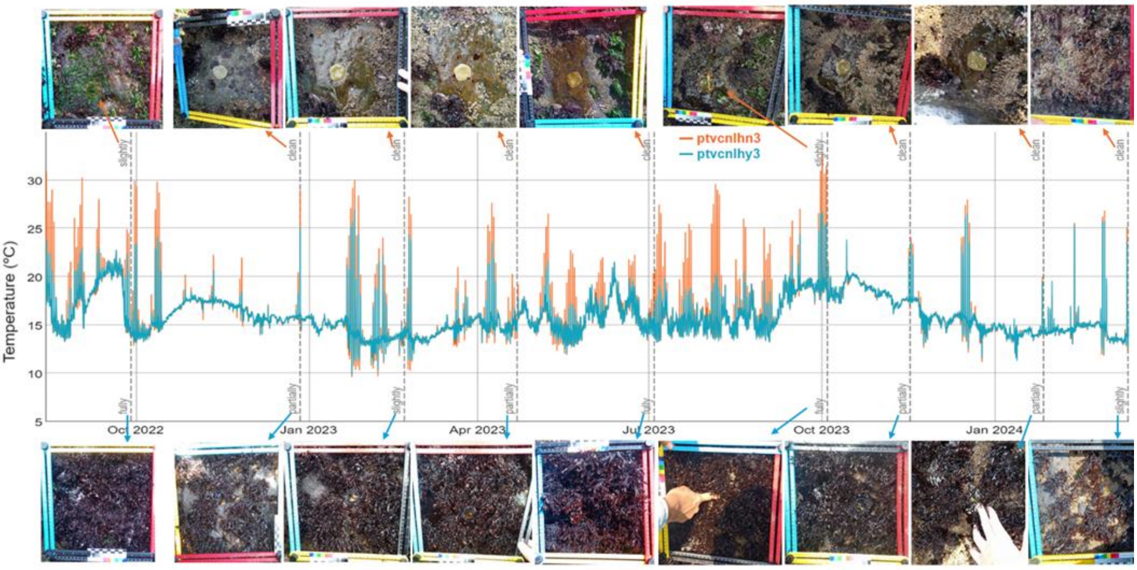


Figure 11. Algae cover timeline in Praia Norte at low level. Orange and blue lines represent the temperature registered by the control and study loggers, respectively.

As expected, the loss of part or total coverage of the study patches can bring the temperature closer or equal to the temperatures registered in bare rock, making the microhabitat a harsher environment for some of the associate fauna.

DISCUSSION

Temperature

Assessing the intertidal microhabitats temperature *in situ* below algae proved to be challenging for some species. As mentioned before, this ecosystem is subject to strong environmental gradients and periods of marine and terrestrial factors. Besides, intertidal is one of the most thermally variable habitats and of extreme topographic complexity. This leads to variability of species presence and cover along the year, resulting in some algae covered loggers in our sampling sites to be naked during long stretches of time. Despite the difficulty in maintaining good algae coverage during the sampling period, our results showed that the temperature in bare rock tends to be higher than under algae. This is likely the result of the shade and increase humidity provided by the algae, modifying the microhabitat at the scale of environmental stressors (Bertness et al., 1999) The positive correlation shows that the algae amelioration is more evident when the temperature is higher. Likewise, the strong positive correlation can be linked with the loggers' immersed time and/or loss of cover, which leaves the study logger with environmental characteristics similar to bare rock. The exceptions identified at Praia da Empa and Cabo Raso could also be linked to a reduction in cover and/or heightened sun exposure of the study logger after algae loss, relative to the control logger. According to Helmuth & Hofmann (2001), significant spatial variability resulting from substratum angle can result in considerable temperature variations, even if located only a few centimeters away.

At Praia Norte, in the north of Portugal, in the top level the algae cover was constant over the year given by a bushy, large *Ascophyllum nodosum* canopy. Hence, we use data collected there to compare the effect of algae cover over time, encompassing the four seasons. The correlation results from the top level (upper intertidal) at Praia Norte suggests that in these microhabitats (hot and cold), the temperature difference between bare rock and under the algae is more pronounced. Focused on algae removal and accompanying surveys, Gutiérrez et al. (2023) demonstrated that the presence of the algae Porphyra/Pyropia (P/P) serves to moderate temperatures within the understory mussel beds during daytime air exposure in warmer periods, which not only lowers mortality rates but also improves the physiological condition of the mussels. Upper zonation tends to be set by thermal and desiccation stressors during low tides, at the same time, biogenic structures such as barnacles can offer crucial refugees while simultaneously increasing the surface area available for mobile invertebrates (Moisez et al., 2020). Microhabitats originated by different surface orientations can be thermally variable between them, especially in low tide, and organisms can experience higher temperatures in sun-exposed microhabitats than in shaded ones (Chapperon et al., 2016; Seabra et al., 2011). Though, the same pattern in temperature range between microhabitats was visible in all sites, with lower temperatures in cold microhabitats than in hot ones. The same for the zonation, where the low level presents lower temperature than the top level. These differences between zonation are described in a few studies (Gunderson et al., 2019; Harley & Helmuth, 2003; Stickle et al., 2017) and were an expected outcome that we were able to confirm them.

The maximum temperature registered along the coast varied as expected for the summer period (increasing towards the south), however, the minimum temperature observed during winter didn’t follow the same pattern, with the north and south having lower minimum temperatures than the centre. These slightly lower temperatures in both north and south regions, compared to central region, may be explained by the complex upwelling system (emergence of cold water at the surface) of the Portuguese coast, the northern winds and or ocean currents (Fiuza, 1983; Relvas et al., 2007; Sánchez et al., 2007). In Helmuth et al. (2006), a similar contrast with general trend with latitude was observed at specific locations (hot and cold spots), likely due modifying factors. The temperature differences registered within pairs showed to be greater in northern regions, decreasing the variability towards the south. The morphological type of the algae and vertical variability across intertidal zones can also be very pronounced from northern to southern sites, with certain macroalgae species experiencing a reduction in cover or vanishing entirely, whereas other species became more prominent and significant in terms of their coverage (Gaspar et al., 2017; Umanzor et al., 2017). During extreme short-term warmer and colder events, we can obtain bigger positive and negative temperature differences, respectively, between bare rock and algae coverage. This means that the capacity of algae to ameliorate the environment beneath them results in a lower temperature during the hottest days (summer) and a slightly higher temperature during the coldest days (winter), compared to the temperature of bare rock. The importance of thermal refuges in intertidal ecosystems is widely recognized during the summer months (Bertness et al., 1999; Coombes et al., 2013; Hesketh & Harley, 2023; Lathlean et al., 2017), however the ecological importance of thermally favorable microhabitats in winter remains inadequately explored. A recent study conducted by Reid & Harley (2021) showed that sheltered microhabitats, such as crevices or areas beneath algae canopy provided a warmer environment for a gastropod, *Littorina scutulata*, than surrounding exposed areas during winter. Given the current climate situation, the ongoing increase in extreme temperatures will make the role of algae in buffering increasingly crucial for the survival of different species.

Seasons

The analyses of seasonal data were mainly focused on the top level of Praia Norte due to the choice and existence of good pairs and due to the higher temperature variations recorded in upper levels. The inconsistency in annual algae coverage didn't allow us to carry out the same type of analysis for the other sites. Environmental fluctuations due to seasonality can also affect coverage, restricting or enhancing algae reproduction and growth rates (Dethier & Williams, 2009). With this, the clear patterns of seasonality help us to see how thermally variable this type of ecosystem and its microhabitats can be (Figure 5A - B). Another observation we can draw from this is the different buffer effect intensities, especially between winter and summer. As mentioned earlier, algae can make the environment underneath them colder or warmer during temperature peaks.

Comparisons of maximum and minimum temperatures within summers and winters revealed inter-annual variations, with the summer of 2023 colder than the previous one. This happens due to local environmental and topographic factors, like the ones study here (e.g., zonation and exposure or surface orientation). So, we may also have to look at this data carefully because this decrease in temperature is limited to the northern region (the other regions have no data for the summer of 2022). The northwestern coast of the Iberian Peninsula, the Galician and Portuguese west coast sub-regions, is distinguished by the Canary current upwelling system and is heavily impacted by freshwater discharge (Arístegui et al., 2009). Regions marked by a high thermal upwelling index are likely to function effectively as temporary refugia, playing a critical role in organisms’ survival/persistence with the actual climatic conditions (Lourenço et al., 2016; Salois et al., 2022). Despite this, latitudinally, we have lower maximum, minimum and average temperature values during the summer and winter seasons in the northern region, which increases towards the south. (**Appendix D – 1.1 and 1.2**).

Buffer effect

Although we concluded that, in terms of exposure, south-facing surfaces are warmer than north-facing surfaces, we had to figure out whether the algae cover could indeed create a more favourable environment than a bare rock shaded (figure 6). The significant result of the test allowed us to reinforce the idea of thermal buffering role that algae can provide, especially with the global warming trend (Coombes et al., 2013; Watt & Scrosati, 2013). However, this result can vary depending on the type of algae, the amount of cover it can provide and zonation (Gaspar et al., 2017). The research heavily relied on data from Praia Norte, as it was the only site in the study that featured good pairs of loggers at the upper level all year. Furthermore, the algae that covered these pairs only exists in this location along the entire Portuguese coastline. *Ascophyllum nodosum* is a prominent cold-water brown seaweed that thrives in intertidal environments, and its geographical range is largely limited to the North Atlantic Ocean (Viana et al., 2014). In northern Portugal, *A. nodosum* is represented by a small and isolated population that has exhibited stability over the last few decades, being the southernmost population of this species (Borges et al., 2020). The structural complexity of canopy-forming algae, like this species, and a multilayered community are able to protect the lower layers from desiccation, extreme light and high temperature (Bordeyne et al., 2017). A study from Bertness et al. (1999), compared the temperature below *A. nodosum* and clean rock and obtained thermal buffer of 8 ºC - 10 ºC. These values are lower than those obtained in our study, but they still show the ability to ameliorate the temperature during the summer.

Taking into consideration that an ideal experimental design to evaluate the buffer effect of different algae species is not possible because we find different species at different latitudes, it would still be interesting to compare the relative buffer effect of each species for an overall evaluation.

Regarding the other algae species covering the loggers, filtering the data to include only medium and good coverage restricted the number of data, which may have conditioned the analysis. The GLM results with singularities or no significant effect on temperature may show just that. However, when we analysed the species without the interaction with the cover, they all significantly affected the temperature (**Appendix D – 7**). The analysis of the buffer effect percentage was also limited by the filtering of the data, yet it was possible to extract enough information. A study regarding the influence of seaweed canopies on rocks and engineered structures showed percentage thermal buffer values similar to those in the top level of the current study (Coombes et al., 2013).

Biological data

The use of long-term SST satellite data contributed to the high volume of data needed to aggregate the sites and be able to make large-scale comparisons between coastal communities. The application of satellite-derived sea surface temperatures (SSTs) is essential for understanding the implications of temperature changes on the distribution patterns of species across different geographic areas. Besides, satellites are able to cover larger geographic areas and have more historical data available than *in situ* devices. However, satellite remote sensing is not useful to study specific microhabitats from intertidal rocky shores. Differences observed between SST data of satellite and in situ sensors imply thermal contamination of the satellite pixel. This is especially true for pixels located along the coastline, which include ocean areas and nearby land. This fact alone could lead to an overestimation of the intra-seasonal thermal variability (Bernardello et al., 2016; Brewin et al., 2018). The use of satellite SST data in the study was solely to define distinct thermal regions and was not used for comparisons at the microhabitat level.

The differences observed in species richness between regions and zonation levels can be seen in other studies held on the Portuguese intertidal coast (Araújo et al., 2005; Boaventura et al., 2002; Luís & Ferreira, 2012). These variations, especially the persistence and volume of algae canopy can be also justified by the input of nutrients and the amount of sunlight (Lanari & Coutinho, 2014; Leibold, 1999), essential for them to thrive. The loss of algae cover also appears to be a common event in *in situ* studies, especially between seasons transitions (Kordas et al., 2015; Orlando-Bonaca et al., 2021), likely due to different thermal tolerances for each species (Davison & Pearson, 1996) and/or isolated and small patches (Lamote et al., 2012). A study conducted by Flukes et al. (2014) concluded that, under projected climate change scenarios, the partial loss of the kelp canopy will likely result in a transformation of understory communities, leading to a predominance of foliose algae. This change is significant for sessile invertebrates and may have repercussions for the future recovery and recruitment of kelp areas. The decrease in canopy-forming species and the corresponding modifications in habitat structure, that involve the replacement of cover by smaller and more ephemeral species, such as turfs, will create a bottom-up effect that impacts the entire food web (Álvarez-Losada et al., 2020; Fernández, 2016).

To our knowledge, the results presented here represent one of the first studies to address several topographical aspects of the intertidal at the same time for different zonation levels and over a long period of time. Although there are already some studies that focus on the thermal buffer effect of algae and its potential effects on associated communities (Bertness et al., 1999; Watt & Scrosati, 2013), many do not take into account the microhabitats provided by north-facing and south-facing surfaces, which are a significant factor shown here to contribute with differences that may reach 20ºC in the same local at the same time. Others only focus on summer, which is the time of year with the greatest temperature extremes, overlooking the fact that winter can also affect the physiology of algae and associated communities. Even within the summer, studies focused on the months of July and August may be missing short-lived events in June and September, as described in this study.

Despite the challenges usually encountered during field work along different latitudes and coastal communities, we successfully compared temperature variations across various microhabitats and throughout an annual cycle. The findings regarding algae thermal buffer effect underscored the significance of algae cover and its variability across both vertical and horizontal gradients, in addition to the importance of the orientation of the surfaces on which they are located.

Moreover, the implementation of a long-term network of small temperature sensors allowed for the establishment of an experimental framework that will support continuous monitoring across different microhabitats. It is essential for future investigations to examine a range of factors that are either unrelated or only indirectly related to temperature fluctuations, including wave exposure and wind effects.

Methodological constraints

A. Algae presence

Some constraints were found in our methodology during the sampling period regarding the choice of the study patches. The size of the patch, its location and the canopy of the algae must be taken into consideration, since, during events such as warmer or cooler weather, storms or windstorms, some of these isolated and small patches were lost, leaving the loggers exposed and unsuitable for this study. This kind of "patch problem" or community complexity issues have been discussed by Bordeyne et al. (2017). Taking this into account, obtain better experimental results in the future will demand a better evaluation of the algae patches as well as the choice of the type of algae due to their intrinsic seasonality.

B. Unexpected types of coverage

Regular visits to the study sites revealed other potential limitations. In coasts exposed to hydrodynamism, as the ones included in our study, sand movements are quite frequent, especially when the sites are close to long stretches of sand. The loggers in the low intertidal were sometimes covered by a layer of sand sometimes over 5cm deep which has significantly influenced the temperature measurements. By comparing loggers located close by, one "clean" and another covered with sand (see **Appendix B** – 2, "san"), we verified a difference of -5.2 ºC to 3.6 ºC between them. According to Befus et al. (2013), the temperature measures on loggers that are close to the surface, even buried under 5cm of sand, are only subjected to small temperature changes that are non-significant. Below that mark, deeper than 5 cm of sand, the temperature attenuation is stronger.

Another limitation are the "honeycombs" of *Sabellaria alveolata*, a common biogenic reef of lower intertidal rocky shores along the Portuguese coast. This polychaete is an important ecosystem engineer, making it a species, and the reef it creates, a habitat of interest for conservation, especially in the UK. This species self-constructs its colony by using mucus to aggregate sand in long individual tubes attached to rocks. These cemented sand grains by an organic adhesive may form colonies that cover entire reefs(Porras et al., 1996) (see **Appendix B** – 2, "sab"). and, sometimes, temperature loggers. If this represented a rare constraint it is also an opportunity for future work regarding the buffer effect of different intertidal organisms. The lack of information regarding this biogenic reef influence on temperature amelioration leaves another target for future work. Besides algae, it would be interesting to evaluate the buffer effect offered to many intertidal organisms that inhabit holes and crevices of this honeycomb worm colonies.

REFERENCES

Aguzzi, J., Doya, C., Tecchio, S., De Leo, F. C., Azzurro, E., Costa, C., Sbragaglia, V., Del Río, J., Navarro, J., Ruhl, H. A., Company, J. B., Favali, P., Purser, A., Thomsen, L., & Catalán, I. A. (2015). Coastal observatories for monitoring of fish behaviour and their responses to environmental changes. *Reviews in Fish Biology and Fisheries*, *25*(3), 463–483. https://doi.org/10.1007/S11160-015-9387-9/FIGURES/7

Álvarez-Losada, Ó., Arrontes, J., Martínez, B., Fernández, C., & Viejo, R. M. (2020). A regime shift in intertidal assemblages triggered by loss of algal canopies: A multidecadal survey. *Marine Environmental Research*, *160*, 104981. https://doi.org/10.1016/J.MARENVRES.2020.104981

Amstutz, A., Firth, L. B., Spicer, J. I., & Hanley, M. E. (2021). Facing up to climate change: Community composition varies with aspect and surface temperature in the rocky intertidal. *Marine Environmental Research*, *172*, 105482. https://doi.org/10.1016/J.MARENVRES.2021.105482

Araújo, R., Bárbara, I., Sousa-Pinto, I., & Quintino, V. (2005). Spatial variability of intertidal rocky shore assemblages in the northwest coast of Portugal. *Estuarine, Coastal and Shelf Science*, *64*(4), 658–670. https://doi.org/10.1016/J.ECSS.2005.03.020

Arístegui, J., Barton, E. D., Álvarez-Salgado, X. A., Santos, A. M. P., Figueiras, F. G., Kifani, S., Hernández-León, S., Mason, E., Machú, E., & Demarcq, H. (2009). Sub-regional ecosystem variability in the Canary Current upwelling. *Progress in Oceanography*, *83*(1–4), 33–48. https://doi.org/10.1016/J.POCEAN.2009.07.031

Báez, J. C., Gimeno, L., & Real, R. (2021). North Atlantic Oscillation and fisheries management during global climate change. *Reviews in Fish Biology and Fisheries 2021 31:2*, *31*(2), 319–336. https://doi.org/10.1007/S11160-021-09645-Z

Baumann, H., & Doherty, O. (2013). Decadal Changes in the World's Coastal Latitudinal Temperature Gradients. *PLOS ONE*, *8*(6), e67596. https://doi.org/10.1371/JOURNAL.PONE.0067596

Baxter, T., Coombes, M., & Viles, H. (2022). No evidence that seaweed cover enhances the deterioration of natural cement-based mortar in intertidal environments. *Earth Surface Processes and Landforms*, *47*(15), 3453–3464. https://doi.org/10.1002/ESP.5467

Befus, K. M., Cardenas, M. B., Erler, D. V., Santos, I. R., & Eyre, B. D. (2013). Heat transport dynamics at a sandy intertidal zone. *Water Resources Research*, *49*(6), 3770–3786. https://doi.org/10.1002/WRCR.20325

Bell, E. C. (1995). Environmental and morphological influences on thallus temperature and desiccation of the intertidal alga Mastocarpus papillatus Kützing. *Journal of Experimental Marine Biology and Ecology*, *191*(1), 29–55. https://doi.org/10.1016/0022-0981(95)00037-R

Bernardello, R., Serrano, E., Coma, R., Ribes, M., & Bahamon, N. (2016). A comparison of remote-sensing SST and in situ seawater temperature in near-shore habitats in the western Mediterranean Sea. *Marine Ecology Progress Series*, *559*, 21–34. https://doi.org/10.3354/MEPS11896

Bertness, M. D., & Leonard, G. H. (1997). The role of positive interactions in communities: Lessons from intertidal habitats. In *Ecology* (Vol. 78, Issue 7, pp. 1976–1989). https://doi.org/10.1890/0012-9658(1997)078[1976:TROPII]2.0.CO;2

