Growth rate rather than temperature affects the B/Ca ratio in the calcareous red alga *Lithothamnion corallioides*

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Abstract. The B/Ca ratio in calcareous marine species is informative of past seawater CO_3^{2-} concentrations, but scarce data exist on B/Ca in coralline algae (CA). Recent studies suggest influences of temperature and growth rates on B/Ca, the effect of which could be critical for the reconstructions of surface ocean pH and atmospheric pCO_2. In this paper, we present the first LA-ICP-MS analyses of Mg, Sr, Li and B in the coralline algaCA *Lithothamnion corallioides* collected from different geographic settings and depths across the Mediterranean Sea and in the Atlantic Ocean. We produced the first data on temperature proxies (Mg, Li and Sr/Ca) and B/Ca in a coralline algalCA species grown in different Basins (the Mediterranean Sea and the Atlantic Ocean), from across the photic zone depthsshallow to deep waters (12 m, 40 m, 45 m and 66 m depth). We tested the B/Ca correlation with temperature proxies and growth rates, in order to evaluate their possible effect on B incorporation. Our results showed a growth rate influence on B/Ca, especially in the deepest sample (Pontian Isl., Italy; 66 m) and in the shallowest sample (Morlaix, Atlantic coast of France; 12 m), where the growth rates were respectively 0.11 mm/yr and 0.13 mm/yr and the B/Ca was respectively 462.8 ± 49.2 μmol/mol and 726.9 ± 102.8 μmol/mol. A positive correlation between B/Ca and the temperature proxies was found only in Morlaix, where the seasonal temperature variation (ΔT) was the highest (8.90 °C). Thisese pieces of evidence suggests that growth rates, triggered by the different ΔT and light availability across depth, affect the B incorporation in *L. corallioides*.

1 Introduction

Warming and acidification are major anthropogenic perturbations of present-day oceans (Alverson et al., 2001; Feely et al., 2009; Le Quéré et al., 2009; Hansen et al., 2010; Hönisch et al., 2012; Ciais et al., 2013). Ocean acidification reduces the saturation state of calcite and aragonite, lowering the dissolution threshold of biominerals and threatening habitat-forming species of critical ecological importance such as coralline red algae and corals (Morse et al., 2006; Hoegh-Guldberg et al., 2007; Andersson et al., 2008, 2011; Basso, 2012; Ragazzola et al., 2012; Ries et al., 2016). Coralline algae, which precipitate high Mg-calcite (>8-12 mol% $MgCO_3$) (Morse et al., 2006), are particularly suitable as proxy archives for paleoclimate reconstruction because of their worldwide distribution and their longevity by indeterminate growth, with no ontogenetic trend

(Halfar et al., 2008). That is, the growth trend of coralline algae does not slow down asymptotically with age, as in bivalves, thus preserving the resolution of the geochemical signals in the later stages of growth (Adey, 1965; Frantz et al., 2005; Halfar et al., 2008). Moreover, coralline algae thin sections under optical microscopy reveal bands that reflect the growth pattern (Cabioch, 1966; Basso, 1995a, b; Foster, 2001), similarly to tree rings (Ragazzola et al., 2016) that can be targeted for high-resolution geochemical analyses. Seasonal growth bands, indeed, consist of the perithallial alternation of dark and light bands that together constitute the annual growth patterns (Freiwald and Henrich, 1994; Basso, 1995a, b; Kamenos et al., 2009). Dark bands correspond to slow-growing cells produced in the cold season, which are shorter, thick-walled and with lower Mg contents; while light bands are fast-growing cells produced in the warm season, which are longer, less calcified and with higher Mg concentrations (Kamenos et al., 2009; Ragazzola et al., 2016).

Trace element variations in marine calcareous species inform the reconstruction of changes in the environmental parameters, which characterized the seawater during their growth (Hetzinger et al., 2011). Boron is incorporated into the mineral lattice of calcareous marine species during calcite precipitation. In the ocean, B occurs in two molecular species: boric acid $B(OH)_3$ and borate ion $B(OH)_4^-$ (Dickson, 1990), which are related by the following acid-base equilibrium reaction:

$$B(OH)_3 + H_2O \leftrightarrow B(OH)_4^- + H^+ \hspace{2cm} \text{Eq. (1)}$$

that shows the dependence of the two species concentration on pH. In typical surface seawater conditions, the equilibrium constant of the reaction K_B is $10^{-8.6}$ which is equal to a pK_B of 8.6 (Dickson, 1990), very similar to seawater pH (~ 8) (Zeebe and Wolf-Gladrow, 2001). Hence, the reaction described in Eq. (1) is at equilibrium. As the pH lowers, based on Eq. (1), the $[H^+]$ in seawater increases together with the $[B(OH)_3]$, while the $[B(OH)_4^-]$ decreases. Boron has two stable isotopes: the heavier ^{11}B (80.1% of the total abundance) and the lighter ^{10}B (19.9%) with an enrichment factor $\varepsilon^{11}B$ ($\delta^{11}B(OH)_3 - \delta^{11}B(OH)_4^-$) equal to 1.0272 ± 0.0006‰ (Klochko et al., 2006). The current seawater isotopic composition $\delta^{11}B_{sw}$ is 39.61‰ (Foster et al., 2010). The isotopic composition of $B(OH)_3$ and $B(OH)_4^-$ changes with pH, being both enriched in $\delta^{11}B$ with increasing pH (Dickson, 1990). The first analyses of the isotopic signal of marine carbonates evidenced a strong similarity with the isotopic composition of $B(OH)_4^-$ in solution, suggesting that borate would preferentially be incorporated into marine carbonates (Vengosh et al., 1991; Hemming and Hanson, 1992). Therefore, the $\delta^{11}B$ of marine carbonates should increase with pH according to the $\delta^{11}B$ of $B(OH)_4^-$.

The $\delta^{11}B$ of borate is closely related to the pCO_2, seawater $[CO_3^{2-}]$, pH and $[B(OH)_4^-]$, which in turn are mainly controlled by the balance between the total alkalinity (TA) and the dissolved inorganic carbon (DIC) (Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007). Recent magic angle spinning nuclear magnetic resonance (MAS NMR) techniques, though, revealed that 30-48% of $B(OH)_3$ is incorporated in corals, foraminifera, and calcareous red algae (Klochko et al., 2009; Rollion-Bard et al., 2011; Cusack et al., 2015). The amount of incorporated boric acid seems to be unrelated to the boron species concentrations in seawater (Cusack et al., 2015) or pH (Mavromatis et al., 2015) and could be the consequence of a coordination change during biomineralization (Klochko et al., 2009; Mavromatis et al., 2015).

The above-described theoretical overview frames the role of the B content and its isotopic signature ($\delta^{11}B$) in calcareous marine species, as recorders of information about the seawater carbonate system. The $\delta^{11}B$ is used to reconstruct past seawater pH

65 (Hönisch and Hemming, 2005; Foster, 2008; Douville et al., 2010; Paris et al., 2010; Rae et al., 2011). and Tthe boron-to-calcium ratio (B/Ca) proved to beis informative about past seawater CO_3^{2-} concentrations in different empirical studies on benthic foraminifera (Yu and Elderfield, 2007; Yu et al., 2007; Rae et al., 2011) And in synthetic aragonite (Holcomb et al., 2016). .

Warming and acidification are major anthropogenic perturbations of present-day oceans (Alverson et al., 2001; Feely et al., 2009; Le Quéré et al., 2009; Hansen et al., 2010; Hönisch et al., 2012; Ciais et al., 2013). Ocean acidification reduces the saturation state of calcite and aragonite, lowering the dissolution threshold of biominerals and threatening habitat-forming species of critical ecological importance such as coralline red algae (CA) and corals (Morse et al., 2006; Hoegh-Guldberg et al., 2007; Andersson et al., 2008, 2011; Basso, 2012; Ragazzola et al., 2012; Ries et al., 2016). CA, which precipitate high Mg-calcite (>8-12 mol% $MgCO_3$) (Morse et al., 2006), are particularly suitable as proxy archives for paleoclimate reconstruction because of their worldwide distribution and their longevity by indeterminate growth, with no ontogenetic trend (Adey, 1965; Frantz et al., 2005; Halfar et al., 2008). Moreover, CA thin sections under optical microscopy reveal bands that reflect the growth pattern (Cabioch, 1966; Basso, 1995a, b; Foster, 2001), similarly to tree rings (Ragazzola et al., 2016) that can be targeted for high-resolution geochemical analyses. Seasonal growth bands, indeed, consist of the perithallial alternation of dark and light bands that together constitute the annual growth patterns (Freiwald and Henrich, 1994; Basso, 1995a, b; Kamenos et al., 2009). Dark bands correspond to slow-growing cells produced in the cold season, which are shorter, thick-walled and with lower Mg contents; while light bands are fast-growing cells produced in the warm season, which are longer, less calcified and with higher Mg concentrations (Kamenos et al., 2009; Ragazzola et al., 2016).