Bertness, M. D., Leonard, G. H., Levine, J. M., Schmidt, P. R., & Ingraham, A. O. (1999). TESTING THE RELATIVE CONTRIBUTION OF POSITIVE AND NEGATIVE INTERACTIONS IN ROCKY INTERTIDAL COMMUNITIES. *Ecology*, *80*(8), 2711–2726. https://doi.org/10.1890/0012-9658(1999)080

Blanco, A., Larrinaga, A. R., Neto, J. M., Troncoso, J., Méndez, G., Domínguez-Lapido, P., Ovejero, A., Pereira, L., Mouga, T. M., Gaspar, R., Martínez, B., Lemos, M. F. L., & Olabarria, C. (2021). Spotting intruders: Species distribution models for managing invasive intertidal macroalgae. *Journal of Environmental Management*, *281*, 111861. https://doi.org/10.1016/J.JENVMAN.2020.111861

Boaventura, D., Alexander, M., Della Santina, P., Smith, N. D., Ré, P., Da Fonseca, L. C., & Hawkins, S. J. (2002). The effects of grazing on the distribution and composition of low-shore algal communities on the central coast of Portugal and on the southern coast of Britain. *Journal of Experimental Marine Biology and Ecology*, *267*(2), 185–206. https://doi.org/10.1016/S0022-0981(01)00372-0

Boaventura, D., Ré, P., Da Fonseca, L. C., & Hawkins, S. J. (2002). Intertidal rocky shore communities of the continental Portuguese coast: Analysis of distribution patterns. *Marine Ecology*, *23*(1), 69–90. https://doi.org/10.1046/j.1439-0485.2002.02758.x

Booth, J. A. T., McPhee-Shaw, E. E., Chua, P., Kingsley, E., Denny, M., Phillips, R., Bograd, S. J., Zeidberg, L. D., & Gilly, W. F. (2012). Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Continental Shelf Research*, *45*, 108–115. https://doi.org/10.1016/J.CSR.2012.06.009

Bordeyne, F., Migné, A., & Davoult, D. (2017). Variation of fucoid community metabolism during the tidal cycle: Insights from in situ measurements of seasonal carbon fluxes during emersion and immersion. *Limnology and Oceanography*, *62*(6), 2418–2430. https://doi.org/10.1002/LNO.10574

Borges, D., Araujo, R., Azevedo, I., & Pinto, I. S. (2020). Sustainable management of economically valuable seaweed stocks at the limits of their range of distribution: Ascophyllum nodosum (Phaeophyceae) and its southernmost population in Europe. *Journal of Applied Phycology*, *32*(2), 1365–1375. https://doi.org/10.1007/S10811-019-02002-5/FIGURES/3

Brewin, R. J. W., Smale, D. A., Moore, P. J., Dall'Olmo, G., Miller, P. I., Taylor, B. H., Smyth, T. J., Fishwick, J. R., & Yang, M. (2018). Evaluating Operational AVHRR Sea Surface Temperature Data at the Coastline Using Benthic Temperature Loggers. *Remote Sensing 2018, Vol. 10, Page 925*, *10*(6), 925. https://doi.org/10.3390/RS10060925

Bryndum-Buchholz, A., Tittensor, D. P., Blanchard, J. L., Cheung, W. W. L., Coll, M., Galbraith, E. D., Jennings, S., Maury, O., & Lotze, H. K. (2019). Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. *Global Change Biology*, *25*(2), 459–472. https://doi.org/10.1111/GCB.14512

Bulleri, F. (2009). Facilitation research in marine systems: state of the art, emerging patterns and insights for future developments. *Journal of Ecology*, *97*(6), 1121–1130. https://doi.org/10.1111/J.1365-2745.2009.01567.X

Bulleri, F., Eriksson, B. K., Queirós, A., Airoldi, L., Arenas, F., Arvanitidis, C., Bouma, T. J., Crowe, T. P., Davoult, D., Guizien, K., Iveša, L., Jenkins, S. R., Michalet, R., Olabarria, C., Procaccini, G., Serrão, E. A., Wahl, M., & Benedetti-Cecchi, L. (2018). Harnessing positive species interactions as a tool against climate-driven loss of coastal biodiversity. *PLOS Biology*, *16*(9), e2006852. https://doi.org/10.1371/JOURNAL.PBIO.2006852

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J. S., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Taschetto, A. S., Timmermann, A., Wu, L., Yeh, S. W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X. T., … Zhong, W. (2021). Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment 2021 2:9*, *2*(9), 628–644. https://doi.org/10.1038/s43017-021-00199-z

Cardoso, A. C., Arenas, F., Sousa-Pinto, I., Barreiro, A., & Franco, J. N. (2020). Sea urchin grazing preferences on native and non-native macroalgae. *Ecological Indicators*, *111*, 106046. https://doi.org/10.1016/J.ECOLIND.2019.106046

Cardoso, P. G., Dolbeth, M., Sousa, R., Relvas, P., Santos, R., Silva, A., & Quintino, V. (2019). The Portuguese Coast. *World Seas: An Environmental Evaluation Volume I: Europe, the*

Americas and West Africa, 189–208. https://doi.org/10.1016/B978-0-12-805068-2.00009-7

Carreras, C., García-Cisneros, A., Wangensteen, O. S., Ordóñez, V., Palacín, C., Pascual, M., & Turon, X. (2020). East is East and West is West: Population genomics and hierarchical analyses reveal genetic structure and adaptation footprints in the keystone species Paracentrotus lividus (Echinoidea). *Diversity and Distributions*, *26*(3), 382–398. https://doi.org/10.1111/DDI.13016

Casoli, E., Mancini, G., Ventura, D., Belluscio, A., & Ardizzone, G. (2021). Double Trouble: Synergy between Habitat Loss and the Spread of the Alien Species Caulerpa cylindracea (Sonder) in Three Mediterranean Habitats. *Water 2021, Vol. 13, Page 1342*, *13*(10), 1342. https://doi.org/10.3390/W13101342

Catalán, A. M., Valdivia, N., & Scrosati, R. A. (2020). Interhemispheric comparison of scale-dependent spatial variation in the structure of intertidal rocky-shore communities. *Ecosphere*, *11*(6), e03068. https://doi.org/10.1002/ECS2.3068

Chan, N. (2021). Linking ocean and climate change governance. *Wiley Interdisciplinary Reviews: Climate Change*, *12*(4), e711. https://doi.org/10.1002/WCC.711

Chapperon, C., Volkenborn, N., Clavier, J., Séité, S., Seabra, R., & Lima, F. P. (2016). Exposure to solar radiation drives organismal vulnerability to climate: Evidence from an intertidal limpet. *Journal of Thermal Biology*, *57*, 92–100. https://doi.org/10.1016/J.JTHERBIO.2016.03.002

Chappuis, E., Terradas, M., Cefalì, M. E., Mariani, S., & Ballesteros, E. (2014). Vertical zonation is the main distribution pattern of littoral assemblages on rocky shores at a regional scale. *Estuarine, Coastal and Shelf Science*, *147*, 113–122. https://doi.org/10.1016/J.ECSS.2014.05.031

Chust, G., Taboada, F. G., Alvarez, P., & Ibaibarriaga, L. (2023). Species acclimatization pathways: Latitudinal shifts and timing adjustments to track ocean warming. *Ecological Indicators*, *146*, 109752. https://doi.org/10.1016/J.ECOLIND.2022.109752

Coombes, M. A., Naylor, L. A., Viles, H. A., & Thompson, R. C. (2013). Bioprotection and disturbance: Seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. *Geomorphology*, *202*, 4–14. https://doi.org/10.1016/J.GEOMORPH.2012.09.014

Davison, I. R., & Pearson, G. A. (1996). Stress tolerance in intertidal seaweeds. *Journal of Phycology*, *32*(2), 197–211. https://doi.org/10.1111/J.0022-3646.1996.00197.X

De Lombaerde, E., Vangansbeke, P., Lenoir, J., Van Meerbeek, K., Lembrechts, J., Rodríguez-Sánchez, F., Luoto, M., Scheffers, B., Haesen, S., Aalto, J., Christiansen, D. M., De Pauw, K., Depauw, L., Govaert, S., Greiser, C., Hampe, A., Hylander, K., Klinges, D., Koelemeijer, I., … De Frenne, P. (2022). Maintaining forest cover to enhance temperature buffering under future climate change. *Science of The Total Environment*, *810*, 151338. https://doi.org/10.1016/J.SCITOTENV.2021.151338

Dethier, M. N., & Williams, S. L. (2009). Seasonal stresses shift optimal intertidal algal habitats. *Marine Biology*, *156*(4), 555–567. https://doi.org/10.1007/S00227-008-1107-8/TABLES/3

Elsberry, L. A., & Bracken, M. E. S. (2021). Functional redundancy buffers mobile invertebrates against the loss of foundation species on rocky shores. *Marine Ecology Progress Series*, *673*, 43–54. https://doi.org/10.3354/MEPS13795

Fernández, C. (2016). Current status and multidecadal biogeographical changes in rocky intertidal algal assemblages: The northern Spanish coast. *Estuarine, Coastal and Shelf Science*, *171*, 35–40. https://doi.org/10.1016/J.ECSS.2016.01.026

Firth, L. B., White, F. J., Schofield, M., Hanley, M. E., Burrows, M. T., Thompson, R. C., Skov, M. W., Evans, A. J., Moore, P. J., & Hawkins, S. J. (2015). Facing the future: the importance of substratum features for ecological engineering of artificial habitats in the rocky intertidal. *Marine and Freshwater Research*, *67*(1), 131–143. https://doi.org/10.1071/MF14163

Fiuza, A. F. G. (1983). Upwelling Patterns off Portugal. *NATO Conference Series, (Series) 4: Marine Sciences*, *10 A*, 85–98. https://doi.org/10.1007/978-1-4615-6651-9_5

Flukes, E. B., Johnson, C. R., & Wright, J. T. (2014). Thinning of kelp canopy modifies understory assemblages: the importance of canopy density. *Marine Ecology Progress Series*, *514*, 57–70. https://doi.org/10.3354/MEPS10964

Freitas, D., Arenas, F., Vale, C. G., Pinto, I. S., & Borges, D. (2023). Warning of warming limpets: sea temperature effects upon intertidal rocky assemblages. *Journal of the Marine Biological Association of the United Kingdom*, *103*, e7. https://doi.org/10.1017/S0025315422001096

Galland, G., Harrould-Kolieb, E., & Herr, D. (2012). The ocean and climate change policy. *Http://Dx.Doi.Org/10.1080/14693062.2012.692207*, *12*(6), 764–771. https://doi.org/10.1080/14693062.2012.692207

Gandra, M., Seabra, R., & Lima, F. P. (2015). A low-cost, versatile data logging system for ecological applications. *Limnology and Oceanography: Methods*, *13*(3), 115–126. https://doi.org/10.1002/LOM3.10012

García, F. C., Bestion, E., Warfield, R., & Yvon-Durochera, G. (2018). Changes in temperature alter the relationship between biodiversity and ecosystem functioning. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(43), 10989–10994. https://doi.org/10.1073/PNAS.1805518115/SUPPL_FILE/PNAS.1805518115.SAPP.PDF

Gaspar, R., Pereira, L., & Neto, J. M. (2017). Intertidal zonation and latitudinal gradients on macroalgal assemblages: Species, functional groups and thallus morphology approaches. *Ecological Indicators*, *81*, 90–103. https://doi.org/10.1016/J.ECOLIND.2017.05.060

Gunderson, A. R., Abegaz, M., Ceja, A. Y., Lam, E. K., Souther, B. F., Boyer, K., King, E. E., You Mak, K. T., Tsukimura, B., & Stillman, J. H. (2019). Hot Rocks and Not-So-Hot Rocks on the Seashore: Patterns and Body-Size Dependent Consequences of Microclimatic Variation in Intertidal Zone Boulder Habitat. *Integrative Organismal Biology*, *1*(1). https://doi.org/10.1093/IOB/OBZ024

Gutiérrez, J. L., Bagur, M., Lorenzo, R. A., & Palomo, M. G. (2023). A facultative mutualism between habitat-forming species enhances the resistance of rocky shore communities to heat waves. *Frontiers in Ecology and Evolution*, *11*, 1278762. https://doi.org/10.3389/FEVO.2023.1278762/BIBTEX

Harley, C. D. G. (2008). Tidal dynamics, topographic orientation, and temperature-mediated mass mortalities on rocky shores. *Marine Ecology Progress Series*, *371*, 37–46. https://doi.org/10.3354/MEPS07711

Harley, C. D. G., & Helmuth, B. S. T. (2003). Local- and regional-scale effects of wave exposure, thermal stress, and absolute versus effective shore level on patterns of intertidal zonation. *Limnology and Oceanography*, *48*(4), 1498–1508. https://doi.org/10.4319/LO.2003.48.4.1498

Harley, C. D. G., Hughes, A. R., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., Rodriguez, L. F., Tomanek, L., & Williams, S. L. (2006). The impacts of climate change in coastal marine systems. In *Ecology Letters* (Vol. 9, Issue 2, pp. 228–241). https://doi.org/10.1111/j.1461-0248.2005.00871.x

Hastings, R. A., Rutterford, L. A., Freer, J. J., Collins, R. A., Simpson, S. D., & Genner, M. J. (2020). Climate Change Drives Poleward Increases and Equatorward Declines in Marine Species. *Current Biology*, *30*(8), 1572-1577.e2. https://doi.org/10.1016/j.cub.2020.02.043

Hays, G. C. (2017). Current Biology Ocean currents and marine life. *Current Biology*, *27*, R470–R473. https://doi.org/10.1016/j.cub.2017.01.044

He, Q., & Silliman, B. R. (2019). *Current Biology Review Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene*. https://doi.org/10.1016/j.cub.2019.08.042

Helmuth, B. (2002). *How do we Measure the Environment? Linking Intertidal Thermal Physiology and Ecology Through Biophysics 1*. *42*, 837–845.

Helmuth, B., Broitman, B. R., Blanchette, C. A., Gilman, S., Halpin, P., Harley, C. D. G., O’donnell, M. J., Hofmann, G. E., Menge, B., & Strickland, D. (2006). MOSAIC PATTERNS OF THERMAL STRESS IN THE ROCKY INTERTIDAL ZONE: IMPLICATIONS FOR CLIMATE CHANGE. *Ecological Monographs*, *76*(4), 461–479. https://doi.org/10.1890/0012-9615(2006)076

Helmuth, B., Broitman, B. R., Yamane, L., Gilman, S. E., Mach, K., Mislan, K. A. S., & Denny, M. W. (2010). Organismal climatology: analyzing environmental variability at scales relevant to physiological stress. *Journal of Experimental Biology*, *213*(6), 995–1003. https://doi.org/10.1242/JEB.038463

Helmuth, B., Choi, F., Matzelle, A., Torossian, J. L., Morello, S. L., Mislan, K. A. S., Yamane, L., Strickland, D., Szathmary, P. L., Gilman, S. E., Tockstein, A., Hilbish, T. J., Burrows, M. T., Power, A. M., Gosling, E., Mieszkowska, N., Harley, C. D. G., Nishizaki, M., Carrington, E., … Zardi, G. (2016). Long-term, high frequency in situ measurements of intertidal mussel bed temperatures using biomimetic sensors. *Scientific Data 2016 3:1*, *3*(1), 1–11. https://doi.org/10.1038/sdata.2016.87

Helmuth, B., Mieszkowska, N., Moore, P., & Hawkins, S. J. (2006). Living on the edge of two changing worlds: Forecasting the responses of rocky intertidal ecosystems to climate change. In *Annual Review of Ecology, Evolution, and Systematics* (Vol. 37, pp. 373–404). https://doi.org/10.1146/annurev.ecolsys.37.091305.110149

Helmuth, B. S. T., & Hofmann, G. E. (2001). Microhabitats, thermal heterogeneity, and patterns of physiological stress in the rocky intertidal zone. *Biological Bulletin*, *201*(3), 374–384. https://doi.org/10.2307/1543615

Helmuth, B., Yamane, L., Lalwani, S., Matzelle, A., Tockstein, A., & Gao, N. (2011). Hidden signals of climate change in intertidal ecosystems: What (not) to expect when you are expecting. *Journal of Experimental Marine Biology and Ecology*, *400*(1–2), 191–199. https://doi.org/10.1016/J.JEMBE.2011.02.004

Herrero, J. J., Simes, D. C., Abecasis, R., Relvas, P., Garel, E., Ventura Martins, P., & Santos, R. (2023). Monitoring invasive macroalgae in southern Portugal: drivers and citizen science contribution. *Frontiers in Environmental Science*, *11*, 1324600. https://doi.org/10.3389/FENVS.2023.1324600/BIBTEX

Hesketh, A. V., & Harley, C. D. G. (2023). Extreme heatwave drives topography-dependent patterns of mortality in a bed-forming intertidal barnacle, with implications for associated community structure. *Global Change Biology*, *29*(1), 165–178. https://doi.org/10.1111/GCB.16390

Hoegh-Guldberg, O., Cai, R., Poloczanska, E. S., Brewer, P. G., Sundby, S., Hilmi, K., Fabry, V. J., & Jung, S. (2014). *The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)].*

Intergovernmental Panel on Climate Change (IPCC). (2022). Changing Ocean, Marine Ecosystems, and Dependent Communities. In *The Ocean and Cryosphere in a Changing Climate* (pp. 447–588). France. https://doi.org/10.1017/9781009157964.007

IPCC. (2023). Synthesis Report. Contribution of Working Group I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on climate change Core writing team. In: Pachauri RK, Reisinger A (eds). *Cambridge University Press 32 Avenue of the Americas, New York, NY 10013-2473, USA*, 996. https://doi.org/10.59327/IPCC/AR6-9789291691647

Kašpar, V., Hederová, L., Macek, M., Müllerová, J., Prošek, J., Surový, P., Wild, J., & Kopecký, M. (2021). Temperature buffering in temperate forests: Comparing microclimate models based on ground measurements with active and passive remote sensing. *Remote Sensing of Environment*, *263*, 112522. https://doi.org/10.1016/J.RSE.2021.112522

Koch, M., Bowes, G., Ross, C., & Zhang, X. H. (2013). Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Global Change Biology*, *19*(1), 103–132. https://doi.org/10.1111/J.1365-2486.2012.02791.X

Konar, B., Iken, K., & Edwards, M. (2009). Depth-stratified community zonation patterns on Gulf of Alaska rocky shores. *Marine Ecology*, *30*(1), 63–73. https://doi.org/10.1111/J.1439-0485.2008.00259.X

Kordas, R. L., Dudgeon, S., Storey, S., & Harley, C. D. G. (2015). Intertidal community responses to field-based experimental warming. *Oikos*, *124*(7), 888–898. https://doi.org/10.1111/OIK.00806

Kostylev, V. E., Erlandsson, J., Mak, Y. M., & Williams, G. A. (2005). The relative importance of habitat complexity and surface area in assessing biodiversity: Fractal application on rocky shores. *Ecological Complexity*, *2*(3), 272–286. https://doi.org/10.1016/J.ECOCOM.2005.04.002

Kröger, S., Parker, E. R., Metcalfe, J. D., Greenwood, N., Forster, R. M., Sivyer, D. B., & Pearce, D. J. (2009). Sensors for observing ecosystem status. *Ocean Science*, *5*(4), 523–535. https://doi.org/10.5194/OS-5-523-2009

Lamote, M., Johnson, L. E., & Lemoine, Y. (2012). Photosynthetic responses of an intertidal alga to emersion: The interplay of intertidal height and meteorological conditions. *Journal of Experimental Marine Biology and Ecology*, *428*, 16–23. https://doi.org/10.1016/J.JEMBE.2012.05.021

Lanari, M. de O., & Coutinho, R. (2014). Reciprocal causality between marine macroalgal diversity and productivity in an upwelling area. *Oikos*, *123*(5), 630–640. https://doi.org/10.1111/J.1600-0706.2013.00952.X

Lathlean, J. A., Ayre, D. J., & Minchinton, T. E. (2011). Rocky intertidal temperature variability along the southeast coast of Australia: comparing data from in situ loggers, satellite-derived SST and terrestrial weather stations. *Marine Ecology Progress Series*, *439*, 83–95. https://doi.org/10.3354/MEPS09317

Lathlean, J. A., Seuront, L., & Ng, T. P. T. (2017). On the edge: The use of infrared thermography in monitoring responses of intertidal organisms to heat stress. *Ecological Indicators*, *81*, 567–577. https://doi.org/10.1016/J.ECOLIND.2017.04.057

Lauchlan, S. S., & Nagelkerken, I. (2020). Species range shifts along multistressor mosaics in estuarine environments under future climate. *Fish and Fisheries*, *21*(1), 32–46. https://doi.org/10.1111/FAF.12412

Leemans, R., & Eickhout, B. (2004). Another reason for concern: regional and global impacts on ecosystems for different levels of climate change. *Global Environmental Change*, *14*(3), 219–228. https://doi.org/10.1016/J.GLOENVCHA.2004.04.009

Leeuwis, R. H. J., & Gamperl, A. K. (2022). Adaptations and plastic phenotypic responses of marine animals to the environmental challenges of the high intertidal zone. In

Oceanography and Marine Biology: An Annual Review, Volume 60 (pp. 625–679). CRC Press. https://doi.org/10.1201/9781003288602-13

Lefort, S., Aumont, O., Bopp, L., Arsouze, T., Gehlen, M., & Maury, O. (2015). Spatial and body-size dependent response of marine pelagic communities to projected global climate change. *Global Change Biology*, *21*(1), 154–164. https://doi.org/10.1111/GCB.12679

Leibold, M. A. (1999). Biodiversity and nutrient enrichment in pond plankton communities. *Evolutionary Ecology Research*, *1*(1), 73–95.

Leung, J. Y. S., Russell, B. D., & Connell, S. D. (2019). Adaptive Responses of Marine Gastropods to Heatwaves. *One Earth*, *1*(3), 374–381. https://doi.org/10.1016/J.ONEEAR.2019.10.025

Lima, F., Burnett, N., Helmuth, B., Kish, N., Aveni-Deforge, K., & S., D. (2011). Monitoring the Intertidal Environment with Biomimetic Devices. In *Biomimetic Based Applications*. https://doi.org/10.5772/14153

Lima, F. P., Ribeiro, P. A., Queiroz, N., Hawkins, S. J., & Santos, A. M. (2007). Do distributional shifts of northern and southern species of algae match the warming pattern? *Global Change Biology*, *13*(12), 2592–2604. https://doi.org/10.1111/J.1365-2486.2007.01451.X

Lima, F. P., & Wethey, D. S. (2009). Robolimpets: Measuring intertidal body temperatures using biomimetic loggers. *Limnology and Oceanography: Methods*, *7*(MAY), 347–353. https://doi.org/10.4319/lom.2009.7.347

Lima, F. P., & Wethey, D. S. (2012). Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nature Communications 2012 3:1*, *3*(1), 1–13. https://doi.org/10.1038/ncomms1713

Liulea, S., Serrão, E. A., & Santos, R. (2023). *Spread and Impact of the Invasive Brown Algae Rugulopteryx Okamurae On The Algarve Coast, Southern Portugal (Ne Atlantic)*. https://doi.org/10.2139/SSRN.4446622

Loos, L. M. van der, Bafort, Q., Bosch, S., Ballesteros, E., Bárbara, I., Bercibar, E., Blanfuné, A., Bogaert, K., Bouckenooghe, S., Boudouresque, C.-F., Brodie, J., Cecere, E., Díaz-Tapia, P., Engelen, A. H., Gunnarson, K., Shabaka, S. H., Hoffman, R., Husa, V., Israel, Á., … Clerck, O. De. (2023). Non-indigenous seaweeds in the Northeast Atlantic Ocean, the Mediterranean Sea and Macaronesia: a critical synthesis of diversity, spatial and temporal patterns. *BioRxiv*, 2023.06.05.543185. https://doi.org/10.1101/2023.06.05.543185

Lourenço, C. R., Zardi, G. I., McQuaid, C. D., Serrão, E. A., Pearson, G. A., Jacinto, R., & Nicastro, K. R. (2016). Upwelling areas as climate change refugia for the distribution and genetic diversity of a marine macroalga. *Journal of Biogeography*, *43*(8), 1595–1607. https://doi.org/10.1111/JBI.12744

Luís, J., & Ferreira, G. (2012). *Latitudinal and climatic driven changes in local patterns of intertidal macroalgae: implications for biodiversity and ecosystem functioning*. http://www.llgc.org.uk/

Madeira, D., Narciso, L., Cabral, H. N., & Vinagre, C. (2012). Thermal tolerance and potential impacts of climate change on coastal and estuarine organisms. *Journal of Sea Research*, *70*, 32–41. https://doi.org/10.1016/J.SEARES.2012.03.002

Mainka, S. A., & Howard, G. W. (2010). Climate change and invasive species: double jeopardy. *Integrative Zoology*, *5*(2), 102–111. https://doi.org/10.1111/J.1749-4877.2010.00193.X

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., & Knowlton, N. (2020). Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B*, *375*(1794). https://doi.org/10.1098/RSTB.2019.0104

Marcelli, M., Piermattei, V., Madonia, A., & Mainardi, U. (2014). Design and Application of New Low-Cost Instruments for Marine Environmental Research. *Sensors 2014, Vol. 14, Pages 23348-23364*, *14*(12), 23348–23364. https://doi.org/10.3390/S141223348

Martins, J., Almada, F., Gonçalves, A., Duarte-Coelho, P., & Jorge, P. E. (2017). Home sweet home: evidence for nest-fidelity in the rocky intertidal fish, the shanny Lipophrys pholis. *Journal of Fish Biology*, *90*(1), 156–166. https://doi.org/10.1111/JFB.13171

McAfee, D., Bishop, M. J., & Williams, G. A. (2022). Temperature-buffering by oyster habitat provides temporal stability for rocky shore communities. *Marine Environmental Research*, *173*, 105536. https://doi.org/10.1016/J.MARENVRES.2021.105536

Meager, J. J., Schlacher, T. A., & Green, M. (2011). Topographic complexity and landscape temperature patterns create a dynamic habitat structure on a rocky intertidal shore. *Marine Ecology Progress Series*, *428*, 1–12. https://doi.org/10.3354/MEPS09124

Mieszkowska, N., Burrows, M. T., Hawkins, S. J., & Sugden, H. (2021). Impacts of Pervasive Climate Change and Extreme Events on Rocky Intertidal Communities: Evidence From Long-Term Data. *Frontiers in Marine Science*, *8*, 322. https://doi.org/10.3389/FMARS.2021.642764/BIBTEX

Mills, G., & Fones, G. (2012). A review of in situ/IT methods and sensors for monitoring the marine environment. *Sensor Review*, *32*(1), 17–28. https://doi.org/10.1108/02602281211197116/FULL/XML

Miner, C. M., Burnaford, J. L., Ammann, K., Becker, B. H., Fradkin, S. C., Ostermann-Kelm, S., Smith, J. R., Whitaker, S. G., & Raimondi, P. T. (2021). Latitudinal variation in long-term stability of North American rocky intertidal communities. *Journal of Animal Ecology*, *90*(9), 2077–2093. https://doi.org/10.1111/1365-2656.13504

Moisez, E., Spilmont, N., & Seuront, L. (2020). Microhabitats choice in intertidal gastropods is species-, temperature- and habitat-specific. *Journal of Thermal Biology*, *94*, 102785. https://doi.org/10.1016/J.JTHERBIO.2020.102785

Monteiro, C., Pereira, J., Seabra, R., & Lima, F. P. (2022). Fine-scale survey of intertidal macroalgae reveals recent changes in a cold-water biogeographic stronghold. *Frontiers in Marine Science*, *9*, 880074. https://doi.org/10.3389/FMARS.2022.880074/BIBTEX

Montoya, J. M., & Raffaelli, D. (2010). Climate change, biotic interactions and ecosystem services. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1549), 2013–2018. https://doi.org/10.1098/RSTB.2010.0114

Nunez, S., Arets, E., Alkemade, R., Verwer, C., & Leemans, R. (2019). Assessing the impacts of climate change on biodiversity: is below 2 °C enough? *Climatic Change*, *154*(3–4), 351–365. https://doi.org/10.1007/S10584-019-02420-X/FIGURES/5

Orlando-Bonaca, M., Pitacco, V., & Lipej, L. (2021). Loss of canopy-forming algal richness and coverage in the northern Adriatic Sea. *Ecological Indicators*, *125*, 107501. https://doi.org/10.1016/J.ECOLIND.2021.107501

Paquette, A., & Hargreaves, A. L. (2021). Biotic interactions are more often important at species' warm versus cool range edges. *Ecology Letters*, *24*(11), 2427–2438. https://doi.org/10.1111/ELE.13864

Park, J. Y., Stock, C. A., Dunne, J. P., Yang, X., & Rosati, A. (2019). Seasonal to multiannual marine ecosystem prediction with a global Earth system model. *Science*, *365*(6450), 284–288. https://doi.org/10.1126/SCIENCE.AAV6634/SUPPL_FILE/AAV6634-PARK-SM.PDF

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. In *Science* (Vol. 355, Issue 6332). American Association for the Advancement of Science. https://doi.org/10.1126/science.aai9214

Pereira, J., Ribeiro, P. A., Santos, A. M., Monteiro, C., Seabra, R., & Lima, F. P. (2021). A comprehensive assessment of the intertidal biodiversity along the Portuguese coast in the early 2000s. *Biodiversity Data Journal*, *9*, 1–31. https://doi.org/10.3897/BDJ.9.E72961

Pereira, S. G., Lima, F. P., Queiroz, N. C., Ribeiro, P. A., & Santos, A. M. (2006). Biogeographic patterns of intertidal macroinvertebrates and their association with macroalgae distribution along the Portuguese coast. *Hydrobiologia*, *555*(1), 185–192. https://doi.org/10.1007/S10750-005-1115-3/METRICS

Peterson, M. L., Doak, D. F., & Morris, W. F. (2019). Incorporating local adaptation into forecasts of species' distribution and abundance under climate change. *Global Change Biology*, *25*(3), 775–793. https://doi.org/10.1111/GCB.14562

Pettorelli, N., Graham, N. A. J., Seddon, N., Maria da Cunha Bustamante, M., Lowton, M. J., Sutherland, W. J., Koldewey, H. J., Prentice, H. C., & Barlow, J. (2021). Time to integrate global climate change and biodiversity science-policy agendas. *Journal of Applied Ecology*, *58*(11), 2384–2393. https://doi.org/10.1111/1365-2664.13985

Piazzi, L., Bonaviri, C., Castelli, A., Ceccherelli, G., Costa, G., Curini-Galletti, M., Langeneck, J., Manconi, R., Montefalcone, M., Pipitone, C., Rosso, A., & Pinna, S. (2018). Biodiversity in canopy-forming algae: Structure and spatial variability of the Mediterranean Cystoseira assemblages. *Estuarine, Coastal and Shelf Science*, *207*, 132–141. https://doi.org/10.1016/J.ECSS.2018.04.001

Pires, A. P. F., Srivastava, D. S., & Farjalla, V. F. (2018). Is Biodiversity Able to Buffer Ecosystems from Climate Change? What We Know and What We Don't. *BioScience*, *68*(4), 273–280. https://doi.org/10.1093/BIOSCI/BIY013

Pocklington, J. B., Keough, M. J., O'Hara, T. D., & Bellgrove, A. (2019). The Influence of Canopy Cover on the Ecological Function of A Key Autogenic Ecosystem Engineer. *Diversity 2019, Vol. 11, Page 79*, *11*(5), 79. https://doi.org/10.3390/D11050079

Porras, R., Bataller, J. V., Murgui, E., & Torregrosa, M. T. (1996). Trophic Structure and Community Composition of Polychaetes Inhabiting Some Sabellaria alveolata (L.) Reefs Along the Valencia Gulf Coast, Western Mediterranean. *Marine Ecology*, *17*(4), 583–602. https://doi.org/10.1111/J.1439-0485.1996.TB00419.X

Queirós, A. M., Fernandes, J. A., Faulwetter, S., Nunes, J., Rastrick, S. P. S., Mieszkowska, N., Artioli, Y., Yool, A., Calosi, P., Arvanitidis, C., Findlay, H. S., Barange, M., Cheung, W. W. L., & Widdicombe, S. (2015). Scaling up experimental ocean acidification and warming research: from individuals to the ecosystem. *Global Change Biology*, *21*(1), 130–143. https://doi.org/10.1111/GCB.12675

Raffo, M. P., Russo, V. Lo, & Schwindt, E. (2014). Introduced and native species on rocky shore macroalgal assemblages: Zonation patterns, composition and diversity. *Aquatic Botany*, *112*, 57–65. https://doi.org/10.1016/J.AQUABOT.2013.07.011

Reid, H. B., & Harley, C. D. G. (2021). Low temperature exposure determines performance and thermal microhabitat use in an intertidal gastropod (Littorina scutulata) during the winter. *Marine Ecology Progress Series*, *660*, 105–118. https://doi.org/10.3354/MEPS13588

Relvas, P., Barton, E. D., Dubert, J., Oliveira, P. B., Peliz, Á., da Silva, J. C. B., & Santos, A. M. P. (2007). Physical oceanography of the western Iberia ecosystem: Latest views and challenges. *Progress in Oceanography*, *74*(2–3), 149–173. https://doi.org/10.1016/J.POCEAN.2007.04.021

Rinawati, F., Stein, K., & Lindner, A. (2013). Climate Change Impacts on Biodiversity—The Setting of a Lingering Global Crisis. *Diversity 2013, Vol. 5, Pages 114-123*, *5*(1), 114–123. https://doi.org/10.3390/D5010114

Salois, S. L., Gouhier, T. C., Helmuth, B., Choi, F., Seabra, R., & Lima, F. P. (2022). Coastal upwelling generates cryptic temperature refugia. *Scientific Reports 2022 12:1*, *12*(1), 1–15. https://doi.org/10.1038/s41598-022-23717-5

Salvaterra, T., Green, D. S., Crowe, T. P., & O'Gorman, E. J. (2013). Impacts of the invasive alga Sargassum muticum on ecosystem functioning and food web structure. *Biological Invasions*, *15*(11), 2563–2576. https://doi.org/10.1007/S10530-013-0473-4/FIGURES/7

Sánchez de Pedro, R., Fernández, A. N., García-Sánchez, M. J., Flores-Moya, A., & Bañares-España, E. (2023). Parental environment modulates offspring thermal tolerance in a foundational intertidal seaweed. *European Journal of Phycology*, *58*(2), 121–144. https://doi.org/10.1080/09670262.2022.2081731

Sánchez, R. F., Relvas, P., & Delgado, M. (2007). Coupled ocean wind and sea surface temperature patterns off the western Iberian Peninsula. *Journal of Marine Systems*, *68*(1–2), 103–127. https://doi.org/10.1016/J.JMARSYS.2006.11.003

Sarà, G., Milisenda, G., Mangano, M. C., & Bosch-Belmar, M. (2021). The buffer effect of canopy-forming algae on vermetid reefs' functioning: A multiple stressor case study. *Marine Pollution Bulletin*, *171*, 112713. https://doi.org/10.1016/j.marpolbul.2021.112713

Scheibling, R. E., & Gagnon, P. (2006). Competitive interactions between the invasive green alga Codium fragile ssp. tomentosoides and native canopy-forming seaweeds in Nova Scotia (Canada). *Marine Ecology Progress Series*, *325*, 1–14. https://doi.org/10.3354/MEPS325001

Schmidt, A. L., Coll, M., Romanuk, T. N., & Lotze, H. K. (2011). Ecosystem structure and services in eelgrass Zostera marina and rockweed Ascophyllum nodosum habitats. *Marine Ecology Progress Series*, *437*, 51–68. https://doi.org/10.3354/MEPS09276

Seabra, R., Wethey, D. S., Santos, A. M., & Lima, F. P. (2011). Side matters: Microhabitat influence on intertidal heat stress over a large geographical scale. *Journal of Experimental Marine Biology and Ecology*, *400*(1–2), 200–208. https://doi.org/10.1016/j.jembe.2011.02.010

Sergio, F., Blas, J., & Hiraldo, F. (2018). Animal responses to natural disturbance and climate extremes: a review. *Global and Planetary Change*, *161*, 28–40. https://doi.org/10.1016/J.GLOPLACHA.2017.10.009

Shanks, A. L., Rasmuson, L. K., Valley, J. R., Jarvis, M. A., Salant, C., Sutherland, D. A., Lamont, E. I., Hainey, M. A. H., & Emlet, R. B. (2020). Marine heat waves, climate change, and failed spawning by coastal invertebrates. *Limnology and Oceanography*, *65*(3), 627–636. https://doi.org/10.1002/LNO.11331

Silva, C. O., Lemos, M. F. L., Gaspar, R., Gonçalves, C., & Neto, J. M. (2021). The effects of the invasive seaweed Asparagopsis armata on native rock pool communities: Evidences from experimental exclusion. *Ecological Indicators*, *125*, 107463. https://doi.org/10.1016/J.ECOLIND.2021.107463

Simberloff, Daniel. (2010). Invasive species. In *Conservation biology for all.* Oxford University Press. 131–152pp

Somero, G. N. (2010). The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'losers.' *Journal of Experimental Biology*, *213*(6), 912–920. https://doi.org/10.1242/JEB.037473

Sorte, C. J. B., Bernatchez, G., Mislan, K. A. S., Pandori, L. L. M., Silbiger, N. J., & Wallingford, P. D. (2018). Thermal tolerance limits as indicators of current and future intertidal zonation patterns in a diverse mussel guild. *Marine Biology 2018 166:1*, *166*(1), 1–13. https://doi.org/10.1007/S00227-018-3452-6

Sorte, C. J. B., Williams, S. L., & Carlton, J. T. (2010). Marine range shifts and species introductions: comparative spread rates and community impacts. *Global Ecology and Biogeography*, *19*(3), 303–316. https://doi.org/10.1111/J.1466-8238.2009.00519.X

Steigleder, K. M., Copertino, M. S., Lanari, M., Camargo, M., & Fujii, M. T. (2019). Latitudinal gradient in intertidal seaweed composition off the coast of southern Brazil and Uruguay. *Aquatic Botany*, *156*, 47–56. https://doi.org/10.1016/J.AQUABOT.2019.04.003

Steudel, B., Hector, A., Friedl, T., Löfke, C., Lorenz, M., Wesche, M., & Kessler, M. (2012). Biodiversity effects on ecosystem functioning change along environmental stress gradients. *Ecology Letters*, *15*(12), 1397–1405. https://doi.org/10.1111/J.1461-0248.2012.01863.X

Stickle, W. B., Carrington, E., & Hayford, H. (2017). Seasonal changes in the thermal regime and gastropod tolerance to temperature and desiccation stress in the rocky intertidal zone. *Journal of Experimental Marine Biology and Ecology*, *488*, 83–91. https://doi.org/10.1016/J.JEMBE.2016.12.006

Sueiro, M. C., Bortolus, A., & Schwindt, E. (2011). Habitat complexity and community composition: Relationships between different ecosystem engineers and the associated macroinvertebrate assemblages. *Helgoland Marine Research*, *65*(4), 467–477. https://doi.org/10.1007/S10152-010-0236-X/TABLES/4