Most of the literature on boron studies is focused on its isotopic composition (Hemming and Hönisch, 2007; Klochko et al., 2009; Henehan et al., 2013; Fietzke et al., 2015; Cornwall et al., 2017; Ragazzola et al., 2020), whereas less attention has been 85 given to B/Ca records, especially in coralline algaeCA. Recent studies suggest that B/Ca is function of seawater pH, as well as of other environmental variables such as temperature, whose effect should be considered in the attempt to reconstruct surface ocean pH and atmospheric pCO_2 (Wara et al., 2003; Allen et al., 2012; Kaczmarek et al., 2016). To Aachieveing the best reliability of geochemical proxies for climate reconstructions, is indeed crucial, which drives a growing interest has arisen on multiple approaches, by considering multi-proxies for a single environmental factor (D'Olivo et al., 2018; Cuny-Guirrec et al., 90 2019; Zinke et al., 2019; Cuny-Guirrec et al., 2019).; Moreover, it is important to recognize the as well as the influence of multiple factors on a single proxy (Kaczmarek et al., 2016; Donald et al., 2017).

Actually, the effects of temperature and growth rate on B incorporation have been recently investigated through experiments on both synthetic and biogenic carbonates (Wara et al., 2003; Yu et al., 2007; Gabitov et al., 2014; Mavromatis et al., 2015; Uchikawa et al., 2015; Kaczmarek et al., 2016; Donald et al., 2017), showing positive correlations. In particular, B/Ca 95 experiment on the cultured experiment on the coralline alga CA *Neogoniolithon* sp. (Donald et al., 2017), showed a positive correlation of B/Ca with growth rate, and a negative correlation with Sr/Ca, which was proposed by the authors as proxy of DIC. Moreover, a cultured experiment on the high latitude species *Clathromorphum compactum* (Kjellman) Foslie 1898 revealed non-significant temperature influences on B/Ca and a significant inverse relationship with growth rate (Anagnostou

et al., 2019). The ~~current knowledge on the~~ factors which influence the B incorporation in calcareous red algae~~CA~~ are~~is~~ therefore still debated~~controversial~~.

Nevertheless, no studies have been conducted so far on the correlation between temperature proxies (Mg, Sr, Li /Ca) and B/Ca. The Mg/Ca ratio is extensively used as a ~~sea surface~~ temperature proxy ~~(SST)~~ in calcifying species (Barker et al., 2005), including coralline algae~~CA~~ (~~Barker et al., 2005;~~ Halfar et al., 2008; Kamenos et al., 2008; Fietzke et al., 2015; Ragazzola et al., 2020), since the substitution of Mg^{2+} with Ca^{2+} ions in the calcite lattice is an endothermic reaction. Accordingly, Mg incorporation increases with temperature (Moberly, 1968; Berner, 1975; Ries, 2006; Caragnano et al., 2017). Sr/Ca and Li/Ca ratios in calcareous red algae~~CA~~ have also been investigated as climate proxies, showing significant positive correlations with temperature in different species, e.g. *Lithothamnion* spp. (Kamenos et al., 2008; Hetzinger et al., 2011; Caragnano et al., 2014; Darrenougue et al., 2014). The Mg/Li ratio showed a strong correlation with seawater temperature in cultured *Clathromorphum compactum* (Anagnostou et al., 2019), and in empirical studies on high-Mg calcites, including coralline algae (Stewart et al. 2020). Conversely, the Mg/Li calibration did not reveal improvements in the Mg/Ca or Li/Ca proxies in *Lithophyllum* spp. (Caragnano et al., 2014, 2017).

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) allows high-resolution analysis of a broad range of trace elements in solid-state samples. This technique has been widely used in biogenic carbonates to extract records of seawater temperature, salinity and water chemistry (Schöne et al., 2005; Corrège, 2006; Hetzinger et al., 2009, 2011; Fietzke et al., 2015; Ragazzola et al., 2020). The non-geniculate coralline alga *Lithothamnion corallioides* (P. Crouan & H. Crouan) P. Crouan & H. Crouan 1867 is widely distributed in the Mediterranean Sea and in the north-eastern Atlantic Ocean, from Scotland to Canary Islands (Irvine and Chamberlain, 1999; Wilson et al., 2004; Carro et al., 2014), usually constituting maerl beds (Potin et al., 1990; Foster, 2001; Martin et al., 2006; Savini et al., 2012; Basso et al., 2017). It forms rhodoliths as unattached branches (Basso et al., 2016) with obvious banding in longitudinal sections (Basso, 1995b). These characteristics combine to make this species a suitable model for the measurement of geochemical proxies, comparing different environmental settings. In this paper, we provide the first ~~measure by~~ LA-ICP-MS data of~~for the first time the~~ temperature proxies (Mg/Ca, Sr/Ca, Li/Ca) and B/Ca in the coralline alga~~non-geniculated CA~~ *L.~~ithothamnion~~ corallioides* ~~(P. Crouan & H. Crouan) P. Crouan & H. Crouan 1867~~ collected from different geographic settings and depths across the Mediterranean Sea and in the Atlantic Ocean. ~~L. corallioides is widely distributed in the Mediterranean Sea and in the north-eastern Atlantic Ocean, from Scotland to Canary Islands (Irvine and Chamberlain, 1999; Wilson et al., 2004; Carro et al., 2014), usually constituting maerl beds (Potin et al., 1990; Foster, 2001; Martin et al., 2006; Savini et al., 2012; Basso et al., 2017). Here, it forms rhodoliths as unattached branches (Basso et al., 2016) with obvious banding in longitudinal sections (Basso, 1995b). These characteristics combine to make this species a suitable model for the measurement of geochemical proxies, comparing different environmental settings. In this paper, w~~We test the influence of temperature and growth rate on the B/Ca ratio, which could be crucial in assessing the reliability of B/Ca as a proxy of the seawater carbonate system.~~B/Ca ratio versus the temperature proxies and the growth rates in order to evaluate their effects on B incorporation, which, indeed, could distort the B signal used for paleoclimate reconstructions~~.

2 Materials and methods

2.1 Sampling sites and collection of *Lithothamnion corallioides*

135   Samples of the coralline algaCA *L. corallioides* were collected in the Western Mediterranean Sea and in the Atlantic Ocean (Fig. 1). In the Mediterranean Sea, the samples collected in Pontian Islands (Italy) at 66 m depth were gathered by grab during the cruises of the R/V Minerva Uno, in the framework of the Marine Strategy Campaigns 2017 (Table 1). The last two Mediterranean samples were collected by one of the authors (DB) by SCUBA diving during local surveys at 45 m off the coasts of Pomonte (Elba Island, Italy) (Basso and Brusoni, 2004) and at 40 m depth in the Aegadian Islands (Marettimo, Italy).

140   The Atlantic sample was collected by grab at 12 m depth in Morlaix Bay (Brittany, France) (Table 1).
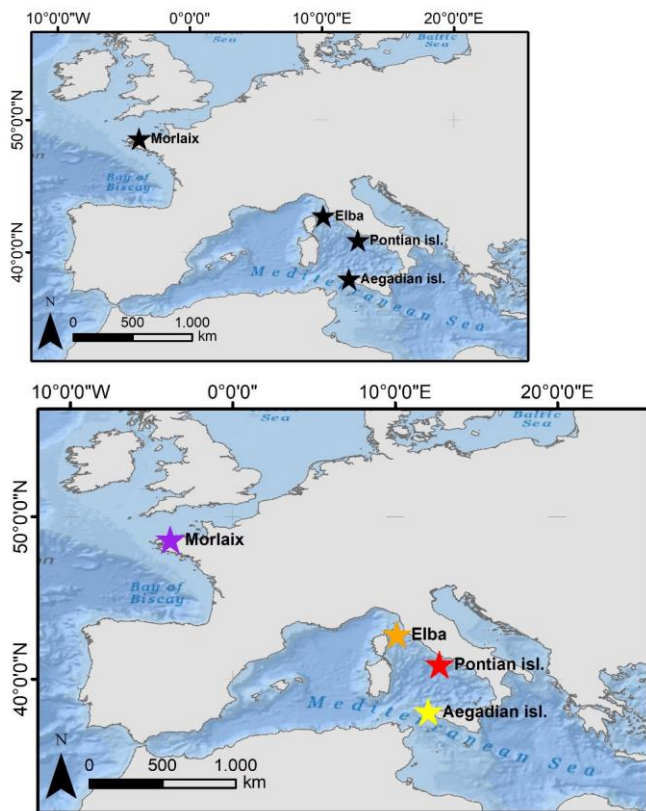
Figure 1: Map showing the distribution of sampling sites where *Lithothamnion corallioides* samples were collected: Morlaix Bay (48°34'42''N, 3°49'36''W); Aegadian Islands (37°97'36''N, 12°14'12''E); Elba (42°44'56.4''N, 10°07'08.4''E) and Pontian Islands (40°54'N, 12°45'E). Service layer credits: Source Esri, GEBCO, NOAA, National Geographic, Garmin, geonames.org and other contributors.

Table 1: *Lithothamnion corallioides* samples used in trace elements analyses.