Thomas, C. D. (2010). Climate, climate change and range boundaries. In *Diversity and Distributions* (Vol. 16, Issue 3, pp. 488–495). John Wiley & Sons, Ltd. https://doi.org/10.1111/j.1472-4642.2010.00642.x

Thompson, P. L., MacLennan, M. M., & Vinebrooke, R. D. (2018). Species interactions cause non-additive effects of multiple environmental stressors on communities. *Ecosphere*, *9*(11), e02518. https://doi.org/10.1002/ECS2.2518

Thyrring, J., & Harley, C. D. G. (2024). Marine latitudinal diversity gradients are generally absent in intertidal ecosystems. *Ecology*, *105*(1), e4205. https://doi.org/10.1002/ECY.4205

Taveira Pinto, F. (2004). The practice of coastal zone management in Portugal. In *Journal of Coastal Conservation* (Vol. 10). http://www.natura2000benefits.org

Tuya, F., Cacabelos, E., Duarte, P., Jacinto, D., Castro, J. J., Silva, T., Bertocci, I., Franco, J. N., Arenas, F., Coca, J., & Wernberg, T. (2012). Patterns of landscape and assemblage structure along a latitudinal gradient in ocean climate. *Marine Ecology Progress Series*, *466*, 9–19. https://doi.org/10.3354/MEPS09941

Umanzor, S., Ladah, L., Calderon-Aguilera, L. E., & Zertuche-González, J. A. (2017). Intertidal macroalgae influence macroinvertebrate distribution across stress scenarios. *Marine Ecology Progress Series*, *584*, 67–77. https://doi.org/10.3354/MEPS12355

Viana, I. G., Bode, A., & Fernández, C. (2014). Growth and production of new recruits and adult individuals of Ascophyllum nodosum in a non-harvested population at its southern limit

(Galicia, NW Spain). *Marine Biology*, *161*(12), 2885–2895. https://doi.org/10.1007/S00227-014-2553-0/TABLES/2

Vinagre, C., Dias, M., Roma, J., Silva, A., Madeira, D., & Diniz, M. S. (2013). Critical thermal maxima of common rocky intertidal fish and shrimps — A preliminary assessment. *Journal of Sea Research*, *81*, 10–12. https://doi.org/10.1016/J.SEARES.2013.03.011

Wahl, M., Werner, F. J., Buchholz, B., Raddatz, S., Graiff, A., Matthiessen, B., Karsten, U., Hiebenthal, C., Hamer, J., Ito, M., Gülzow, E., Rilov, G., & Guy-Haim, T. (2020). Season affects strength and direction of the interactive impacts of ocean warming and biotic stress in a coastal seaweed ecosystem. *Limnology and Oceanography*, *65*(4), 807–827. https://doi.org/10.1002/LNO.11350

Wang, D., Gouhier, T. C., Menge, B. A., & Ganguly, A. R. (2015). Intensification and spatial homogenization of coastal upwelling under climate change. *Nature 2015 518:7539*, *518*(7539), 390–394. https://doi.org/10.1038/nature14235

Wangersky, P. J. (2005). Methods of sampling and analysis and our concepts of ocean dynamics. *Scientia Marina*, *69*(S1), 75–84. https://doi.org/10.3989/SCIMAR.2005.69S175

Watt, C. A., & Scrosati, R. A. (2013). Bioengineer effects on understory species richness, diversity, and composition change along an environmental stress gradient: Experimental and mensurative evidence. *Estuarine, Coastal and Shelf Science*, *123*, 10–18. https://doi.org/10.1016/J.ECSS.2013.02.006

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., Hyde, K. J. W., Morelli, T. L., Morisette, J. T., Muñoz, R. C., Pershing, A. J., Peterson, D. L., Poudel, R., Staudinger, M. D., Sutton-Grier, A. E., Thompson, L., Vose, J., Weltzin, J. F., & Whyte, K. P. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, *733*, 137782. https://doi.org/10.1016/J.SCITOTENV.2020.137782

Wikström, S. A., & Kautsky, L. (2007). Structure and diversity of invertebrate communities in the presence and absence of canopy-forming Fucus vesiculosus in the Baltic Sea. *Estuarine, Coastal and Shelf Science*, *72*(1–2), 168–176. https://doi.org/10.1016/J.ECSS.2006.10.009

Wright, A. J., Wardle, D. A., Callaway, R., & Gaxiola, A. (2017). The Overlooked Role of Facilitation in Biodiversity Experiments. *Trends in Ecology & Evolution*, *32*(5), 383–390. https://doi.org/10.1016/J.TREE.2017.02.011

Wu, R. S. S., Lau, T. C., Fung, W. K. M., Ko, P. H., & Leung, K. M. Y. (2007). An 'artificial mussel' for monitoring heavy metals in marine environments. *Environmental Pollution*, *145*(1), 104–110. https://doi.org/10.1016/J.ENVPOL.2006.03.053

Xu, M., Fralick, D., Zheng, J. Z., Wang, B., Tu, X. M., & Feng, C. (2017). The Differences and Similarities Between Two-Sample T-Test and Paired T-Test. *Shanghai Archives of Psychiatry*, *29*(3), 184. https://doi.org/10.11919/J.ISSN.1002-0829.217070

Zelnik, Y. R., Arnoldi, J. F., & Loreau, M. (2018). The Impact of Spatial and Temporal Dimensions of Disturbances on Ecosystem Stability. *Frontiers in Ecology and Evolution*, *6*, 421671. https://doi.org/10.3389/FEVO.2018.00224/BIBTEX

APPENDICES

A. STATE OF THE ART

1. Climate change

Climate change has gained an important role in our lives over the past years, mainly due to the imminent threat that it represents to biodiversity, natural ecosystems and humans. Humanity had a main role in it throughout their activities which, consequentially, warmed up the atmosphere, land and ocean. According to IPCC (2023), global surface temperature has increased faster since 1970 than over, at least, the last 2000 years. Data shows that global surface temperature in the first two decades of the 21st century, between 2001 and 2020, was almost 1ºC higher than in between 1850 and 1900. Taking into account the latest calculations, using the time intervals between 1850-1900 and 2013-2022, there is an increase of 1.15ºC (IPCC, 2023). All these factors lead, also, to a rapidly increase on sea surface temperature (SST), which, due to the buffer effect of our Ocean, retains 91% of the excess heat from the climate system. According to IPCC (2023), ocean surface temperatures had an increase of 0.93ºC between 1900 and 2020. Altogether, these factors are affecting the weather and originating extreme climatic episodes, such as heatwaves or heavy precipitation, across the globe (Chan, 2021; IPCC, 2023).

Moreover, the occurrence of extreme events (extreme dry and wet events or heatwaves), along with other anthropogenic stressors (defaunation, overfishing or invasive species), will become more frequent and intense over time and will increase the sensitivity of ecosystems to such events (Malhi et al., 2020). The consequences have already generated irreversible and substantial damage to several ecosystems, like terrestrial, freshwater or coastal and open ocean, and are affecting species in various ways, including range shifts, abundance and microhabitat use (Leemans & Eickhout, 2004; Pecl et al., 2017). Although it may be difficult to predict the exact response of ecosystems, some experimental studies show that their processes vary with the amount of biodiversity present, meaning that higher levels of biodiversity can diminish the impact of these changes (Montoya & Raffaelli, 2010). Surely, changes and pressures in the balance of ecosystems will threaten biodiversity and ecological communities. In such complex systems as natural ecosystems, small climate variations can condition their function and the species survival. Some of the species will be unable to rapidly adapt to the new conditions, leading them to local extinction, others may already have shifted their distribution range driven by their climate tolerances (Peterson et al., 2019; Thomas, 2010) and relocate to safer grounds. Local communities are dispersing and receiving warm-adapted species and the occurrence of phenological change in populations are dissociating species interactions (Rinawati et al., 2013).

Regarding the oceanic environment, climate change affects the temperature and may change the strength of ocean currents, responsible for fauna and flora dispersion, as well as the redistribution of heat and nutrients (Hays, 2017). In this context, it is projected that upwelling seasons will initiate earlier, endure for longer intervals, and intensify more significantly at higher latitudes along upwelling coasts (Wang et al., 2015). These features play a crucial role in shaping the phenology of key processes within marine ecosystems, particularly in relation to the larval transport or recruitment of organisms inhabiting rocky intertidal zones (Wang et al., 2015). Oscillation events, such as ENSO (El Niño-Southern Oscillation) or NAO (North Atlantic Oscillation), can increase the frequency and magnitude of their activity due to changes by global warming (Báez et al., 2021; Cai et al., 2021).

Even though the ocean has the ability to mitigate and regulate climate, through its capacity to store heat and gases (Chan, 2021; Galland et al., 2012), as already mention above, marine ecosystems suffer major biological changes in their structure and functions, such as ocean productivity, species distribution, abundance, and also, consequences to the ecosystem good and service (Bryndum-Buchholz et al., 2019). In terms of the direct effects of climate change in marine species, the life cycle of an individual is impacted by consequent adjustments in physiology, morphology and behaviour (Harley et al. 2006). At the population level, the dispersal and recruitment of organisms are influenced by changes in transport/carrying processes, and at community level, the effects are driven in abundance and strength interaction of the species present (Harley et al. 2006). The overall combination of these factors will result in emergent ecological responses such as species distribution, productivity, changes in indigenous biodiversity and their microevolutionary processes.

2. Biodiversity as a climatic buffer

Understanding the role of biodiversity on the stability and function of ecosystems is vital, especially with this warming trend, since we are facing huge extinction rates and we expect them to continue growing (Steudel et al., 2012). With that, impacts of biodiversity loss, driven by global warming are likely to be facilitated by traits, such as thermal tolerance that condition species' fitness (García et al., 2018). Some reviews have suggested that the shape of the biodiversity-ecosystem function relationship changes with environmental stress and the effects of abiotic factors, such as temperature, may maximize the environmental severity (Wright et al., 2017).

Stressors impose severe and frequent changes, leading to different consequences on ecological communities and in species responses (Sarà et al., 2021). Some of these disturbances may involve changing their behaviour (Paquette & Hargreaves, 2021), life history traits (Shanks et al., 2020), morphology (Lefort et al., 2015), physiology (Leung et al., 2019) or their genetic structure (Carreras et al., 2020). All the previous changes lead up to individual-level responses, that may affect population responses, followed by community responses, and so on, until it reaches the whole ecosystem (Sergio et al., 2018). This suggests that such changes can also alter the structure and composition of populations/communities, the distribution range of native species or provide conditions for invasive species to expand and stablish (Lauchlan & Nagelkerken, 2020; Queirós et al., 2015; Sarà et al., 2021). Even more, the stability of an ecosystem can be disturbed by the interplay between spatial and temporal dimensions, which may cause drastic ecological consequences (e.g., regime shifts or population extinction) (Zelnik et al., 2018). Analysing these data may allow to establish if there are underlying dynamics affecting them.

Pires et al. (2018) shown that biodiversity can promote the stability of an ecosystem, whatever the type of organism used for the study or the approach followed. The more species are present the greater will be the effect of biodiversity on the amelioration of the physiological strain and in the promotion of sensitive species growth (Wright et al., 2017). Interaction between species can also work as a buffer against stressors, diminishing its impacts on communities and may facilitate their responses to multiple stressors (Thompson et al., 2018). Furthermore, habitat-formers, such as macroalgae and bivalves, are of extreme importance in shaping community structure and ecosystem functioning, but also create conditions for the persistence of species under intense changes (Bulleri et al., 2018).

So, we can say that some species or habitats have special abilities to counteract or, at least, minimize some of the climate change effects. Some of their different mechanisms of facilitation (e.g., Reduce/enhance of predation and herbivory, reduce of competition, amelioration of physical stress, provision of secondary substrata or enhance nutrients) are relatively common in coastal habitats, especially in rocky intertidal and subtidal zones (Bulleri, 2009). Examples of their buffer abilities can be seen in some studies that show how they can provide shelter to other species (McAfee et al., 2022), their function as autogenic ecosystem engineers (Pocklington et al. 2019), or even, how important foundation species are during thermal stress (Elsberry & Bracken, 2021).

3. The importance of algae in rocky shore habitats

Within ocean systems, coastal zones are the most densely populated areas on the planet, overwhelming the coastal ecosystems and increasing the threat of global climate change (He & Silliman, 2019). A key element that has been increasing in recent years is the temperature. As previously mentioned, it has been responsible for several changes in these ecosystems, especially in marine organisms (e.g., species physiology and behaviour) (Madeira et al., 2012). Habitat complexity of these coastal systems plays an important role as a driver of ecosystem structure and function (Meager et al., 2011). A good example is the intertidal rocky shores. These are considered a model system for understanding how topographic complexity works and how it affects the temperature in those habitats (Meager et al., 2011). Ecologically speaking this is a very important factor that affects all the underlying ecosystem. Being one of the most thermally variable and stressful habitats on the planet (Harley, 2008), the intertidal organisms live between “terrestrial” and marine conditions, meaning that they are subject both to changes in water temperature, during immersion, and to atmospheric temperature during emersion (Sorte et al., 2018; Vinagre et al., 2013). In fact, intertidal organisms live very close to their thermal tolerance. It is noteworthy that mid- to high-intertidal species, which exhibit greater eurythermal and heat-tolerant characteristics, may paradoxically face a higher risk from climate change compared to their less heat-tolerant counterparts (Harley et al. 2006).

The environmental heterogeneity of this habitat offers a variety of different microhabitats and niches contributing to within-habitat diversity due to its complex structure, allowing species to co-exist (Kostylev et al., 2005). So, a way that organisms, mostly mobile species, have to survive and escape intertidal environmental stressors (e.g., high and low temperature, desiccation, sun exposure and wave action) is to use these microhabitats as shelters and thermal refuges (Leeuwis & Gamperl, 2022). Selecting the topographic orientation can be an excellent way to ameliorate the daily fluctuations of temperature that they are subjected to. Shaded surfaces (facing North) can enable a cooler environment for the organism, unlike exposed solar radiation surface (facing South), where daily temperature changes can differ dramatically between organisms situated just meters apart but in opposite direction (Seabra et al. 2011, Amstutz et al. 2021). Unfortunately, sessile organisms don’t have such luck and, meaning, they are highly subjected to environmental stressors, which can lead to higher mortality and significant consequences for community dynamics (Helmuth et al. 2010). Another alternative to ameliorate environmental stressors may come from structuring or foundation species, like algae, where they can create sheltered niches for these species.

Primary producers, like algae, are the base of the food web and play a role in deep-sea productivity. Some keystone species provide 3D structure, creating important habitats (i.e., nursery areas for juvenile fish, shellfish and invertebrate species). Others, such as crustose coralline algae, can enable larval settlement of marine invertebrates and can create foundations for an entire ecosystem (Koch et al., 2013; Schmidt et al., 2011). Likewise, canopy-forming algae constitute important secondary substrates, working as ecosystem engineers, providing buffered refuges and, thus, increasing diversity (Pocklington et al., 2019; Sarà et al., 2021; Wikström & Kautsky, 2007). Sub-canopy (e.g., *Mastocarpus stellatus)* or encrusting (e.g., *Hildenbrandia sp*.) algae may, also, contribute to the gross community production by taking advantage of incident light unused by the dominant species (Bordeyne et al., 2017). However, when these canopies suffer damage or disappear, they are replaced by low lying, smaller and structurally less complex species of persistent turf-forming algae, which fulfil the habitat (Piazzi et al., 2018). These are commonly defined as mat-forming algae (Piazzi et al., 2018). Thus, complex and complementarity communities are essential since they act as a natural filter, protecting the underlaying community (Bordeyne et al., 2017). This means that, when algae are isolated, they are more prompt to suffer from environmental stressors than in a multilayered community (Bordeyne et al., 2017).

4. Horizontal and vertical gradient

Predicting how species respond to global warming is a challenging task, especially when it comes to the intertidal rocky shores. Since temperature determines the distribution patterns of ectothermic species, this is reflected on their latitudinal and vertical distribution (Somero, 2010). When looking at a broader scale, an increase in thermal conditions with latitude is usually found. Along coastlines, a much more heterogeneous pattern emerges both in space and seasonality. Spatially, across hemispheres and ocean basins where areas with similar oceanic characteristics may differ, and seasonally, where SST changes can lead to different degrees of thermal stress on the same species regarding their life stage (Lima & Wethey, 2012). Coastal latitudinal temperature gradients (CLTG) may drive important ecological gradients, such as decline in species diversity, as morphology, physiology and life history traits that are either directly or indirectly affected by temperature (Baumann & Doherty, 2013). The temperature patterns along coastlines are markedly more heterogeneous than those in the open ocean and, this variation is probably caused by the small regional difference in oceanographic and climatic features (Baumann & Doherty, 2013). These features, along with the habitat heterogeneity and species interactions, can create species-rich hot spots regarding the latitude, that may balance the standard latitudinal decline in species richness (Thyrring & Harley, 2024). Yet, shifts in coastal temperature patterns, such as more extreme seasons and disruptive climate events, may affect the interactions and connectivity between populations (Baumann & Doherty, 2013).

When looking at a finer scale, horizontal and vertical gradients emerge. Horizontally, it can be compared to a latitudinal transition, where the much longer-than-wide characteristic of the intertidal habitats enables comparisons along kms of coastlines; vertically and at a smaller scale, changes can be seen from top to bottom stratification.

According to different spatial and temporal properties, horizontal variations in community structure can be originated by the combination of abiotic factors (e.g., temperature, desiccation, wave action), biotic interactions (e.g., predation, competition) and dispersal processes (Catalán et al., 2020). Amongst this wide range of factors, SST may provide some answers for temporal shifts in community composition and species distribution, although, it should not be the only one taken into consideration. According to Miner et al. (2021), the correlation between temperature and community changes seems clear. Their results show that small temperature changes lead to slight community shifts, and, on the other hand, larger temperature changes lead to major shifts. Other authors demonstrated how the latitudinal gradient works, especially in algae (Steigleder et al., 2019; Tuya et al., 2012), but when compared to vertical variation on intertidal assemblages, this variation becomes more evident and with a greater impact (Chappuis et al., 2014).

These vertical variations can be well observed between the intertidal levels, no matter how narrow or small they may be. Daily tidal variations, along abiotic stressors and biotic factors can contribute directly or indirectly to the vertical patterns of species and the structure of communities observed across the intertidal zonation (Catalán et al., 2020). These vertical zonation patterns can be highly variable between geographic regions, however, the general patterns of abundance and species richness are usually superior at lower depths (i.e., infralittoral and shallow subtidal) and decreasing towards higher levels (i.e., supralittoral) (Konar et al., 2009). Similar results have been found on other studies with algae (Araújo et al., 2005; Gaspar et al., 2017). These highlight the interaction between different functional groups and the presence of certain type of species, such as habitat-modifiers, that can become essential for community development along with their distribution in time and space. The same can be said for introduced and non-native species (Raffo et al., 2014).

Shifts or expansions along the distribution range of a species and, consequently, their occupation of non-native niches can also be considered a consequence of global warming. Biological invasions take place when a non-native species is introduced into a habitat or ecosystem, subsequently establishing itself, proliferating, and inflicting harm on biodiversity, human development, or public health (Mainka & Howard, 2010). Although there is some disagreement, the range shifts of native species and human introductions of non-native species can both be considered a biological invasion, since they involve the movement of organisms from a donor community into a receiver community, and thus can have ecological and evolutionary implications (Simberloff, 2010; Sorte et al., 2010). In the North Atlantic Ocean and Mediterranean Sea, the number of reported invasive species (or non-native) is remarkable in coastal areas (Loos et al., 2023). The damage originated by invasive algae species from all around the world have been recorded, such as *Sargassum muticum* (Salvaterra et al., 2013), *Caulerpa cylindracea* (Casoli et al., 2021), *Asparagopsis armata* (Silva et al., 2021), *Codium fragile subsp. fragile* (Scheibling & Gagnon, 2006) and *Colpomenia peregrina* (Blanco et al., 2021), and the consequences go from direct impacts on native algal assemblages to indirect repercussions to the native fauna.