Sampling site	Longitude/Latitude	Water depth (m)	Collection date
Aegadian Isl.	37°97'36''N, 12°14'12''E	40	25/08/1993
Elba	42°44'56.4''N, 10°07'08.4''E	45	01/12/1990
Morlaix	48°34'42''N, 3°49'36''W	12	02/05/1991
Pontian Isl.	40°54'N, 12°45'E	66	14/07/2017

The identification of the algal samples was achieved by morphological analyses of epithallial and perithallial cells using a Field Emission Gun Scanning Electron Microscope (SEM-FEG) Geomini 500 Zeiss. Samples were prepared for SEM according to Basso (1995a). Morphological identification was based on Adey & McKibbin (1970) and Irvine & Chamberlain (1994). Other information about maerl species distribution in Morlaix was provided by Carro et al. (2014) and Melbourne et al. (2017). *L. corallioides* was selected as the target species because of its presence in both Mediterranean and Atlantic waters. The samples selection started from a much wider collection than the one eventually selected for the chemical analyses. Particularly, the Atlantic sample (Morlaix) was used as voucher specimen for the subsequent identification of the Mediterranean samples, since *Phymatolithon* spp. and *L. corallioides* are the only major components of the Morlaix maerl in the Atlantic maerl (Hall-Spencer et al. 2010; Carro et al., 2014; Melbourne et al., 2017). Hence, once its inclusion under excluded the belonging to the genus *Phymatolithon* was excluded, the Morlaix sample identified as *L. corallioides* was used as a reference for the most reliable identification of the other Mediterranean samples.

2.2 Sample preparation

The selected algal branches were embedded included in Epo-Fix resin, which was stirred for 2 minutes with a hardener (13% w/w); they treated samples were then left do dry kept drying at room temperature for 24 hours. Afterwards, the treated included branches were cut by an IsoMet diamond wafering blade 15HC along the direction of growth. In the laboratory of the Institute of Geosciences and Earth Resources (IGG) of the National Research Council (CNR) in Pavia (Italy), the sections were polished with a MetaServ Grinder-Polisher (400 RPM) using a diamond paste solution, finally cleaned ultrasonically in distilled water for 10 minutes and dried at 30°C for 24 hours.

2.3 Trace elements analyses and environmental data

LA-ICP-MS analyses were carried out at the IGG-CNR laboratory of Pavia (Italy), on one algal branch per sampling site. ^{43}Ca, ^{7}Li, ^{25}Mg, ^{88}Sr and ^{11}B contents were measured using an Agilent ICP-QQQ 8900 quadrupole ICP-MS coupled to an Excimer laser ablation system (193 nm wavelength). Element/Ca ratios were calculated for these from the above cited isotopes, as well

170   as Mg/Li ratio~~in agreement with Yu et al., (2005) and Darrenougue et al., (2014)~~. Measurements were performed with laser energy densities of 4 J/cm² and helium as carrier gas. The laser transects crossed the algal growth direction with a spot size of 50 μm, targeting each growth band change which marked the transition between the cells usually produced in the warm season and those usually produced in the cold season, hereinafter referred to as long and short cells (Fig. 2, S1). NIST 612 was used as an external standard (e.g. Fietzke et al., 2010; Jochum et al., 2012), whereas Ca was adopted as an internal standard.

175   Accuracy and precision were higher than 4% and 8% respectively. Each analysis was carried out in MS/MS mode for 3 minutes by acquiring 60 seconds of background before and after the sampling period by the laser on the polished surface. ~~NIST 612 was used as an external standard whereas Ca was adopted as an internal standard.~~ The first part of the signal was not used for the integration to avoid surface contamination. The Glitter software (v. 4.4.4) was used for data reduction.

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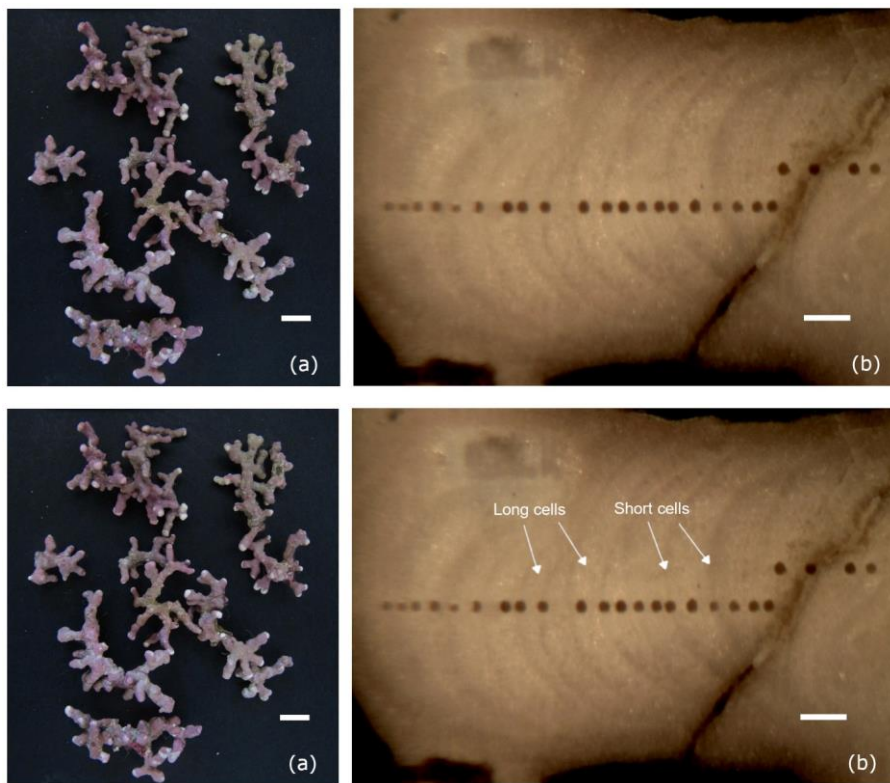
Figure 2: (a) Thalli of *Lithothamnion corallioides* collected in Morlaix (scale bar = 5 mm). (b) Longitudinal section through the *L. corallioides* branch sampled in Morlaix showing the LA-ICP-MS transects targeting each growth bands (scale bar = 200 μm).

In the absence of in-situ environmental data, the seawater temperature ~~data~~ ha~~s~~ve been extracted by ~~at least~~ 11 years of monthly reanalysis spanning 1980-2017 from ORAS5 (Ocean ReAnalysis System 5), at 0.25-degree horizontal resolution (Zuo et al., 2019). The time interval of extraction (11 years) approximately covered the period of algal growth crossed by the laser transects. ~~The nearest sea point of the three-dimensional numerical grid was considered for each sample location. Details of the time interval considered for each sampling site are shown in Table 2.~~ Minimum, maximum and mean values, as reported in Table 1~~2~~, refer to the temperature at sampling depth and have been measured on the entire time interval of extraction~~for which the data have been extracted~~. The amplitude of seawater temperature variation (ΔT) represents the temperature fluctuations during the algal growth and has been measured as the difference between the maximum and minimum temperature registered over 11 years.

All the elements were plotted against the average seawater temperature values of the coldest and warmest months in Morlaix Bay. Missing element ratios were calculated as the means of known values.

Carbon system parameters~~data~~ for~~in~~ each ~~sampling~~ site have also been estimated~~xtracted~~. Even if t~~T~~hey were not available in the same time interval of temperature data~~,~~. ~~Nevertheless,~~ the seasonal variations occurring in the extracted period have allowed the characterization of the sampling sites. Monthly mean seawater pH has been derived by the CMEMS (E.U. Copernicus Marine Service Information) global biogeochemical hindcast spanning 1993-2018, at 0.25-degree horizontal resolution. Monthly means of DIC in 2019 and 2020 have been extracted by CMEMS biogeochemical analysis and forecasts for the Mediterranean Sea, at 0.042-degree horizontal resolution (Salon et al., 2019; Bolzon et al., 2020). In the Atlantic site, monthly means of DIC in 2019 and 2020 were derived from CMEMS IBI biogeochemical forecasts, at 0.028-degree horizontal resolution. ~~covering the years 2019-2020.~~ The pH and DIC data showed consistent variations among sites, despite being derived from different biogeochemical models. Minimum, maximum and mean values of DIC, as reported in Table 2, refer to sampling depth and have been measured on the entire time interval of extraction.

2.4 Growth rate estimation

Growth rates were estimated under light microscope by ~~microscopical analysis,~~ measuring the length of the LA-ICP-MS transect and dividing it by the number of annual growth bands. The obtained values, expressed in linear extension over year (mm/yr), were cross-referenced with Mg/Ca results in order to check for the correspondence of Mg peaks with growth bands. This step was helpful in highlighting faint bands and to achieve a more reliable estimate of the algal growth. Intermediate Mg/Ca values, indeed, would probably correspond to middle seasons. Short cells were referred to slow-growing cells in dark bands, usually produced in the cold season; long cells corresponded to fast-growing cells in light bands, usually produced in the warm season (Kamenos et al., 2009; Ragazzola et al., 2016).

2.5 Data elaboration and statistical analyses

Statistics were performed on both the dataset with all the spot analyses and the dataset with the records from long and short cells separately.