5. Measuring the temperature

Monitoring marine ecosystems, in the current context of environmental issues, has become a major goal in the scientific community. The high demand for developing monitoring methods, which until recently were more focused on freshwater applications, faced some challenges imposed by the marine environment, such as the need to cover large areas, the complexity of the currents and tides, pollution, the need of boats and ships to reach sampling sites and the delays between sampling and analysis of the gathered data (Mills & Fones, 2012). During the past century, advances in tools and technologies allowed to start measuring a larger array of variables, such as physical and chemical data (Wangersky, 2005). Nowadays, besides the traditional sampling methods already in use, a big effort has been made to provide more precise and quality data using small and at low-cost sensors (Marcelli et al., 2014). From devices that mimic mussels for the monitorization of metals dissolved in the water (Cd, Cr, Cu.Pb and Zn) or the body temperature (Helmuth et al., 2016; Lima & Wethey, 2009; Wu et al., 2007), videocam and tags for tracking changes in fish behaviour and distribution, respectively (Aguzzi et al., 2015; Martins et al., 2017) and sensors that register environmental data, such as temperature, salinity, hypoxia and pH (Booth et al., 2012; Gandra et al., 2015).

All have been used to gather real *in loco* data to understand the current status and predict future scenarios in the ocean (Park et al., 2019).

Nearshore, the combination of remote measurement sensors, with *in situ* sensors, are of extreme importance, allowing for more reliable data (Kröger et al., 2009). An example is the use of satellites, which recently made assessing temperature changes possible, and thus, the influence of temperature on the distribution and fitness of species. However, these remote sensors have limitations. When resorting only to them, they present difficulties estimating data in small areas and in complex habitats, such as the intertidal rocky shores (Lathlean et al., 2011). Some studies have compared temperature data recorded from both types of sensors, remote and *in situ*, and concluded that sensors, such as satellites, are unable to detect most of the short-term events and under or overestimate them as well as extreme unseasonably cold/warm events (Bernardello et al., 2016; Brewin et al., 2018; Lathlean et al., 2011). Thus, *in situ* technologies are an important tool to provide continuous or semi-continuous monitorizations and transmit information telemetrically, helping in long term monitorizations and solving some of the challenges outlined above (Mills & Fones, 2012).

Studies involving temperature loggers in the context of algae, predominantly concentrate on their effectiveness in reducing the erosion of geological formations and man-made structures (Baxter et al., 2022; Coombes et al., 2013), as well as on the physiological aspects and thermoregulation of algal species (Bell, 1995; Helmuth, 2002). The ones that focus specifically on canopy-forming algae buffer effect are scarce and only study a shorter period of time or only small parts of the microhabitats are taken into consideration.

6. Case of study in Portugal

Extending over 800 kilometers, the Portuguese coastline adjacent to the Atlantic Ocean predominantly follows a north-south alignment along the western shore, while it transitions to an east-west direction along the southern coast in the Algarve area (Taveira Pinto, 2004). Along the Portuguese west coast, upwelling is prevalent during the summer season, facilitated by the steady and powerful northerly winds known as the "Portuguese trades"(Fiuza, 1983). The supply of cold waters via upwelling processes is not directly associated with climatic conditions, which presents an opportunity for regional divergence from global warming impacts in refugia, offering protection against both existing and future climate changes (Lourenço et al., 2016). Furthermore, it is well known that the Portuguese coast is located within a biogeographic transition zone, where temperate and subtropical waters converge, resulting in the overlap of the northern and southern distribution limits of numerous species (Boaventura et al., 2002; Cardoso et al., 2019; Pereira et al., 2006). This characteristic is particularly advantageous for exploring how temperature varies with latitude and the implications of such temperature changes for biological communities.

The temperature distributions along the Portuguese coastline exhibit a distinct latitudinal gradient that persists throughout the year, where the pronounced upwelling during the warmer months further accentuates this gradient (Lima et al., 2007). According to Boaventura et al. (2002), the intertidal communities in Portugal exhibit distribution patterns that can be viewed as a combination of the patterns found along the northeast Atlantic coasts and those of the Mediterranean. The latitudinal differences observed from northern to southern Europe reveal that animal-dominated communities are more prevalent in the sheltered areas located further south. Likewise, as one travels southward, there is a notable reduction in the dominance of large brown algae at lower shore levels, with red algal turfs becoming increasingly prominent (Boaventura et al., 2002).

Studies concerning intertidal algae on the Portuguese coast primarily focus on distribution patterns and associated communities (Boaventura et al., 2002; Gaspar et al., 2017; Pereira et al., 2006), effects of grazing (Boaventura et al., 2002; Cardoso et al., 2020), invasive macroalgae (Herrero et al., 2023; Liulea et al., 2023), as well as thermal gradients and climate change (Monteiro et al., 2022; Sánchez de Pedro et al., 2023). To our knowledge, there are no studies focussing on the thermal buffer effect or thermal amelioration by algae on Portugal's intertidal coast, making this study the first of its kind.

B. LIST OF SPECIES

Table B 1. Presence/absence of the species recorded at the study sites. '*' - algae species that provided coverage for the study dataloggers, Turf represented by the algae: Ulva spp, C. ustulatus, Halopteris sp., Corallinacea and C. aciculatis.; "P" - presence of the species at the site; "P*" - presence of the species obtained in the article of (J. Pereira et al., 2021).

Group	**Phylum**	**Species**	**PM**	**PN**	**PE**	**CB**	**PA**	**PO**
Algae	Chlorophyta	*Bryopsis hypnoides*			P	P	P	
Algae	Chlorophyta	*Bryopsis pennata*			P	P	P	P
Algae	Chlorophyta	*Bryopsis plumosa*			P	P	P	
Algae	Chlorophyta	*Chaetomorpha sp.*	P		P	P		
Algae	Chlorophyta	*Cladophora sp.*		P	P	P		
Algae	Chlorophyta	*Codium adhaerens*		P		P	P	P
Algae	Chlorophyta	*Codium sp.*	P	P	P	P	P	P
Algae	Chlorophyta	*Codium tomentosum*	P					
Algae	Chlorophyta	*Ulva clathrata*		P	P	P		P
Algae	Chlorophyta	*Ulva compressa/intestinalis*		P	P	P		P
Algae	Chlorophyta	*Ulva linza*				P		P
Algae	Chlorophyta	*Ulva sp.*	P	P	P	P	P	
Algae	Chlorophyta	*Valonia sp.*				P		P
Algae	Ochrophyta	*Ascophyllum nodosum**		P				
Algae	Ochrophyta	*Bifurcaria bifurcata*	P	P	P	P	P	P
Algae	Ochrophyta	*Cladostephus spongiosus*	P*		P	P	P	P
Algae	Ochrophyta	*Colpomenia peregrina*			P	P		
Algae	Ochrophyta	*Colpomenia sinuosa*					P	P
Algae	Ochrophyta	*Colpomenia sp.*			P	P	P	P
Algae	Ochrophyta	*Cutleria adspersa*				P		
Algae	Ochrophyta	*Cystoseira humilis*	P					
Algae	Ochrophyta	*Cystoseira sp.*			P	P		
Algae	Ochrophyta	*Desmarestia aculeata*	P*					
Algae	Ochrophyta	*Dictyopteris polypodioides*					P	
Algae	Ochrophyta	*Dictyota cyanoloma*				P	P	P
Algae	Ochrophyta	*Dictyota dichotoma*	P		P	P	P	P
Algae	Ochrophyta	*Dictyota implexa*		P				
Algae	Ochrophyta	*Dictyota sp.*	P	P	P	P	P	P
Algae	Ochrophyta	*Ectocarpales*	P					
Algae	Ochrophyta	*Ericaria selaginoides*	P	P	P	P		P
Algae	Ochrophyta	*Ericaria sp.*					P	P
Algae	Ochrophyta	*Fucus guiryi*		P			P	P
Algae	Ochrophyta	*Fucus senegaloides*		P				
Algae	Ochrophyta	*Fucus sp.**			P	P	P	P
Algae	Ochrophyta	*Fucus spiralis*	P					P
Algae	Ochrophyta	*Fucus vesiculosus*		P				
Algae	Ochrophyta	*Gongolaria baccata*	P					
Algae	Ochrophyta	*Halopteris scoparia*				P	P	P
Algae	Ochrophyta	*Halopteris sp.*		P	P	P		
Algae	Ochrophyta	*Himanthalia elongata*	P*					

Algae	Ochrophyta	_Laminaria digitata_		P				
Algae	Ochrophyta	_Laminaria hyperborea_	P*					
Algae	Ochrophyta	_Laminaria ochroleuca_	P	P				
Algae	Ochrophyta	_Laminaria sp._		P	P	P		
Algae	Ochrophyta	_Padina pavonica_					P	P
Algae	Ochrophyta	_Pelvetia canaliculata*_	P					
Algae	Ochrophyta	_Petalonia fascia_					P	
Algae	Ochrophyta	_Phyllariopsis sp._		P	P	P	P	P
Algae	Ochrophyta	_Pseudoralfsia verrucosa_		P				
Algae	Ochrophyta	_Ralfsia sp._	P	P	P	P	P	P
Algae	Ochrophyta	_Rugulopterix okamurae_		P				P
Algae	Ochrophyta	_Saccharina sp._			P			
Algae	Ochrophyta	_Saccorhiza polyschides_	P	P	P	P		
Algae	Ochrophyta	_Sargassaceae*_			P			
Algae	Ochrophyta	_Sargassum muticum_	P	P				
Algae	Ochrophyta	_Sargassum sp._	P*	P				P
Algae	Ochrophyta	_Sphacelaria sp._			P	P		
Algae	Ochrophyta	_Zanardinia typus_						P
Algae	Rhodophyta	_Acrosorium ciliolatum_	P*		P	P		
Algae	Rhodophyta	_Ahnfeltiopsis devoniensis_	P	P	P	P	P	
Algae	Rhodophyta	_Amphiroa sp._			P		P	P
Algae	Rhodophyta	_Anotrichium tenue_			P	P		
Algae	Rhodophyta	_Antithamnion sp._			P			P
Algae	Rhodophyta	_Apoglossum ruscifolium_			P	P		
Algae	Rhodophyta	_Asparagopsis armata_	P	P	P	P	P	P
Algae	Rhodophyta	_Bornetia secundiflora_			P	P		
Algae	Rhodophyta	_Calliblepharis ciliata_	P					
Algae	Rhodophyta	_Calliblepharis jubata_	P	P	P	P	P	
Algae	Rhodophyta	_Callithamnion sp._			P	P		
Algae	Rhodophyta	_Callithamnion tetricum_	P*					
Algae	Rhodophyta	_Callophyllis laciniata_	P*					
Algae	Rhodophyta	_Caulacanthus ustulatus_	P	P	P	P	P	P
Algae	Rhodophyta	_Ceramium ciliatum_			P	P		
Algae	Rhodophyta	_Ceramium sp._	P	P	P	P	P	P
Algae	Rhodophyta	_Ceramium virgatum_	P*	P	P			
Algae	Rhodophyta	_Champia parvula_		P	P	P		P
Algae	Rhodophyta	_Chondracanthus acicularis_	P	P	P	P	P	P
Algae	Rhodophyta	_Chondracanthus teedei_			P	P		P
Algae	Rhodophyta	_Chondria coerulescens_	P	P	P	P	P	P
Algae	Rhodophyta	_Chondrus crispus_	P		P	P		
Algae	Rhodophyta	_Chylocladia verticillata_	P*		P	P		
Algae	Rhodophyta	_Compsothamnion thuyoides_	P*					
Algae	Rhodophyta	_Coralina officinalis_				P		
Algae	Rhodophyta	_Corallina sp._	P	P	P	P	P	P
Algae	Rhodophyta	_Cryptopleura ramosa_	P	P	P	P	P	
Algae	Rhodophyta	_Dumontia contorta_	P*					
Algae	Rhodophyta	_Dasya sp._				P		
Algae	Rhodophyta	_Ellisolandia elongata_	P	P	P	P	P	P

Algae	Rhodophyta	*Gastroclonium ovatum*	P*	P		P		
Algae	Rhodophyta	*Gastroclonium reflexum*		P	P	P	P	
Algae	Rhodophyta	*Gelidium corneum*	P			P	P	
Algae	Rhodophyta	*Gelidium pulchellum*	P	P		P	P	P
Algae	Rhodophyta	*Gelidium sp.*		P	P	P	P	P
Algae	Rhodophyta	*Gelidium spinosum*	P*					
Algae	Rhodophyta	*Gigartina pistillata*	P*					
Algae	Rhodophyta	*Gigartina sp.*				P		
Algae	Rhodophyta	*Gracilaria gracilis*	P*					
Algae	Rhodophyta	*Gracilaria multipartita*		P				
Algae	Rhodophyta	*Grateloupia turuturu*	P					
Algae	Rhodophyta	*Gymnogongrus crenulatus*	P*	P		P	P	
Algae	Rhodophyta	*Gymnogongrus griffithsiae*		P				
Algae	Rhodophyta	*Gymnogongrus sp.*	P*					
Algae	Rhodophyta	*Halurus equisetifolius*	P					
Algae	Rhodophyta	*Halurus sp.*	P		P			
Algae	Rhodophyta	*Hildenbrandia rubra*	P				P	P
Algae	Rhodophyta	*Hildenbrandia sp.*		P	P	P	P	P
Algae	Rhodophyta	*Hypoglossum hypoglossoides*	P*				P	
Algae	Rhodophyta	*Hypoglossum sp.*		P	P	P		
Algae	Rhodophyta	*Jania rubens*			P	P	P	P
Algae	Rhodophyta	*Laurencia sp.*			P	P		
Algae	Rhodophyta	*Lithophyllum byssoides*		P	P	P	P	P
Algae	Rhodophyta	*Lithophyllum incrustans*	P	P	P	P	P	P
Algae	Rhodophyta	*Lomentaria articulata*	P	P	P	P	P	
Algae	Rhodophyta	*Mastocarpus stellatus**	P	P		P	P	P
Algae	Rhodophyta	*Mesophyllum alternans*		P				
Algae	Rhodophyta	*Mesophyllum lichenoides*	P	P	P	P	P	P
Algae	Rhodophyta	*Nemalion elminthoides*		P	P	P		
Algae	Rhodophyta	*Nitophyllum punctatum*	P		P	P		P
Algae	Rhodophyta	*Osmundea pinnatifida*	P	P		P	P	P
Algae	Rhodophyta	*Osmundea sp.*	P	P	P	P	P	P
Algae	Rhodophyta	*Osmundea spectabilis*		P				
Algae	Rhodophyta	*Palmaria palmata*	P*					
Algae	Rhodophyta	*Phyllophora pseudoceranoides*		P				
Algae	Rhodophyta	*Phymatolithon lenormandii*	P		P	P	P	P
Algae	Rhodophyta	*Plocamium cartilagineum*	P			P	P	
Algae	Rhodophyta	*Plocamium maggsiae*				P		
Algae	Rhodophyta	*Plocamium sp.*		P	P	P		P
Algae	Rhodophyta	*Polyides rotunda*		P				
Algae	Rhodophyta	*Polysiphonia macrocarpa*	P*					
Algae	Rhodophyta	*Polysiphonia sp.*	P	P	P	P		
Algae	Rhodophyta	*Porphyra sp.*	P	P		P	P	
Algae	Rhodophyta	*Pterocladiella capillacea*					P	
Algae	Rhodophyta	*Pterosiphonia complanata*	P*	P				
Algae	Rhodophyta	*Pterosiphonia pennata*	P*					
Algae	Rhodophyta	*Pterosiphonia sp.*			P	P	P	P
Algae	Rhodophyta	*Rhodothamniella floridula*		P			P	

Algae	Rhodophyta	*Rhodymenia holmesii*		P				
Algae	Rhodophyta	*Schizymenia dubyi*	P*					
Algae	Rhodophyta	*Scinaia furcellata*	P		P	P		
Algae	Rhodophyta	*Scinaia sp.*	P	P	P			
Algae	Rhodophyta	*Vertebrata fruticulosa*			P	P		
Algae	Rhodophyta	*Vertebrata sp.*		P	P	P	P	P
Fish	Chordata	*Anguilla anguilla*		P				
Fish	Chordata	*Apletodon dentatus*			P	P		
Fish	Chordata	*Atherina presbyter*			P			P
Fish	Chordata	*Callionymus lyra*			P		P	
Fish	Chordata	*Chelon labrosus*			P			
Fish	Chordata	*Ciliata mustela*				P		
Fish	Chordata	*Coris sp.*			P	P		
Fish	Chordata	*Coryphoblennius galerita*	P*	P	P	P	P	P
Fish	Chordata	*Dicentrarchus labrax*					P	
Fish	Chordata	*Dicentrarchus punctatus*				P		
Fish	Chordata	*Diplodus cf. cadenati*					P	
Fish	Chordata	*Diplodus cervinus*				P	P	
Fish	Chordata	*Diplodus sargus*			P	P	P	P
Fish	Chordata	*Diplodus vulgaris*			P	P		
Fish	Chordata	*Gobius cobitis*			P	P	P	P
Fish	Chordata	*Gobius paganellus*		P	P	P	P	P
Fish	Chordata	*Lepadogaster candolii*			P	P		
Fish	Chordata	*Lepadogaster lepadogaster*				P	P	P
Fish	Chordata	*Lepadogaster purpurea*				P		P
Fish	Chordata	*Lipophrys pholis*	P*	P	P	P	P	P
Fish	Chordata	*Lipophrys trigloides*			P	P	P	P
Fish	Chordata	*Mugilidae*				P	P	P
Fish	Chordata	*Nerophis lumbriciformis*		P	P	P		P
Fish	Chordata	*Parablennius gattorugine*			P	P		
Fish	Chordata	*Parablennius pilicornis*			P	P		
Fish	Chordata	*Pomatoschistus flavescens*			P		P	
Fish	Chordata	*Scophthalmus maximus*			P			
Fish	Chordata	*Sparus aurata*					P	
Fish	Chordata	*Symphodus melops*				P		
Fungi	Ascomycota	*Hydropunctaria maura*	P	P		P	P	P
Fungi	Ascomycota	*Lichina pygmaea*	P	P		P	P	P
Invertebrate	Annelida	*Alentia gelatinosa*						P
Invertebrate	Annelida	*Alitta virens*				P		
Invertebrate	Annelida	*Bonellia viridis*				P		
Invertebrate	Annelida	*Cirratulidae*			P	P	P	P
Invertebrate	Annelida	*Cirratulus cirratus*			P			
Invertebrate	Annelida	*Eulalia sp.*	P	P	P	P	P	P
Invertebrate	Annelida	*Filograna implexa*	P*					
Invertebrate	Annelida	*Hirudinea*				P		
Invertebrate	Annelida	*Nereididae*			P	P	P	
Invertebrate	Annelida	*Sabellaria alveolata*	P	P	P	P	P	P
Invertebrate	Annelida	*Serpulidae*				P		