215 For each spot, a distinction between long and short cells was made by image analyses meant to distinguish the dark growth bands from the light ones and comparing the results with those obtained by the Mg/Ca ratio measurement. Data from faint bands had been excluded from the dataset.

The Spearman's correlation was tested to provide the statistical comparisons between Mg/Ca, Li/Ca, Sr/Ca and B/Ca records from the LA-ICP-MS analyses in *L. corallioides*. The Kruskal-Wallis test followed by the Dunn's test for comparisons and

220 the One-way ANOVA followed by the Tukey's test for post-hoc analysis were used to compare the geochemical signals among sampling sites and to evidence the differences between group medians and means. All statistical analyses were run in R 3.6.3 software.

3 Results

3.1 Environmental data

225 The temperature data obtained by ORAS5 reanalysis revealed a lower ~~temperature~~amplitude of the seasonal temperature ~~change~~excursion in the Mediterranean samples with respect to the Atlantic one, as shown by the standard deviation and ΔT values in Table 1~~2~~. This difference is explained in terms of the different sampling depths, with the seasonal variations decreasing with increasing depth.

Temperature variations in Morlaix Bay~~the~~ (Atlantic Ocean~~)~~ were higher~~, estimated at 8.90 °C in Morlaix bay (France)~~

230 ~~(minimum monthly mean 8.28 °C and maximum 17.18 °C)~~, registering overall a mean seawater temperature of 12.4~~34~~ °C (Table 1~~2~~). Among Mediterranean samples, mean seawater temperatures were highest in the Aegadian Isl. ~~(16.18 °C)~~, followed by the Elba ~~(14.99 °C)~~ and the Pontian Isl. ~~(14.89 °C)~~ (Table 1~~2~~). Aegadian Isl. also registered the highest temperature variations among the Mediterranean sites ~~(6.07 °C), with the lowest monthly mean of 13.57 °C and the highest of 19.64 °C~~ (Table 1~~2~~). Moderate temperature variations characterized the site in Elba ~~(4.61 °C)~~, which registered the lowest monthly mean

235 temperature among Mediterranean sites ~~(12.88 °C) and the maximum temperature of 17.49 °C~~ (Table 1~~2~~). At the Pontian Isl., consistently with the fact that it is the deepest sampling site at 66 m depth, the lowest seawater temperature variations were found ~~(3.37 °C), with minimum values of 13.34 °C and maximum of 16.70 °C~~ (Table 1~~2~~). The pH estimates at the Mediterranean sites were all similarly high ~8.13 and less variable than the Atlantic site (8.06). The mean pH had slightly higher ~~mean~~ values in Pontian Isl. and Elba ~~(8.13)~~, than~~decreasing in~~ Aegadian Isl. ~~(8.11) and reaching the lowest value in the~~

240 ~~Atlantic Ocean (Morlaix; 8.06)~~ (Table 1~~2~~). Similarly, DIC was higher in the Mediterranean sites and decreased in Morlaix, as this is largely dictating the pH~~Pontian Isl. and Elba (2.32 mol/m³), followed by Aegadian Isl. (2.29 mol/m³) and eventually Morlaix (2.17 mol/m³)~~ (Table 1~~2~~).

Table 2: Environmental data in each sampling site. The minimum and maximum monthly means of temperature are indicated, as well as the highest temperature variation (ΔT), the mean and the standard deviation of the time series. Data from monthly means extracted by 11 years of ORAS5 reanalysis. pH and DIC in each sampling site are also indicated. The minimum, maximum, mean, and standard deviation values have been measured on the time interval 2019-2020. Carbonate system parameters have been extracted from monthly means biogeochemical data provided by CMEMS. ~~(a) Seawater temperature records in each sampling site. The minimum and maximum monthly means of temperature are indicated, as well as the highest temperature variation (ΔT), the mean and the standard deviation of the time series. Data elaborated using the monthly means data extracted by the ORAS5 reanalysis for the time intervals indicated in the last column. (b) pH and DIC data in each sampling site. The minimum, maximum, mean and standard deviation values measured on the time interval 2019-2020 are indicated. Data extracted from monthly means biogeochemical data provided by CMEMS.~~

Sampling site	Depth (m)	Collection date	Temperature (°C)					pH		DIC (µmol/kg)		Growth rates (mm/yr)
			min	max	ΔT	mean	st. dev.	mean	st. dev.	mean	st. dev.	
Aegadian Isl.	40	25/08/1993	13.7	19.0	5.3	16.1	1.4	8.11	0.02	2292.94	8.11	0.13
Elba	45	01/12/1990	12.9	17.5	4.6	15.0	1.2	8.13	0.02	2320.48	6.48	0.14
Pontian Isl.	66	14/07/2017	13.3	16.7	3.4	14.9	0.6	8.13	0.01	2318.50	3.90	0.10
Morlaix	12	02/05/1991	8.3	17.2	8.9	12.4	2.5	8.06	0.04	2165.59	9.62	0.13

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(a)	Sampling site	Temperature (°C)					Time interval
	-	min	max	ΔT	mean	st. dev.	
	Aegadian Isl.	13.57	19.64	6.07	16.18	1.38	1986-2017
	Elba	12.88	17.49	4.61	14.99	1.21	1980-1991
	Morlaix	8.28	17.18	8.90	12.34	2.46	1980-1992
	Pontian Isl.	13.34	16.70	3.37	14.89	0.62	1986-2017

(b)	Sampling site	pH		DIC (mol/m³)	
	-	mean	st. dev.	mean	st. dev.
	Aegadian Isl.	8.11	0.02	2.29	0.01
	Elba	8.13	0.02	2.32	0.01
	Morlaix	8.06	0.04	2.17	0.01
	Pontian Isl.	8.13	0.01	2.32	0.00

3.2 Mg/Ca, Li/Ca, Sr/Ca and Mg/Li

Both Li/Ca and Sr/Ca records had positive correlations with Mg/Ca in our samples of *L. corallioides* ~~(respectively r=0.68, p<<0.001 and r=0.64, p<<0.001)~~ (Fig. 3).

The overall mean Mg/Ca was 225.3 ± 30.4 mmol/mol, registering the minimum value in the sample from Aegadian Isl. (171.7 mmol/mol) and the maximum value in Morlaix (311.2 mmol/mol) (Fig. 4; Table 2).

The Kruskal-Wallis test did not show significant differences in Mg/Ca among samples (~~p>0.05;~~ Table A1;, Fig. 4). Among Mediterranean sites, the algal sample coming from Aegadian Isl. had the highest Mg/Ca mean value ~~(224.9 ± 30.3 mmol/mol),~~

followed by Elba ~~(223.4 ± 26.4 mmol/mol)~~ and Pontian Isl., which had the lowest Mg/Ca mean value of all sampling sites ~~(216.1 ± 21.9 mmol/mol)~~ (Fig. 4). The highest mean Mg/Ca was registered in the sample from Morlaix bay ~~(239.5 ± 41.2 mmol/mol)~~, which also showed a large dispersion of data above the median~~the widest oscillation of~~ Mg/Ca value~~s~~ (Fig. 4).

265

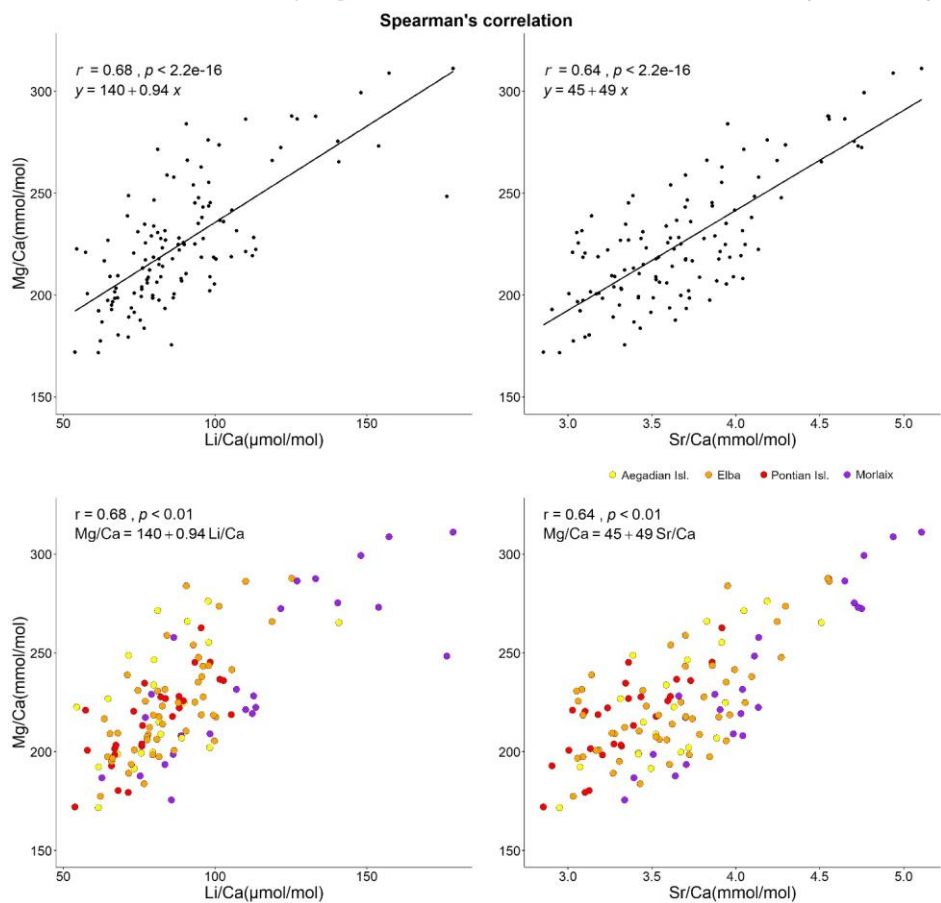



Figure. 3:. Correlation plots of Mg/Ca with Li/Ca and Sr/Ca. For each analyses the Spearman's coefficient r, the p-value and the line equation are given.