Invertebrate	Annelida	*Sipunculidae*						P
Invertebrate	Annelida	*Spirobranchus triqueter*					P	P
Invertebrate	Arthropoda	Amphipoda			P	P		
Invertebrate	Arthropoda	*Anapagurus sp. (hyndmanni)*			P			
Invertebrate	Arthropoda	*Athanas sp.*						P
Invertebrate	Arthropoda	*Balanus sp.* (Balanidae)			P	P		P
Invertebrate	Arthropoda	*Callianassa sp.*		P				
Invertebrate	Arthropoda	*Callianassidae*						P
Invertebrate	Arthropoda	*Cancer pagurus*		P	P	P		
Invertebrate	Arthropoda	*Caprellidae*			P	P		
Invertebrate	Arthropoda	*Carcinus maenas*		P	P	P	P	
Invertebrate	Arthropoda	*Chthamalus montagui*	P	P	P	P	P	P
Invertebrate	Arthropoda	*Chthamalus stellatus*	P	P	P	P	P	P
Invertebrate	Arthropoda	*Clibanarius erythropus*		P	P	P		P
Invertebrate	Arthropoda	*Eriphia verrucosa*			P	P	P	P
Invertebrate	Arthropoda	*Galathea sp.*			P			
Invertebrate	Arthropoda	*Hippolyte sp.*			P			
Invertebrate	Arthropoda	*Idotea sp.*			P	P		
Invertebrate	Arthropoda	*Liocarcinus sp.*			P			
Invertebrate	Arthropoda	*Lysmata sp.*			P			
Invertebrate	Arthropoda	*Maja sp.*			P			P
Invertebrate	Arthropoda	*Mysida*		P				
Invertebrate	Arthropoda	*Necora puber*		P	P	P		P
Invertebrate	Arthropoda	*Pachygrapsus marmoratus*			P	P	P	P
Invertebrate	Arthropoda	*Paguridae*			P	P		
Invertebrate	Arthropoda	*Palaemon elegans*			P	P	P	
Invertebrate	Arthropoda	*Palaemon serratus*	P*		P	P		
Invertebrate	Arthropoda	*Palaemon sp.*		P	P	P	P	P
Invertebrate	Arthropoda	*Perforatus perforatus*	P				P	
Invertebrate	Arthropoda	*Pilumnus hirtellus*			P	P		
Invertebrate	Arthropoda	*Pirimela denticulata*			P	P		
Invertebrate	Arthropoda	*Pisidia longicornis*				P	P	P
Invertebrate	Arthropoda	*Pollicipes pollicipes*	P	P	P	P	P	P
Invertebrate	Arthropoda	*Polybius henslowii*			P			
Invertebrate	Arthropoda	*Porcellana platycheles*		P		P	P	P
Invertebrate	Arthropoda	*Pycnogonida*			P	P		P
Invertebrate	Arthropoda	*Sphaeromatidae*			P	P		P
Invertebrate	Arthropoda	*Stenosoma acuminatum*			P			
Invertebrate	Arthropoda	*Tanaidacea*			P	P		
Invertebrate	Arthropoda	*Tanystylum conirostre*				P		
Invertebrate	Arthropoda	*Xantho hydrophilus*			P	P	P	P
Invertebrate	Arthropoda	*Xantho pilipes*			P	P		
Invertebrate	Arthropoda	*Xantho sp.*		P	P	P		
Invertebrate	Cnidaria	*Actinia fragacea*	P		P	P	P	P
Invertebrate	Cnidaria	*Actinothoe sphyrodeta*	P*		P	P	P	
Invertebrate	Cnidaria	*Aglaophenia sp.*				P		
Invertebrate	Cnidaria	*Andvakia boninensis*			P	P	P	P
Invertebrate	Cnidaria	*Anemonia viridis*	P	P	P	P	P	P

Invertebrate	Cnidaria	*Anthopleura balli*			P	P		
Invertebrate	Cnidaria	*Anthopleura biscayensis*			P	P	P	P
Invertebrate	Cnidaria	*Anthopleura thallia*	P		P	P	P	P
Invertebrate	Cnidaria	*Balanophyllia regia*					P	
Invertebrate	Cnidaria	*Bunodactis verrucosa*		P	P	P	P	
Invertebrate	Cnidaria	*Bunodosoma capense*			P	P	P	P
Invertebrate	Cnidaria	*Calvadosia campanulata*			P			
Invertebrate	Cnidaria	*Cereus pedunculatus*			P	P	P	P
Invertebrate	Cnidaria	*Complex Actinia equina/mediterranea*	P	P	P	P	P	P
Invertebrate	Cnidaria	*Corynactis viridis*			P			P
Invertebrate	Cnidaria	*Cylista sp.*				P		
Invertebrate	Cnidaria	*Ectopleura larynx*				P		
Invertebrate	Cnidaria	*Hydrozoa*			P	P		
Invertebrate	Cnidaria	*Isozoanthus sp.*			P	P		
Invertebrate	Cnidaria	*Obelia sp.*			P	P		
Invertebrate	Cnidaria	*Phymactis papillosa*				P	P	P
Invertebrate	Cnidaria	*Urticina felina*	P					
Invertebrate	Echinodermata	*Aslia lefevrei*				P	P	
Invertebrate	Echinodermata	*Asterias rubens*	P					
Invertebrate	Echinodermata	*Asterina gibbosa*	P	P	P	P		P
Invertebrate	Echinodermata	*Asterina sp.*			P	P		
Invertebrate	Echinodermata	*Coscinosterias tenuispina*					P	P
Invertebrate	Echinodermata	*Cucumariidae*				P	P	
Invertebrate	Echinodermata	*Holothuria arguinensis*						P
Invertebrate	Echinodermata	*Holothuria furskali*						P
Invertebrate	Echinodermata	*Marthasterias glacialis*	P	P	P	P	P	P
Invertebrate	Echinodermata	*Ophioderma longicaudum*				P		P
Invertebrate	Echinodermata	*Ophiothrix fragilis*			P	P	P	P
Invertebrate	Echinodermata	*Ophiuridae*			P	P	P	P
Invertebrate	Echinodermata	*Paracentrotus lividus*	P	P	P	P	P	P
Invertebrate	Echinodermata	*Pawsonia xasicola*				P		
Invertebrate	Mollusca	*Acanthochitona sp.*		P	P	P	P	P
Invertebrate	Mollusca	*Aeolidia filomenae*				P	P	P
Invertebrate	Mollusca	*Aeolidiella alderi*				P	P	P
Invertebrate	Mollusca	*Aeolidiella sanguinea*						P
Invertebrate	Mollusca	*Alvania sp.*			P			
Invertebrate	Mollusca	*Amphorina farrani*			P			
Invertebrate	Mollusca	*Anomia ephippium*			P	P		
Invertebrate	Mollusca	*Anomia sp.*						P
Invertebrate	Mollusca	*Aplysia depilans*			P	P	P	P
Invertebrate	Mollusca	*Aplysia fasciata*		P	P	P		P
Invertebrate	Mollusca	*Aplysia parvula*			P	P	P	
Invertebrate	Mollusca	*Aplysia punctata*			P		P	
Invertebrate	Mollusca	*Aplysia sp.*	P					
Invertebrate	Mollusca	*Barlleia sp.*			P	P		
Invertebrate	Mollusca	*Berghia columbina*				P		
Invertebrate	Mollusca	*Berghia rissodominguezi*						P
Invertebrate	Mollusca	*Bittium reticulatum*			P		P	

Invertebrate	Mollusca	*Bittium sp.*			P	P	P	
Invertebrate	Mollusca	*Calliostoma zizyphinum*			P	P		P
Invertebrate	Mollusca	*Cardita calyculata*			P	P	P	P
Invertebrate	Mollusca	*Cellana rota*				P		
Invertebrate	Mollusca	*Cerithiopsis tubercularis*			P			
Invertebrate	Mollusca	*Diodora graeca*				P		
Invertebrate	Mollusca	*Doriopsilla areolata*						P
Invertebrate	Mollusca	*Doris verrucosa*			P			
Invertebrate	Mollusca	*Edmundsella pedata*			P	P		
Invertebrate	Mollusca	*Elysia viridis*			P	P		P
Invertebrate	Mollusca	*Epitonium clathrus*			P			
Invertebrate	Mollusca	*Epitonium sp.*			P			
Invertebrate	Mollusca	*Erato voluta*						P
Invertebrate	Mollusca	*Euspira sp.*			P			
Invertebrate	Mollusca	*Facelina annulicornis*						P
Invertebrate	Mollusca	*Facelina auriculata*			P	P		
Invertebrate	Mollusca	*Favorinus branchialis*					P	
Invertebrate	Mollusca	*Felimare cantabrica*				P		
Invertebrate	Mollusca	*Felimida Krohni*				P		
Invertebrate	Mollusca	*Felimida purpurea*			P	P		
Invertebrate	Mollusca	*Fissurellidae*				P		
Invertebrate	Mollusca	*Hiatella sp.*				P		
Invertebrate	Mollusca	*Iothia fulva*				P		
Invertebrate	Mollusca	*Irus irus*			P	P		
Invertebrate	Mollusca	*Jujubinus sp.*			P			
Invertebrate	Mollusca	*Lepidochitona cinerea*			P	P	P	P
Invertebrate	Mollusca	*Leptochiton algesirensis*			P	P	P	P
Invertebrate	Mollusca	*Leptochiton sp.*			P	P		
Invertebrate	Mollusca	*Limacia clavigera*			P	P	P	
Invertebrate	Mollusca	*Littorina obtusata*		P				
Invertebrate	Mollusca	*Littorina saxatilis*	P	P				P
Invertebrate	Mollusca	*Marshallora adversa*			P			
Invertebrate	Mollusca	*Melarhaphe neritoides*	P	P	P	P	P	P
Invertebrate	Mollusca	*Mimachlamys varia*			P			
Invertebrate	Mollusca	*Mitrella sp.*						P
Invertebrate	Mollusca	*Modiolus barbatus*			P	P		P
Invertebrate	Mollusca	*Musculus costulatus*			P	P	P	P
Invertebrate	Mollusca	*Mytilidae*				P		P
Invertebrate	Mollusca	*Mytilus sp.*	P	P	P	P	P	P
Invertebrate	Mollusca	*Nucella lapillus*	P		P	P	P	
Invertebrate	Mollusca	*Ocenebra edwardsii*			P	P		P
Invertebrate	Mollusca	*Ocenebra erinaceus*			P	P		
Invertebrate	Mollusca	*Octopus vulgaris*			P	P	P	P
Invertebrate	Mollusca	*Onchidella celtica*			P	P		P
Invertebrate	Mollusca	*Opalia crenata*			P			
Invertebrate	Mollusca	*Patella aspera*	P				P	
Invertebrate	Mollusca	*Patella depressa*	P	P	P	P	P	P
Invertebrate	Mollusca	*Patella pellucida*		P	P	P		

Invertebrate	Mollusca	*Patella rustica*	P	P		P	P	P
Invertebrate	Mollusca	*Patella sp.*	P	P	P	P	P	P
Invertebrate	Mollusca	*Patella ulyssiponensis*	P			P	P	P
Invertebrate	Mollusca	*Patella vulgata*	P			P	P	P
Invertebrate	Mollusca	*Pelagella castanea*					P	
Invertebrate	Mollusca	Perforatus perforatus					P	P
Invertebrate	Mollusca	*Phorcus lineatus*	P	P	P	P	P	P
Invertebrate	Mollusca	*Phorcus sauciatus*		P	P	P	P	P
Invertebrate	Mollusca	*Phorcus sp.*		P		P		
Invertebrate	Mollusca	*Placida denditrica*				P		
Invertebrate	Mollusca	*Pusillina inconspicua*			P	P		
Invertebrate	Mollusca	*Rhyssoplax olivacea*						P
Invertebrate	Mollusca	*Rissoa parva*			P	P	P	P
Invertebrate	Mollusca	*Rostranga rubra*			P			
Invertebrate	Mollusca	*Runcina coronata*			P	P		P
Invertebrate	Mollusca	*Sepia officinalis*			P			
Invertebrate	Mollusca	*Siphonaria pectinata*	P	P	P	P	P	P
Invertebrate	Mollusca	*Skeneopsis planorbis*			P			
Invertebrate	Mollusca	*Spurilla neapolitana*			P	P	P	P
Invertebrate	Mollusca	*Steromphala cineraria*		P	P	P	P	
Invertebrate	Mollusca	*Steromphala pennanti*	P	P	P	P	P	P
Invertebrate	Mollusca	*Steromphala sp.*		P		P	P	
Invertebrate	Mollusca	*Steromphala umbilicalis*	P		P	P	P	P
Invertebrate	Mollusca	*Steromphala varia*			P	P	P	P
Invertebrate	Mollusca	*Stramonita haemastoma*				P		
Invertebrate	Mollusca	*Striarca lactea*			P	P		
Invertebrate	Mollusca	*Tectura virginea*				P	P	
Invertebrate	Mollusca	*Tellina sp.*			P	P		
Invertebrate	Mollusca	*Tricolia pullus*			P	P		P
Invertebrate	Mollusca	*Tritia incrassata*			P	P	P	P
Invertebrate	Mollusca	*Tritia reticulata*			P	P	P	P
Invertebrate	Mollusca	*Tritia varicosa*			P	P	P	P
Invertebrate	Mollusca	*Trivia monacha*				P		P
Invertebrate	Platyhelminthes	*Leptoplana tremellaris*			P	P	P	P
Invertebrate	Platyhelminthes	*Planocera sp.*						P
Invertebrate	Platyhelminthes	*Vorticeros sp.*				P		
Invertebrate	Platyhelminthes	*Yungia aurantiaca*					P	
Invertebrate	Porifera	*Halichondria panacea*	P					
Invertebrate	Porifera	*Hymeniacidon perlevis*	P	P	P	P	P	P
Invertebrate	Porifera	*Leucilla sp.*						P
Tonicate	Chordata	Ascidiacea			P	P		
Tonicate	Chordata	*Botryllus schlosseri*		P	P	P	P	P
TOTAL		370	101	112	216	239	149	156

C. SUPPORT MATERIAL

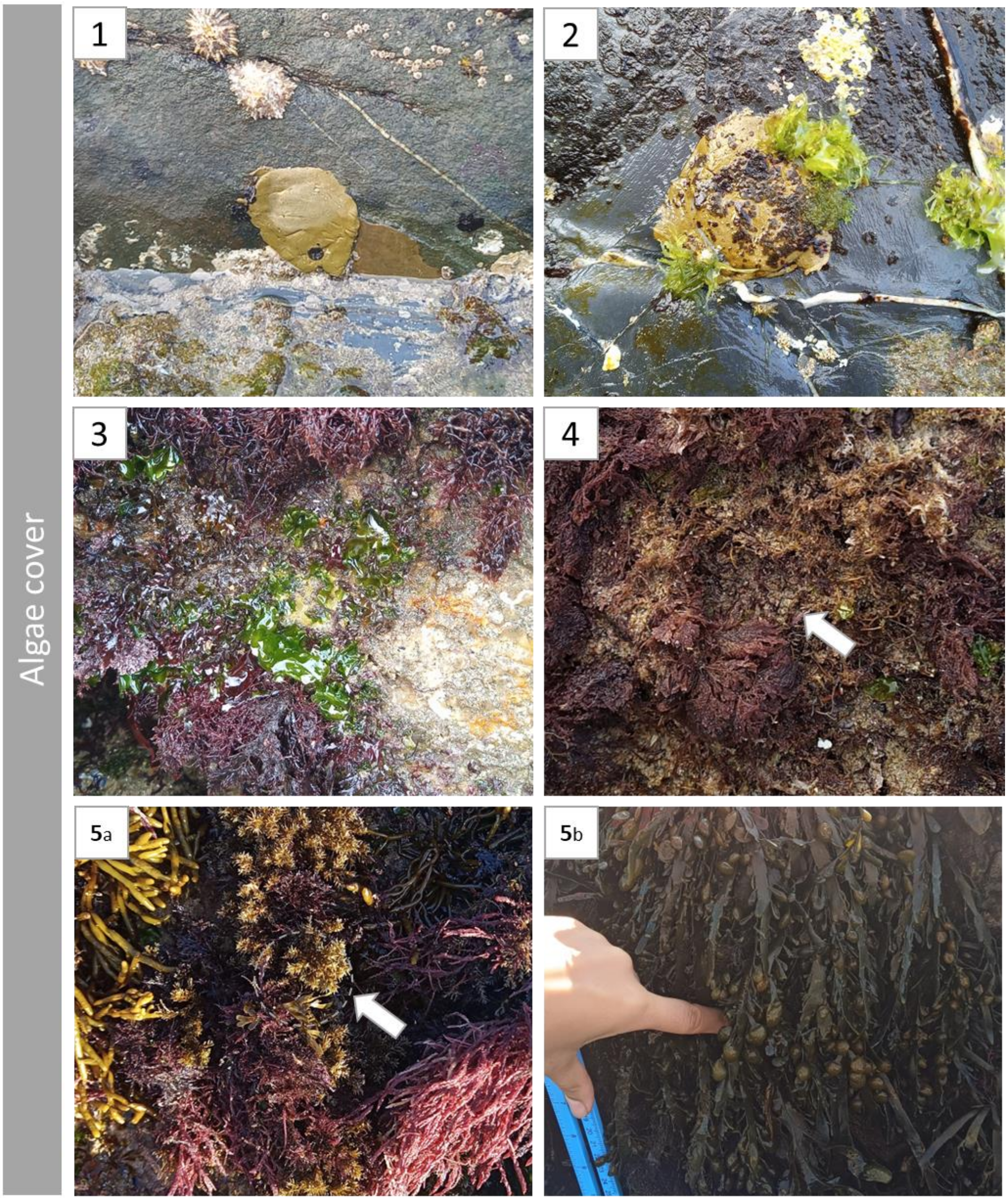


Figure C 1. Examples of the type of algae cover found on top of the study loggers. 1 – clean; 2 – slightly; 3 – partially; 4 – covered; 5a-b – fully.

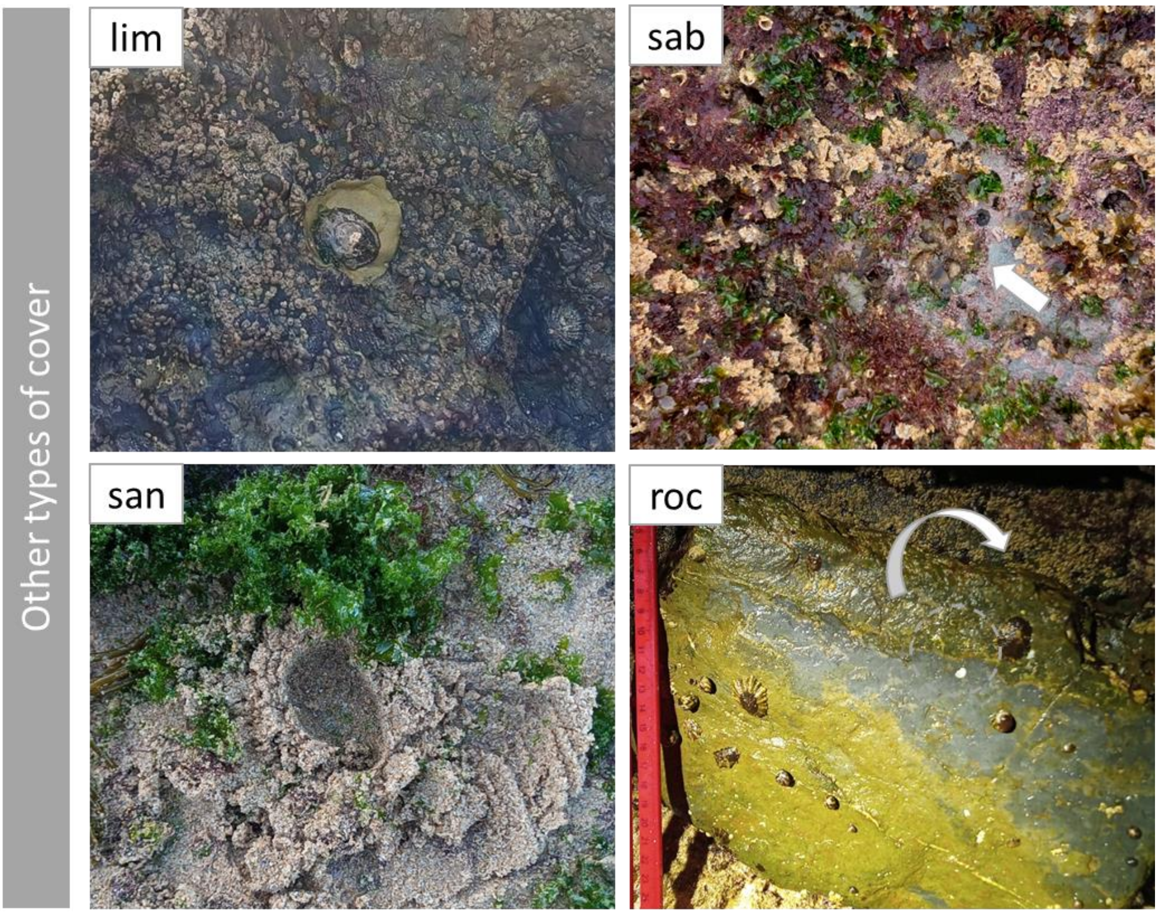


Figure C 2Figure C2. Examples of other type of coverage found on top of the study loggers. lim – limpet; sab – Sabellaria alveolate; san – sand; roc – rock.