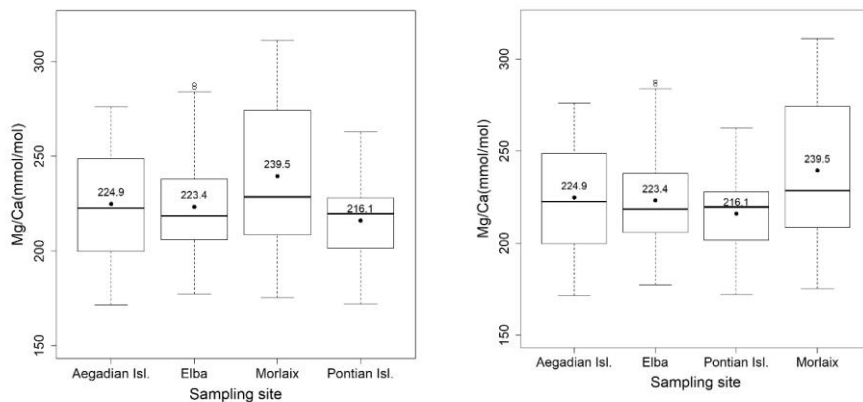



Figure 4: B~~ox~~**ar plot of the statistical tests performed to evaluate the differences of Mg/Ca in *L. corallioides* collected in different sampling sites. The horizontal black lines indicate the median values. The black filled circles and the numbers inside the plot indicate the mean values.**

Long cells had~~were identified as spots with~~ high Mg/Ca values; c~~and positioning on light growth bands. C~~onversely, short cells ~~were located in dark growth bands and~~ corresponded to areas with low Mg/Ca ratio.

The ANOVA test followed by the Tukey's test for multiple comparisons evidenced a significant variability of algal Mg/Ca among 3 sites in long cells (Table A2; Fig. 5). In the long cells of *L. corallioides* collected from Aegadian Isl. and Pontian Isl., the Mg/Ca data showed quite similar distribution (Table A2; Fig. 5). The Mg/Ca of the alga from Pontian Isl. was the lowest ~~(236.6 ± 14.0 mmol/mol)~~ (Fig. 5). In Morlaix a higher Mg/Ca mean value ~~(285.8 ± 18.0 mmol/mol)~~ was registered, significantly different compared to Aegadian ~~(247.5 ± 21.9 mmol/mol)~~ and Pontian Isl. (~~p≤0.001,~~ Table A2; Fig. 5). In short cells, the differences in Mg/Ca among samples were not statistically significant (Table A1~~p>0.05~~). The magnesium incorporation was slightly higher in Morlaix ~~(207.6 ± 18.6 mmol/mol)~~ and very similar between Aegadian and Pontian Isl. samples ~~(respectively 197.2 ± 12.8 mmol/mol and 196.8 ± 15.9 mmol/mol)~~ (Fig. 5).

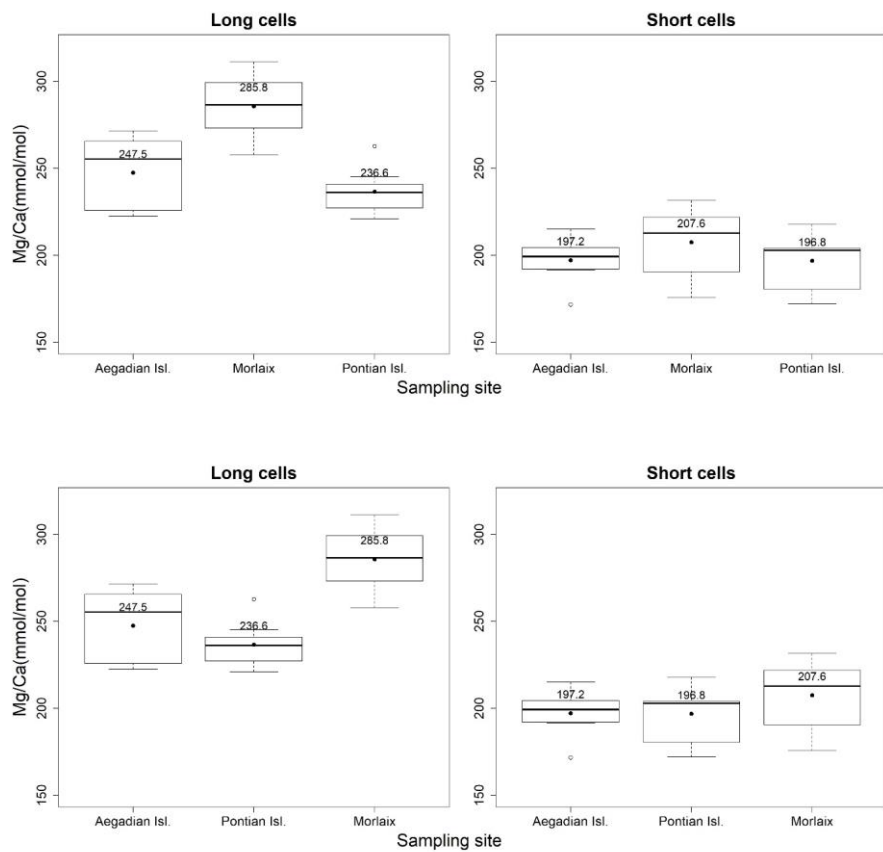



Figure 5: B~~oxar~~ **plot**s **of the statistical tests performed to evaluate the differences of Mg/Ca in the warm and cold cells of** *L.*
corallioides **collected in different sampling sites. The horizontal black lines indicate the median values. The black filled circles and**
the numbers inside the plot indicate the mean values.

Mg/Li values in long and short cells fell in the range found by Anagnostou et al. (2019) for cultured *Clathromorphum*
compactum (Fig. 8). When plotted against the extracted seawater temperature in Morlaix (Fig. 9), Mg/Li results did not reflect
the seasonal oscillations in temperature.

290

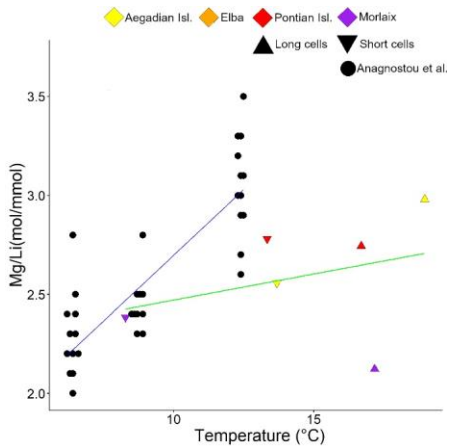



Figure 6: Correlation plot between Mg/Li and seawater temperature. Data are shown for cultured *C. compactum* (Anagnostou et al., 2019) and *L. corallioides* (this paper). *L. corallioides* results are shown separately in long and short cells, per sampling site.

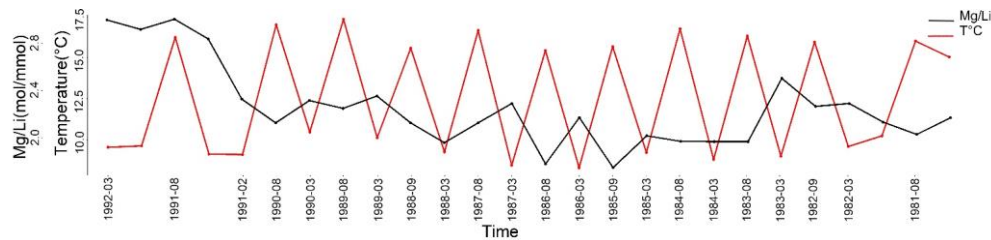



**Figure 7: Mg/Li ratio of *L. corallioides* collected in Morlaix Bay. Note the lack of cyclic variations in Mg/Li results. In the timeline,
295 the coldest and the warmest months have been reported. Mg/Li in the missing bands have been calculated as the means of the values
measured in warm and cold periods. Monthly means of seawater temperature have been extracted by ORAS5 reanalysis.**

3.3 B/Ca

The B/Ca ratio in the sample collected from Morlaix showed a moderate positive correlation with all the examined temperature
300 proxies (Mg/Ca, Li/Ca, Sr/Ca), with a more defined trend when plotted against Li/Ca (r=0.68, ~~p<0.001~~) and slightly less
defined against Mg/Ca (r=0.58, ~~p<0.01~~) and Sr/Ca (r=0.57, ~~p<0.01~~) (Fig. 86). On the contrary, the Spearman's analyses did
not evidence significant correlations between B/Ca and the temperature signals in the algae collected elsewhere (p>0.05).

Overall, the B/Ca ratio in *L. corallioides* was 661.9 ± 138.9 μmol/mol, registering the minimum value in the long cells of the sample from Pontian Isl. (356.0 μmol/mol) and the maximum value in Elba (954.1 μmol/mol) (Fig. ~~9~~7: Table 2).

305 The Kruskal-Wallis coefficient showed~~evidenced~~ a highly significant difference in the B/Ca value among sites ~~(p<<0.0001)~~, particularly in the *L. corallioides* from the Pontian Isl., which had the lowest boron incorporation ~~(a mean B/Ca of 462.8 ±~~ ~~49.2 μmol/mol)~~ (Table A3; Fig. ~~9~~7). The algae collected in Aegadian Isl. had still significantly lower B/Ca compared to those collected in Elba and Morlaix~~; a mean of 610.8 ± 63.9 μmol/mol~~ (Table A3; Fig. ~~9~~7). The highest B/Ca mean value was registered in Elba ~~(757.7 ± 75.5 μmol/mol)~~, with medians comparable to Morlaix ~~(726.9 ± 102.8 μmol/mol by mean)~~ (Table

310 A3; Fig. ~~9~~7).

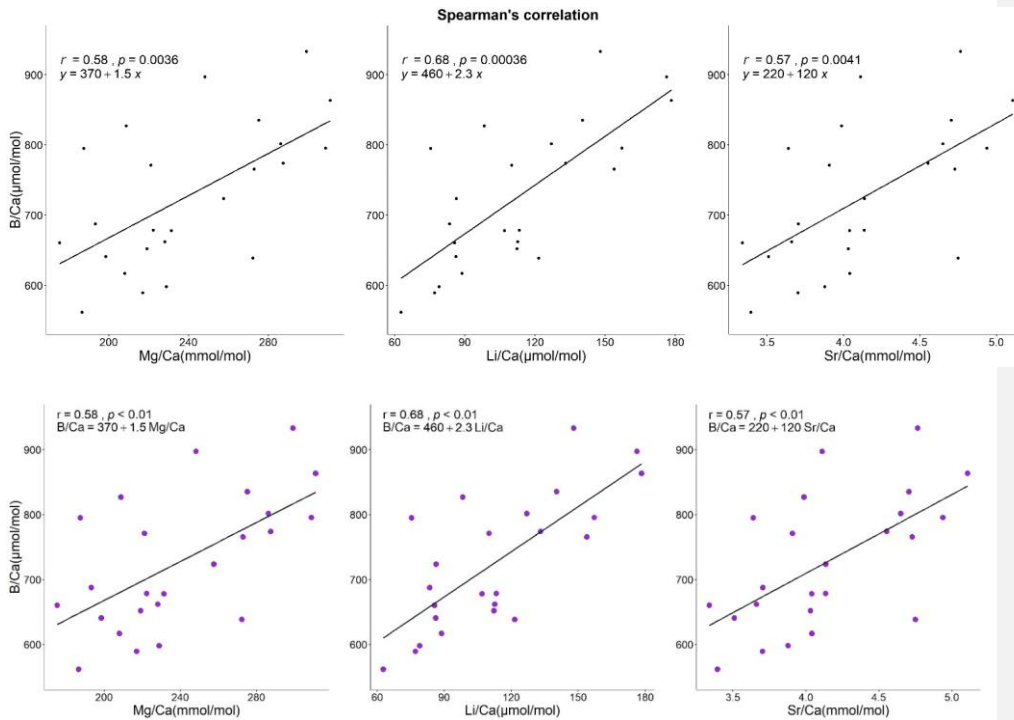



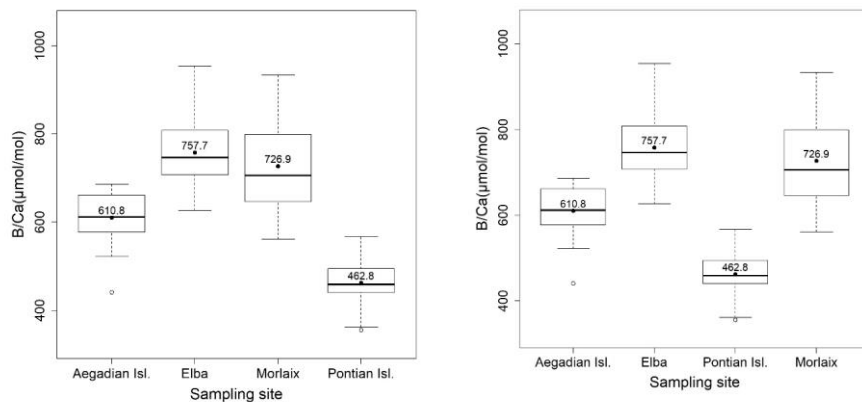
Figure 8~~6~~: Correlation plots of B/Ca with Mg/Ca, Li/Ca and Sr/Ca in *L. corallioides* collected in Morlaix bay. For each analyses the Spearman's coefficient r, the p-value and the line equation are given.

315

Figure 9~~7~~: B~~ox~~ar plot of the statistical tests performed to evaluate the differences of B/Ca in *L. corallioides* collected in different sampling sites. The horizontal black lines indicate the median values. The black filled circles and the numbers inside the plot indicate the mean values.

The ANOVA test followed by the Tukey's test for multiple comparisons by site, for long (Table A4) and short cells (Table

320 A5) separately, showed lower values in the Mediterranean sites and higher values in the Atlantic site~~analogous trend~~ (Fig. 10~~8~~).

The algal cells from Pontian Isl. had the lowest mean B/Ca in both seasons ~~(466.7 ± 58.9 µmol/mol in long cells and 460.8 ± 28.6 µmol/mol in short cells)~~, being significantly different from both the samples from Morlaix and Aegadian Isl. (Table A4, A5; Fig. 10~~8~~). Morlaix had the highest mean B/Ca in both long ~~(792.3 ± 83.8 µmol/mol)~~ and short cells ~~(660.7 ± 69.3~~

325 ~~µmol/mol)~~ (Table A4, A5; Fig. 10~~8~~). *L. corallioides* from Aegadian Isl. had intermediate B/Ca mean value in long cells ~~(602.1 ± 93.5 µmol/mol)~~, differing significantly from both the Morlaix and Pontian Isl. samples (Table A4; Fig. 10~~8~~). In short cells, the sample from Aegadian Isl. slightly differed from the one in Morlaix~~, incorporating 617.7 ± 53.6 µmol/mol of boron by mean~~ (Table A5; Fig. 10~~8~~).

Interestingly, the long cells of all samples had higher median B/Ca values compared to short cells (Fig. 10~~8~~), although only in

330 Morlaix, the differences between B/Ca measured in long and short cells were statistically significant (χ^2=8.4899, p<0.01~~=0.0036~~).

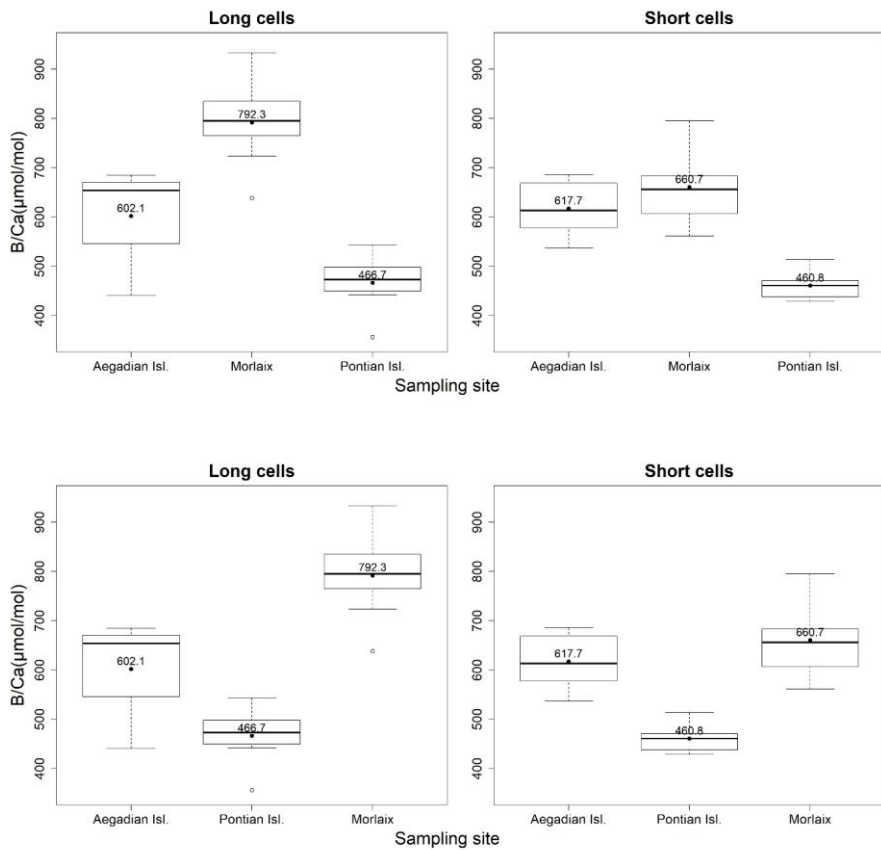



Figure 108: B~~ox~~ar plot~~s~~ of the statistical tests performed to evaluate the differences of B/Ca in the warm and cold cells of *L. corallioides* collected in different sampling sites. The horizontal black lines indicate the median values. The black filled circles and the numbers inside the plot indicate the mean values.