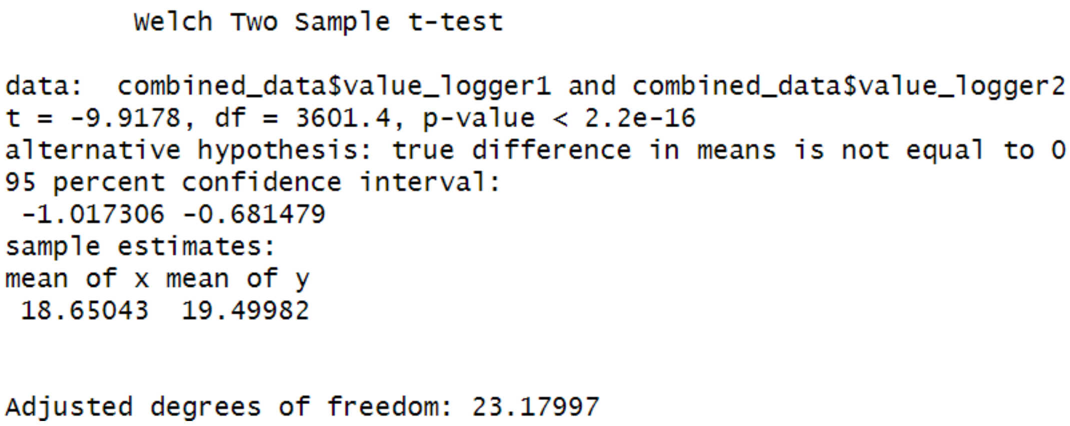
D. COMPLEMENTARY/ADDITIONAL ANALYSES

Table D 2.1. Table of minimum, maximum, mean and temperature differences during winter and for all the study sites. Sites: “mol” - Praia do Moledo, “vcn” - Praia Norte, “emp” - Praia da Empa, “cbr” - Cabo Raso, “alt” - Praia dos Alteirinhos, and “ode” - Praia de Odeceixes. Level and Exposure: “l” - Low level, “t” - Top level; “h” - Hot, “c” - Cold.

sh	lvl	exp	min_temp (Cº)		max_temp (Cº)		mean_temp (Cº)		min_diff(n-y) (Cº)		max_diff(n-y) (Cº)	
			2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
mol	l	c	6.8	7.4	16.2	15.7	14.0	14.2	-1.1	-4.8	1.8	3
		h	8.1	9.1	29.7	24.7	14.2	14.3	-0.9	-5.2	3.6	10
	t	c	3.3	4.4	19.7	20.4	12.4	13.0	-2.8	-2.8	1.5	2.0
		h	4.1	5.2	29.1	26.7	13.6	13.9	-1.9	-1.2	2.7	2.2
vcn	l	c	7.3	8.5	16.3	16.4	14.3	14.4	-1.3	-1.1	1.8	1.6
		h	8.5	10.2	31.8	27	14.4	14.4	-3.2	-1.7	4.9	2.9
	t	c	3.6	5.8	20.2	20.7	12.7	13.2	-2.9	-3.4	5.5	3.5
		h	3.9	4.8	36.7	36.5	14.2	14.2	-5.4	-4.5	18.8	17.1
emp	l	c	10.4	11.4	17.1	19.7	15.3	15.9	-1.6	-1.0	0.8	3.8
		h	8.4	11.2	29.5	29.2	15.3	15.9	-1.7	-1.0	5.0	5.9
	t	c	4.4	6.0	22.4	24.0	14.2	15.2	-3.3	-7.1	3.4	3.5
		h	4.7	6.4	37.5	36.3	15.4	16.0	-3.6	-2.8	7.3	5.1
cbr	l	c	10.2	11.4	17.7	18.8	16.3	15.9	-1.3	-1.0	0.4	1.2
		h	9.2	10.8	23.9	27.5	16.3	15.9	-2.2	-1.4	2.1	2.80
	t	c	5.1	7.7	29.3	29.0	14.2	15.2	-5.3	-5.6	2.5	2.4
		h	4.3	6.5	32.5	36.8	15.1	15.9	-3.7	-3.0	8.1	5.7
alt	l	c	8.4	11	22.6	23.4	15.5	16.1	-1.9	-1.7	2.2	2.2
		h	6.2	9.6	28.6	34.1	15.7	16.2	-2.4	-2.2	4.0	4.8
	t	c	5.6	8.4	23.4	26.0	14.6	15.5	-1.2	-1.4	1.9	1.6
		h	5.9	8.4	33.1	35.6	15.5	16.2	-1.6	-3.1	5.3	4.5
ode	l	c	6.9	11.6	19.0	21.7	15.6	16.2	-3.1	-1.6	1.1	4.10
		h	6.5	10.8	28.6	24.6	15.5	16.1	-3.6	-1.7	3.7	4.40
	t	c	4.1	8.0	25.5	31.7	14.2	15.3	-3.4	-7.9	5.5	4.4
		h	2.9	6.9	39.7	39.8	15.3	16.3	-5.0	-6.1	7.4	5.5

Table D 1.2. Table of minimum, maximum, mean and temperature differences during summer and for all the study sites. Sites: “mol” - Praia do Moledo, “vcn” - Praia Norte, “emp” - Praia da Empa, “cbr” - Cabo Raso, “alt” - Praia dos Alteirinhos, and “ode” - Praia de Odeceixes. Level and Exposure: “l” - Low level, “t” - Top level; “h” - Hot, “c” - Cold.

sh	lvl	exp	min_temp (Cº)		max_temp (Cº)		mean_temp (Cº)		min_diff(n-y) (Cº)		max_diff(n-y) (Cº)	
			2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
mol	l	c	12.9	12.9	27.9	20.1	17.3	15.6	-2.80	-2.4	2.40	2.1
		h	12.9	12.9	33.1	29.7	17.4	15.7	-9	-0.5	8.1	7.6
	t	c	13.6	13.2	39.3	31.9	19.7	19.2	-3.3	-4.0	5.20	5.8
		h	13.3	13.0	40.7	42.5	20.0	19.4	-2.4	-3.5	11.1	5.9
vcn	l	c	13.2	13.2	25.7	20.8	17.8	15.8	-1.60	-1.2	1.8	4.2
		h	13.2	13.0	30.9	30.3	18.0	16.0	-1.3	-1.0	8.4	10.4
	t	c	14	13.4	33.6	32.3	20.0	19.1	-2.2	-2.40	11.1	9.9
		h	13.3	13.4	43.1	42.0	21.5	20.8	-4.10	-4.40	20	19.7
emp	l	c		14.0		26.0		16.5		-1.10		5.3
		h		14.0		33.6		16.7		-3.15		13.1
	t	c		13.5		36.2		18.0		-11.2		2.8
		h		13.4		44.1		19.3		-5.8		8.9
cbr	l	c		14.3		25.3		16.9		-0.5		3.9
		h		14.2		29.9		17.0		-0.7		6.1
	t	c		14.2		35.6		18.8		-6.8		4.5
		h		14.3		40.9		19.5		-5.8		10.7
alt	l	c		14.3		32.7		18.3		-3.8		8.1
		h		13.7		39.5		18.1		-3.4		8.3
	t	c		13.4		38.9		20.4		-4.9		3.0
		h		14.2		45.1		21.8		-5.4		12.2
ode	l	c		14.3		32.8		17.5		-1.1		9.4
		h		14.0		34.7		17.6		-1.6		8.0
	t	c		13.2		41.5		20.1		-8.6		6.0
		h		12.4		46.1		20.7		-8.5		8.30



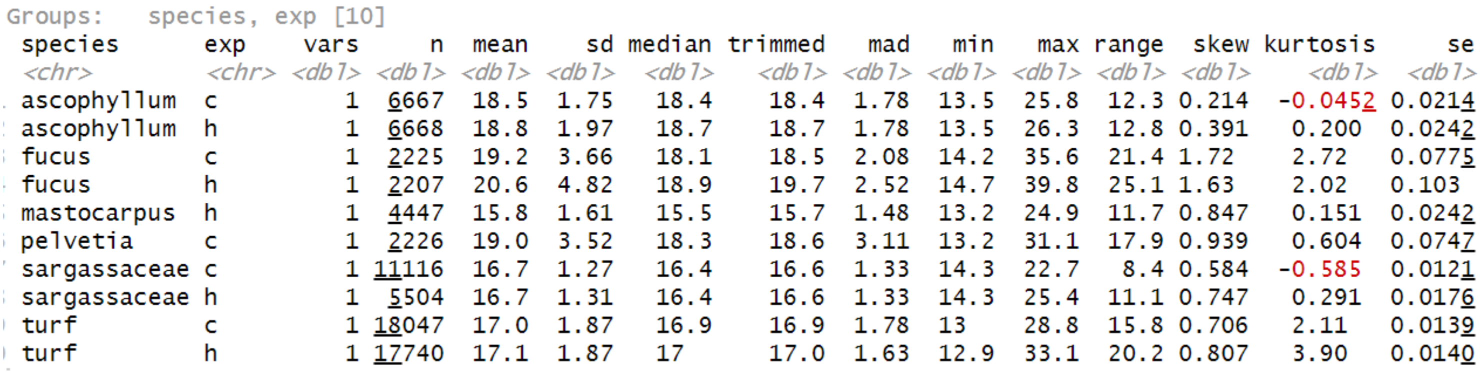
```
        Welch Two Sample t-test

data:  combined_data$value_logger1 and combined_data$value_logger2
t = -9.9178, df = 3601.4, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -1.017306 -0.681479
sample estimates:
mean of x mean of y
 18.65043  19.49982


Adjusted degrees of freedom: 23.17997
```

Figure D2. Result from the Welch Two Sample t-test

.



```
Groups:   species, exp [10]
 species      exp    vars     n  mean    sd median trimmed   mad   min   max range  skew kurtosis     se
 <chr>        <chr> <dbl> <dbl> <dbl> <dbl>  <dbl>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>    <dbl>  <dbl>
 ascophyllum  c         1  6667  18.5  1.75   18.4    18.4  1.78  13.5  25.8  12.3 0.214  -0.0452 0.0214
 ascophyllum  h         1  6668  18.8  1.97   18.7    18.7  1.78  13.5  26.3  12.8 0.391   0.200  0.0242
 fucus        c         1  2225  19.2  3.66   18.1    18.5  2.08  14.2  35.6  21.4 1.72    2.72   0.0775
 fucus        h         1  2207  20.6  4.82   18.9    19.7  2.52  14.7  39.8  25.1 1.63    2.02   0.103 
 mastocarpus  h         1  4447  15.8  1.61   15.5    15.7  1.48  13.2  24.9  11.7 0.847   0.151  0.0242
 pelvetia     c         1  2226  19.0  3.52   18.3    18.6  3.11  13.2  31.1  17.9 0.939   0.604  0.0747
 sargassaceae c         1 11116  16.7  1.27   16.4    16.6  1.33  14.3  22.7   8.4 0.584  -0.585  0.0121
 sargassaceae h         1  5504  16.7  1.31   16.4    16.6  1.33  14.3  25.4  11.1 0.747   0.291  0.0176
 turf         c         1 18047  17.0  1.87   16.9    16.9  1.78  13    28.8  15.8 0.706   2.11   0.0139
 turf         h         1 17740  17.1  1.87   17      17.0  1.63  12.9  33.1  20.2 0.807   3.90   0.0140
```

Figure D3. Descriptive statistics from temperature x algae species boxplot

Table D4. Percentage of the mean reduction in daily temperature variability (Buffer effect).

			Month	winter_mean	summer_mean
Region	Beach	Vert grad	Exp\Rep		
North	Moledo	Low	Cold	5,20%	0,50%
			Hot		18,25%
		Top	Cold		8,75%
			Hot		6,25%
	Praia Norte	Low	Cold	6,25%	3,90%
			Hot	6,50%	23,00%
		Top	Cold	23,20%	32,20%
			Hot	59,97%	69,37%
Cental	Empa	Low	Cold	5,60%	9,09%
			Hot	8,20%	16,20%
		Top	Cold	3,70%	
			Hot	29,70%	
	Cabo Raso	Low	Cold	4,70%	13,10%
			Hot		18,80%
		Top	Cold		
			Hot		
South	Alteirinhos	Low	Cold	14,90%	25,50%
			Hot		11,70%
		Top	Cold		
			Hot		16,20%
	Odeceixe	Low	Cold	8,90%	12,73%
			Hot	10,85%	14,25%
		Top	Cold	16,10%	
			Hot	16,10%	

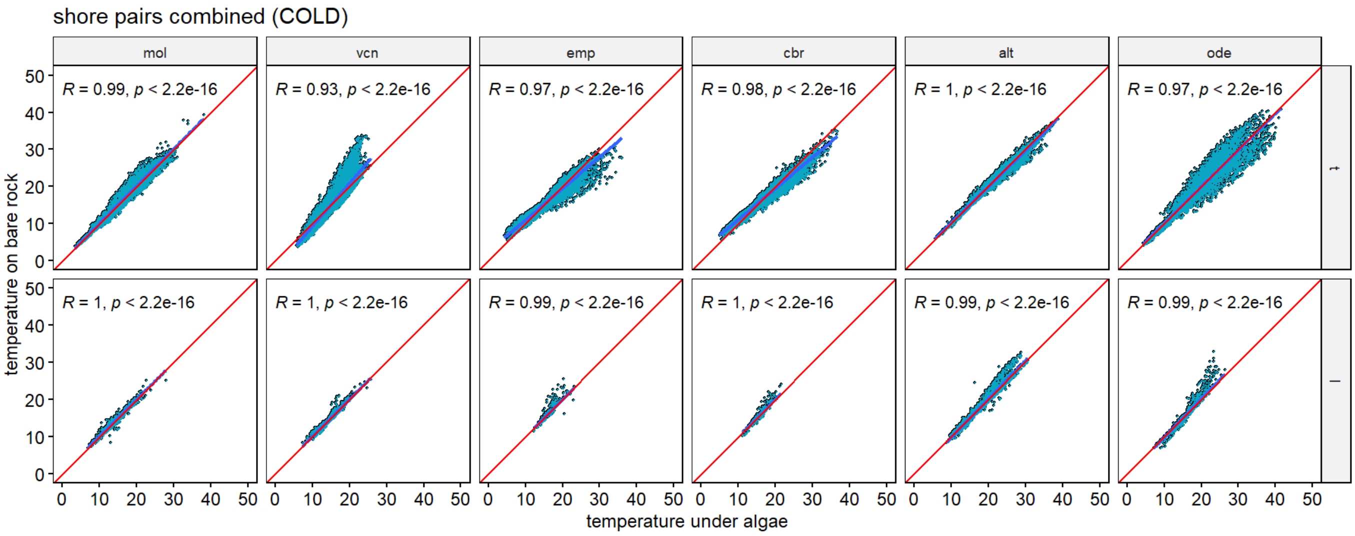


Figure D5.1. Scartterplot of shore pairs combined in “cold” exposure, divided by level. “l” - Low level, “t” - Top level. Exposure. Pearson test. Blue line - confidence interval for the regression line.

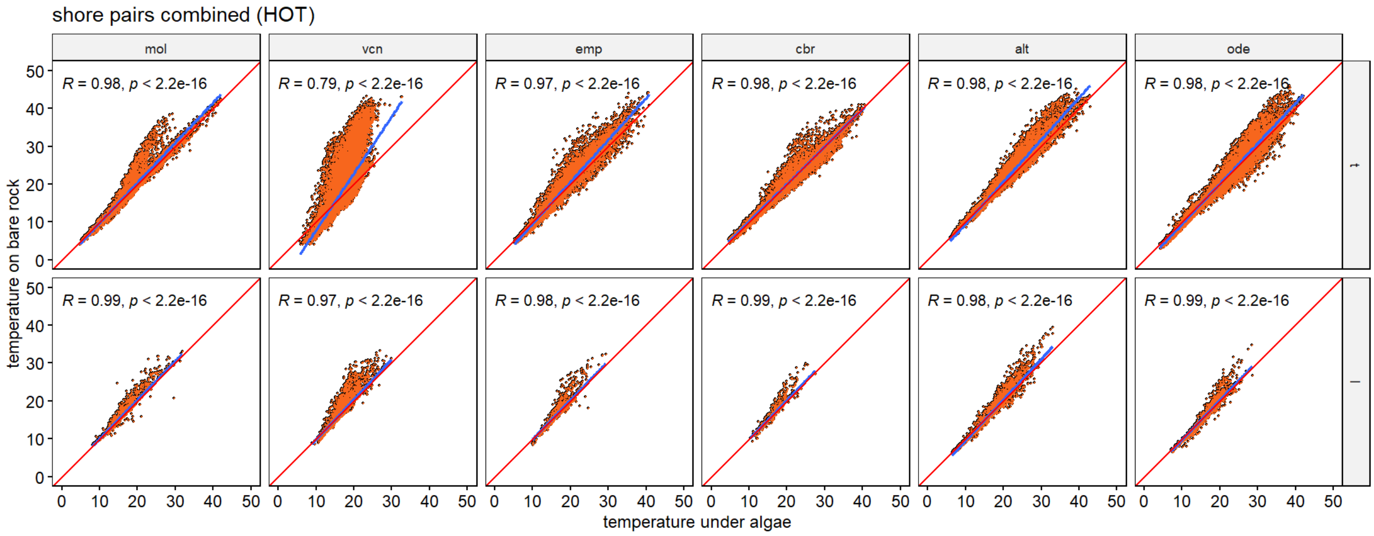


Figure D5.2. Scartterplot of shore pairs combined in “hot” exposure, divided by level. “l” - Low level, “t” - Top level. Exposure. Pearson test. Blue line - confidence interval for the regression line.