Table 2: Element/Ca ratio measurements in *L. corallioides*.

Sampling site	B/Ca (µmol/mol)		Mg/Ca (mmol/mol)		Li/Ca (µmol/mol)		Sr/Ca (mmol/mol)		Mg/Li (mol/mmol)	
	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.	mean	st. dev.
Aegadian Isl.	610.8	63.9	224.9	30.3	81.9	18.4	3.7	0.4	2.8	0.5

Elba	757.7	75.5	223.4	26.4	85.2	14.3	3.6	0.4	2.7	0.3
Pontian Isl.	462.8	49.2	216.1	21.9	79.6	14.6	3.3	0.3	2.8	0.4
Morlaix	726.9	102.8	239.5	41.2	113.1	32.9	4.1	0.5	2.2	0.4
total	**661.9**	**138.9**	**225.3**	**30.4**	**89.0**	**23.3**	**3.7**	**0.5**	**2.6**	**0.4**

3.4 Growth rates

340 In the sample from Aegadian Isl., the LA-ICP-MS transect was 1.31 mm long and 10 years of growth have been detected by coupling microscopical imaging and Mg/Ca peaks, resulting in 0.13 mm/yr of growth rate. In the Elba sample the laser transect was 1,15 mm long, crossing 8 years of growth, with a resulting growth rate of 0.14 mm/yr. The Pontian Isl. sample had 1.08 mm of transect including 11 years of growth, hence a growth rate of 0.10 mm/yr. Finally, the transect from Morlaix sample was 1.38 mm long, counting 11 years and resulting in 0.13 mm/yr of growth rate.

345 Growth rates did not show any linear relationship with Mg, Li and Sr/Ca, but they were positively correlated with the samples mean B/Ca values (Fig. 119).

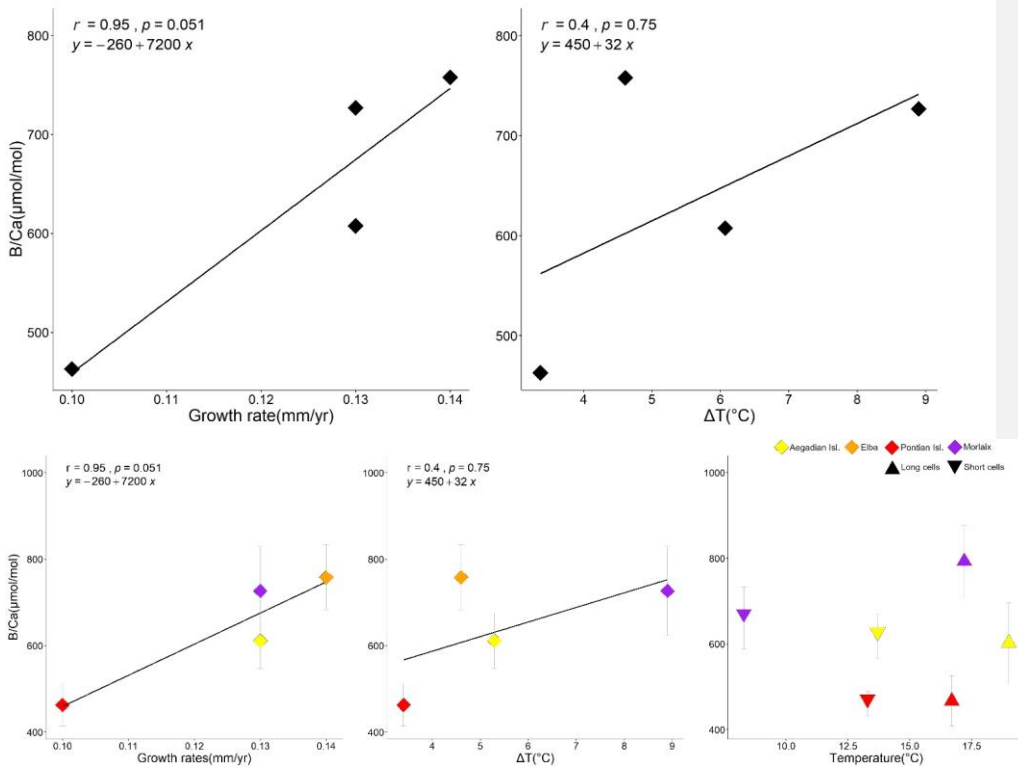



Figure 119: Correlation plots of growth rates and seawater temperature with B/Ca in *L. corallioides* samples analysed in this study. Spearman's coefficient r, the p-value and the line equation are given. Temperature variations (ΔT) correspond to the differences between the maximum and minimum temperature registered over 11 years of monthly reanalysis (ORAS5). The B/Ca means measured in long and short cells correspond respectively to the maximum and minimum temperature. ~~Correlation plots of growth rates and seawater temperature variations (ΔT) with B/Ca in L. corallioides samples analysed in this study. Spearman's coefficient r, the p-value and the line equation are given.~~

4 Discussion

In general, temperature variations affect many physiological processes involved in the biomineralization, and the rate of calcification, along with the preservation state of mineral structures, influences the content of trace elements in carbonates, ~~along with the preservation state of mineral structures~~ (Lorens, 1981; Rimstidt et al., 1998; Gussone et al., 2005; Noireaux et al., 2015; Kaczmarek et al., 2016). Trace elements concentrations recorded from the four *L. corallioides* branches analysed in

360   this study were consistent with previously published values for other calcareous red algae (Chave, 1954; Hemming and Hanson, 1992; Hetzinger et al., 2011; Darrenougue et al., 2014). Particularly, the range of Mg/Ca ratios resulted in this study extended from 172 to 311 mmol/mol, comparable to previous studies on rhodoliths of *Lithothamnion glaciale* Kjellman 1883 grown at 6-15 °C (148-326 mmol/mol) (Kamenos et al., 2008). The B/Ca ratios in *L. corallioides* from our results range from 356 to 954 μmol/mol, higher than the range measured in *Neogoniolithon* sp. (352-670 μmol/mol) (Donald et al., 2017) and *C.*

365 *compactum* (320-430 μmol/mol) (Anagnostou et al., 2019), both cultured with controlled pCO$_2$ and a pH ranging from 7.2 to 8.2. The high resolution given by laser ablation should be more effective in measuring the heterogeneity of B/Ca across the thallus, thus explaining the wider range of our data.

In order to provide high-resolution geochemical data on long and short cells separately, we considered only the results from

370 the spots where ~~the positive/negative Mg/Ca peaks correspond respectively to~~ the light/dark bands resulting from the image analyses corresponded to obvious Mg/Ca peaks. Hence, laser spots lying on faint bands and with intermediate Mg/Ca peaks were discarded, as probably belonging to middle seasons~~light bands and with positive Mg/Ca peaks were identified as long cells; short cells were instead those included in dark bands and with negative Mg/Ca peaks~~. Thanks to this expedient, we also avoided artefacts due to the Mg/Ca heterogeneity across the algal thallus (Fietzke et al., 2015; Nash and Adey, 2017a, b). In

375 the sample from Elba the growth bands were not clearly visible, preventing the analyses of trace elements on long and short cells separately (Fig. S1).

The ~~results of the statistical analyses on~~ Mg/Ca results evidenced a strong relationship with the seawater temperatures extracted from ORAS5 (Table 1~~2~~; Fig. 12), as expected. *L. corallioides* from Aegadian Isl. had slightly higher Mg/Ca values, followed by Elba and Pontian Isl. (Fig. 4). This was consistent with local temperature values in the Mediterranean (Table 1~~2~~), since

380 Pontian Isl. registered the lowest mean value ~~(14.89 °C)~~ and the lowest ~~temperature variation (ΔT) (3.37°C)~~, while Aegadian Isl. showed the highest mean temperature ~~(16.18 °C)~~ and ΔT ~~(6.07°C)~~.

On the contrary, the sample from Morlaix, collected at 12 m depth, showed high Mg/Ca values in both long and short cells (Table A2; Fig. 5). The monthly mean temperatures had the highest variations during the year (ΔT in Table 1~~2~~), due to the shallow depth (12 m). Temperature correlates~~covaries with irradiance and both correlate~~ to seasons, influencing~~which~~

385 ~~influence~~ primary production, respiration and calcification in *L. corallioides* (Payri, 2000; Martin et al., 2006) as well as other calcareous red algae~~CA~~ (Roberts et al., 2002). The high seasonality that characterized the sample from Morlaix, represented by the high ΔT (Table 1), was probably responsible for the highest variation of Mg/Ca values and undoubtedly accounted for most of the differences with Mediterranean samples.