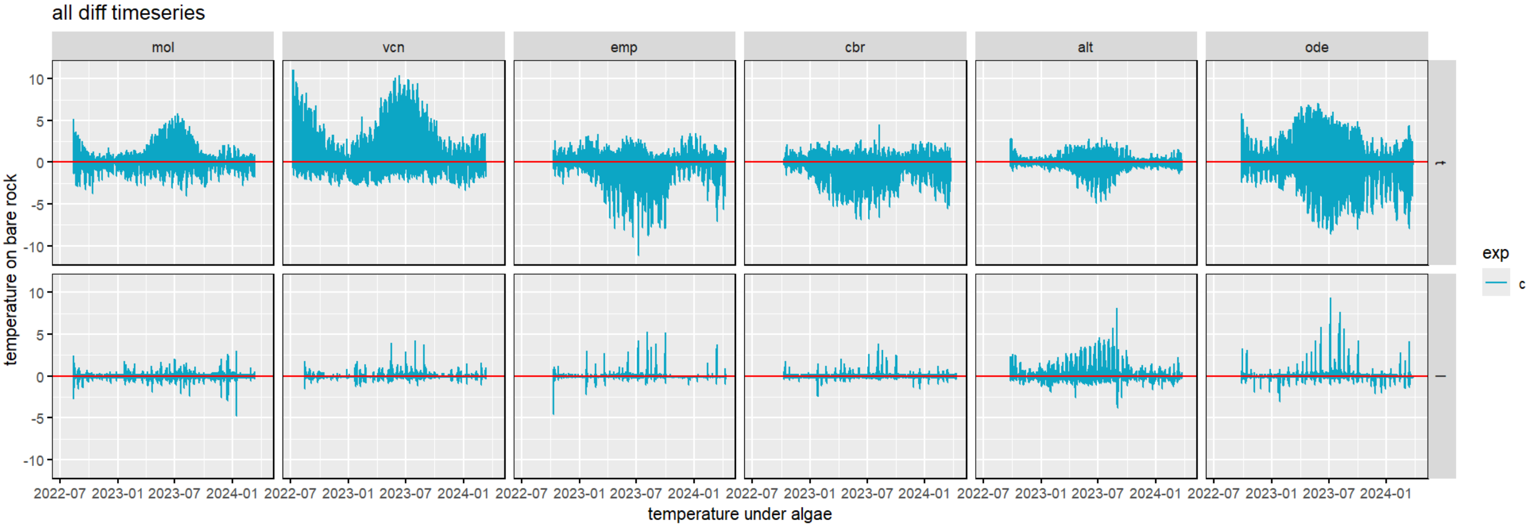


Figure D6.1. Temperature difference between pairs of loggers for each site and level, in “cold” exposure. Level: “l” - Low level, “t” - Top level.

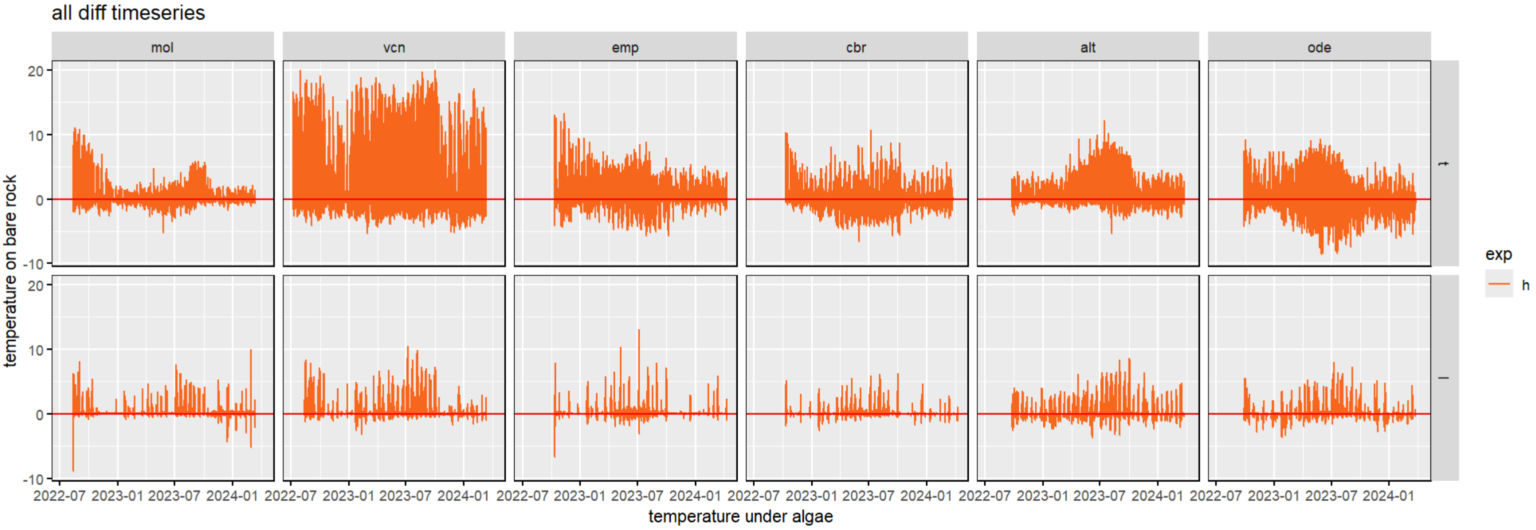
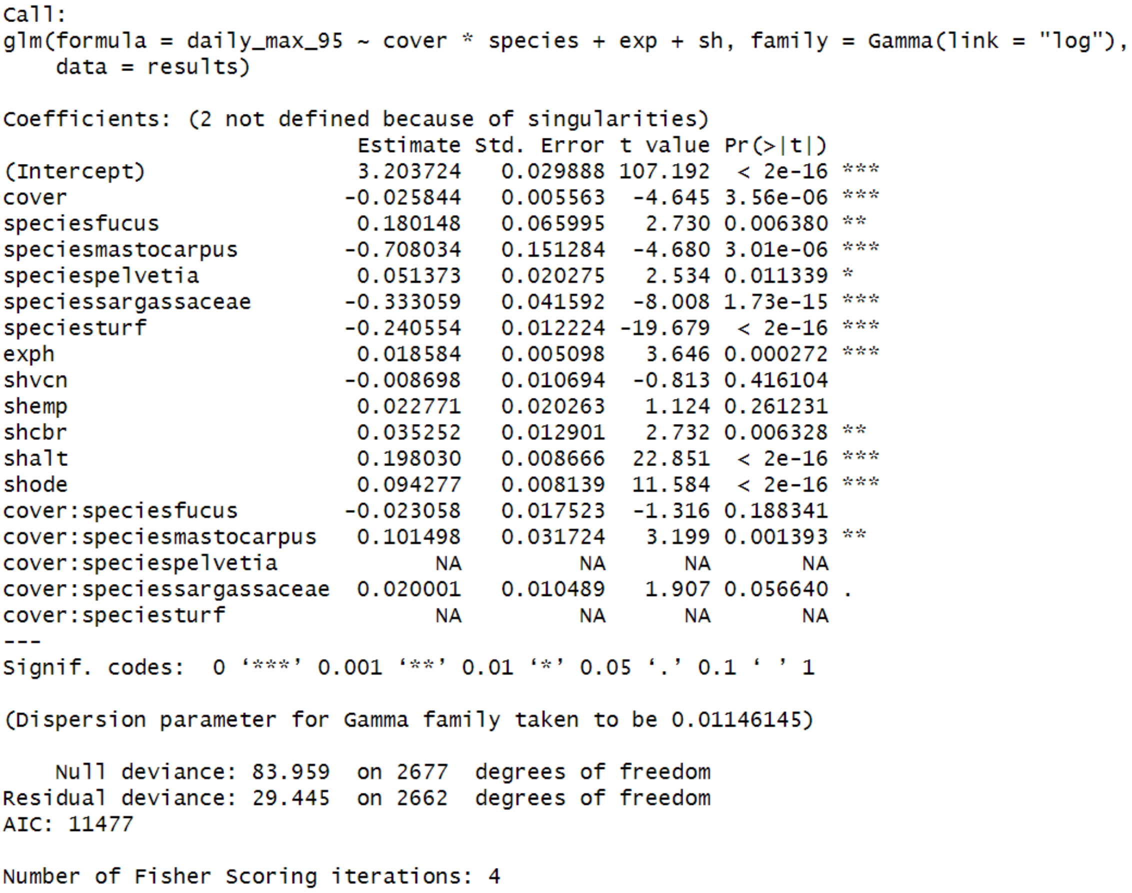


Figure D6.2. Temperature difference between pairs of loggers for each site and level, in “hot exposure. Level: “l” - Low level, “t” - Top level.



```
Call:
glm(formula = daily_max_95 ~ cover * species + exp + sh, family = Gamma(link = "log"),
    data = results)

Coefficients: (2 not defined because of singularities)
                           Estimate Std. Error t value Pr(>|t|)    
(Intercept)                3.203724   0.029888 107.192  < 2e-16 ***
cover                     -0.025844   0.005563  -4.645 3.56e-06 ***
speciesfucus               0.180148   0.065995   2.730 0.006380 ** 
speciesmastocarpus        -0.708034   0.151284  -4.680 3.01e-06 ***
speciespelvetia            0.051373   0.020275   2.534 0.011339 *  
speciessargassaceae       -0.333059   0.041592  -8.008 1.73e-15 ***
speciesturf               -0.240554   0.012224 -19.679  < 2e-16 ***
exph                       0.018584   0.005098   3.646 0.000272 ***
shvcn                     -0.008698   0.010694  -0.813 0.416104    
shemp                      0.022771   0.020263   1.124 0.261231    
shcbr                      0.035252   0.012901   2.732 0.006328 ** 
shalt                      0.198030   0.008666  22.851  < 2e-16 ***
shode                      0.094277   0.008139  11.584  < 2e-16 ***
cover:speciesfucus        -0.023058   0.017523  -1.316 0.188341    
cover:speciesmastocarpus   0.101498   0.031724   3.199 0.001393 ** 
cover:speciespelvetia            NA         NA      NA       NA    
cover:speciessargassaceae  0.020001   0.010489   1.907 0.056640 .  
cover:speciesturf                NA         NA      NA       NA    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for Gamma family taken to be 0.01146145)

    Null deviance: 83.959  on 2677  degrees of freedom
Residual deviance: 29.445  on 2662  degrees of freedom
AIC: 11477

Number of Fisher Scoring iterations: 4
```

Figure D7. Results from Generalize linear model (GLM). “*” – level of significance.

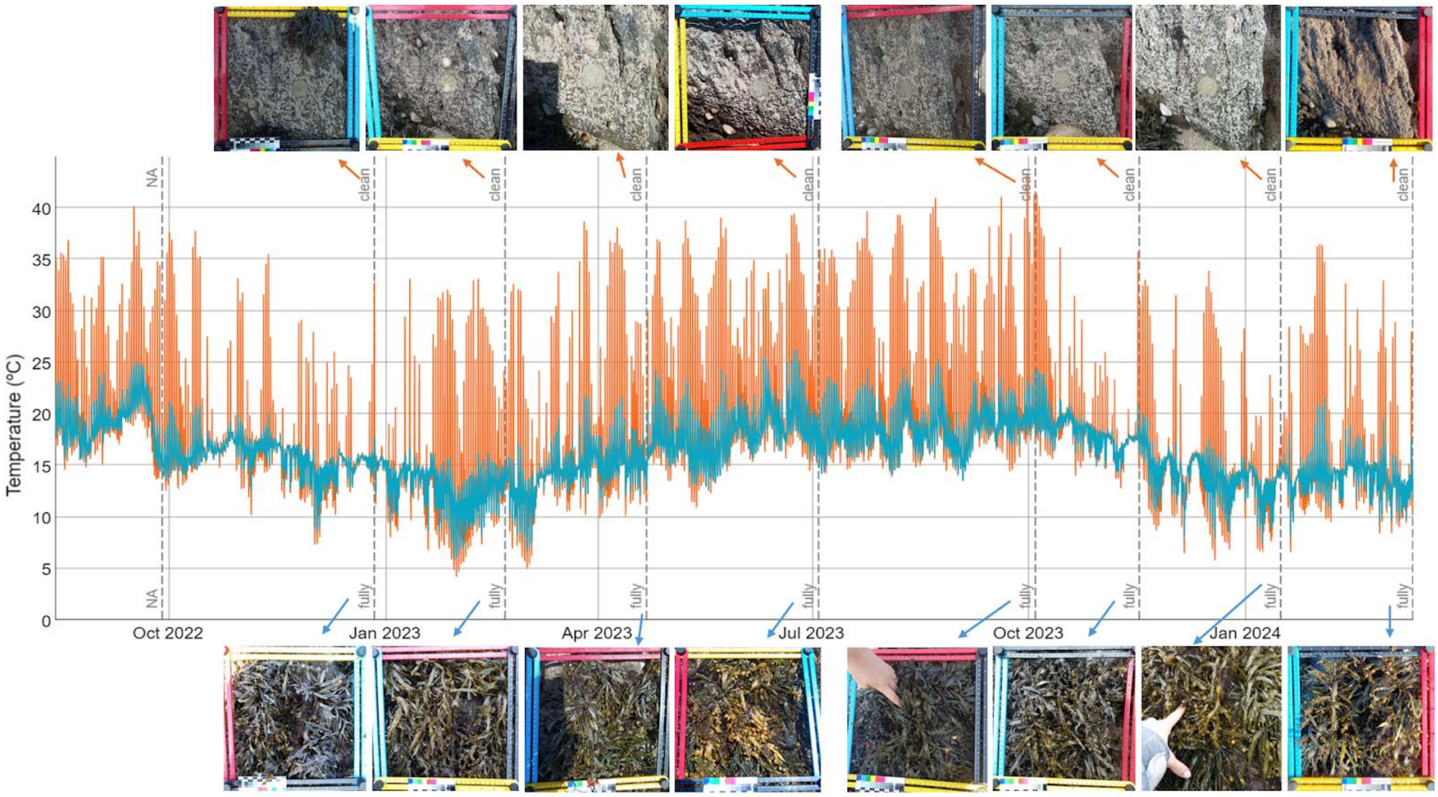


Figure D8.1. Example of algae cover timeline from Praia Norte (Top level, "hot" exposure). Orange lines - logger without algae cover; Blue lines - logger with algae cover.

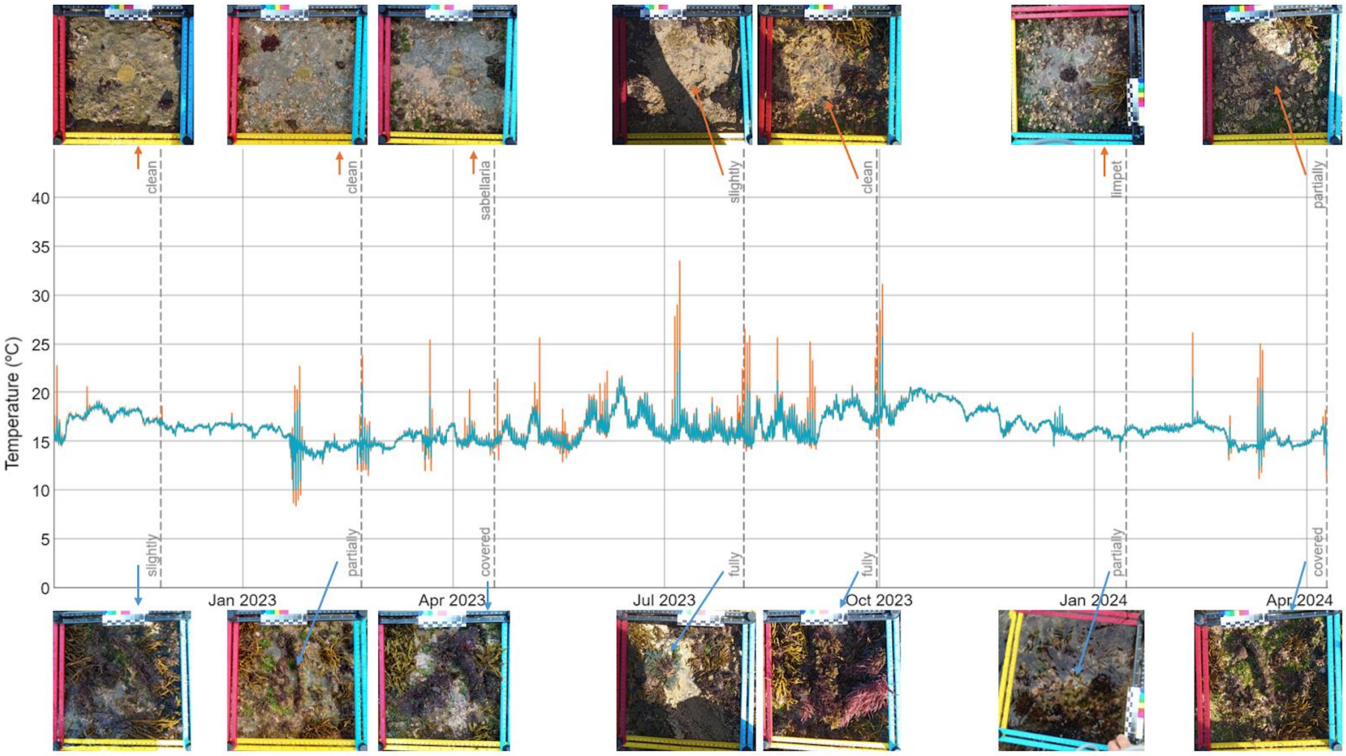


Figure D8.2. Example of algae cover timeline from Praia da Empa (Low level, “hot” exposure). Orange lines - logger without algae cover; Blue lines - logger with algae cover.

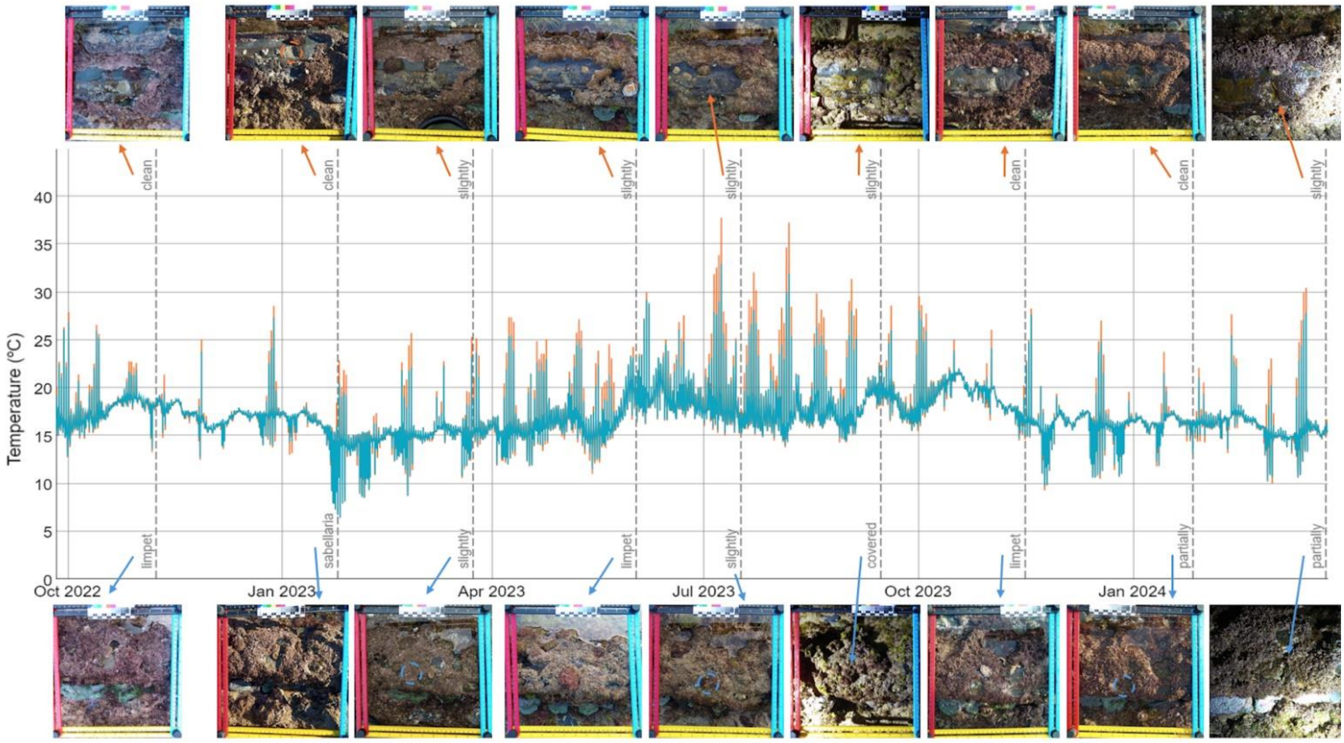


Figure D8.3. Example of algae cover timeline from Praia dos Alteirinhos (Low level, “hot” exposure). Orange lines - logger without algae cover; Blue lines - logger with algae cover.