For the first time, we confirmed here the reliability of the temperature proxies Li/Ca and Sr/Ca on a wild-grown~~deep-water~~

390 ~~Mediterranean CA,~~ coralline alga collected at different depths and locations.

~~Trace elements concentrations recorded from the four~~ *L. corallioides* ~~branches analysed in this study were consistent with previously published values for other CA (Chave, 1954; Hemming and Hanson, 1992; Hetzinger et al., 2011; Darrenougue et al., 2014). Particularly, the range of Mg/Ca ratios resulted in this study extended from 172 to 311 mmol/mol, comparable to~~

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previous studies on rhodoliths of *Lithothamnion glaciale* Kjellman 1883 grown at 6-15 °C (148-326 mmol/mol) (Kamenos et al., 2008).

The B/Ca ratios in *L. corallioides* from our results range from 356 to 954 µmol/mol, higher than the range measured in *Neogoniolithon* sp. (352-670 µmol/mol) (Donald et al., 2017) and *C. compactum* (320-430 µmol/mol) (Anagnostou et al., 2019), both cultured with controlled pCO₂ and a pH ranging from 7.2 to 8.2. The paucity of B/Ca measurements from CA and, most of all, the complete absence of these data on wild deep-water specimens make it difficult to compare our B/Ca data with the literature. This evidence takes stock of the significance of our results and emphasizes the importance of collecting more representative B/Ca data in CA. Nevertheless, Elba and Morlaix samples appeared to have extremely out of range B/Ca values (Fig. 7), compared to the range measured by Donald et al. (2017) and Anagnostou et al. (2019), suggesting the presence of diverse factors.

In general, temperature variations affect many physiological processes involved in the biomineralization and the rate of calcification influences the content of trace elements in carbonates, along with the preservation state of mineral structures (Lorens, 1981; Rimstidt et al., 1998; Gussone et al., 2005; Noireaux et al., 2015; Kaczmarek et al., 2016).

For the first time, we confirmed here the reliability of the temperature proxies Li/Ca and Sr/Ca on a deep-water Mediterranean CA. The results of the statistical analyses on Mg/Ca evidenced a strong relationship with the seawater temperatures extracted from ORAS5 (Table 2), as expected. *L. corallioides* from Aegadian Isl. had slightly higher Mg/Ca values, followed by Elba and Pontian Isl. (Fig. 4). This was consistent with local temperature values in the Mediterranean (Table 2), since Pontian Isl. registered the lowest mean value (14.89 °C) and the lowest temperature variation (ΔT) (3.37°C), while Aegadian Isl. showed the highest mean temperature (16.18 °C) and ΔT (6.07°C).

On the contrary, the sample from Morlaix, collected at 12 m depth, showed high Mg/Ca values in both long and short cells (Table A2; Fig. 5). The monthly mean temperatures had the highest variations during the year (ΔT in Table 2), due to the shallow depth (12 m). Temperature covaries with irradiance and both correlate to seasons, which influence primary production, respiration and calcification in *L. corallioides* (Payri, 2000; Martin et al., 2006) as well as other CA (Roberts et al., 2002). The high seasonality that characterized the sample from Morlaix, was responsible for the highest variation of Mg/Ca values and undoubtedly accounted for most of the differences with Mediterranean samples.

Li/Ca and Sr/Ca records were positively correlated with Mg/Ca in *L. corallioides* (Fig. 3), which, in turn, showed a strong relationship with seawater temperature. Moreover, both Li and Sr/Ca showed periodical oscillations in correspondence to long and short cells, related to seasonal temperature variations (Fig. 12). Therefore, Li/Ca and Sr/Ca could be regarded as temperature proxy in *L. corallioides*, as for Mg/Ca. The coupling of the Mg/Ca ratio with Li/Ca and Sr/Ca represents a multi-proxy approach that minimize the possible species effect and can be considered a useful tool to gather information about past temperature for paleoclimate reconstructions (Halfar et al., 2011; Caragnano et al., 2014; Williams et al., 2014; Fowell et al., 2016; Cuny-Guirriec et al., 2019).

The B/Ca ratio in coralline algae CA has been rarely measured and it is not clear how the environmental factors control its incorporation. The carbonate system primarily drives the changes in B incorporation (Hemming and Hanson, 1992; Yu and

Elderfield, 2007). In benthic foraminifera, B/Ca, indeed, increases with $[CO_3^{2-}]$ (Yu and Elderfield, 2007) and [DIC] (Uchikawa et al., 2015), whereas there is no consensus on the effect of $[CO_3^{2-}]$ on Mg/Ca and Sr/Ca in benthic foraminifera

430 (Rosenthal et al., 2006; Dueñas-Bohórquez et al., 2011). Nevertheless, in culture experiments of the coralline algae *Neogoniolithon* sp. (Donald et al., 2017) and corals (Gagnon et al., 2021), [DIC] had a negative effect on B/Ca. Tthe occurrence of lowhigh DIC concentrations in MorlaixElba (8.32 mol/m3) (Table 12), compared to the Mediterraneanmost of the other sampling sites, could therefore contribute to the high B/Cacaused the increase in B/Ca, but not in Mg/Ca and Sr/Ca. Our results showed indeed consistency between Sr/Ca and Mg/Ca data, without increased values in the sample from Elba. This evidence

435 would exclude both Mg/Ca and Sr/Ca dependence on DIC variations in the CA *L. corallioides*, contrarily to the results of Donald et al. (2017) in *Neogoniolithon* sp. and Keul et al. (2017) in foraminifera.

Nevertheless, based on the extracted pH and DIC data, results (Table 2) did not explain our B/Ca results in the samples from Morlaix and Pontian Isl. Ssignificantly higher values of B/Ca should be expected in the sample from Pontian Isl., similarly to the other Mediterranean sites (Table 1)with the same pH and DIC as Elba (8.13; 2.32 mol/m³), as well as lower values in the

440 sample from Morlaix, where pH and DIC were the lowest (respectively 8.06 and 2.17 mol/m³).
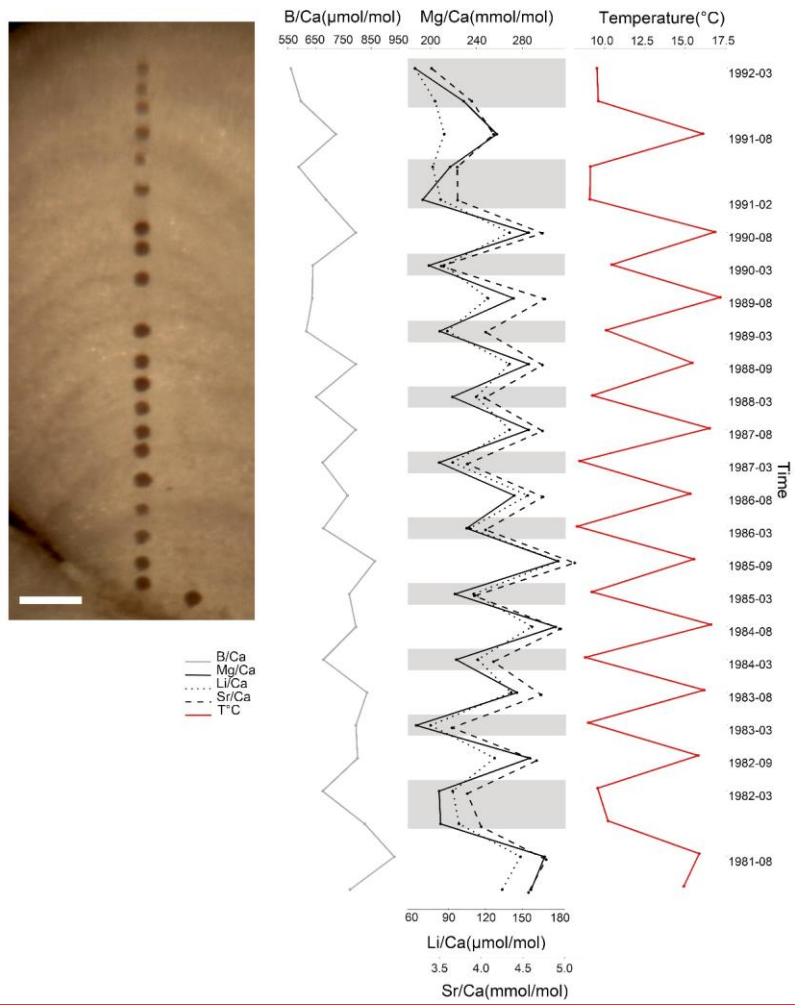
Figure 12: Elements ratio of *L. corallioides* collected in Morlaix Bay (scale bar = 200 µm). Mg, Li and Sr/Ca show cyclic variations the same as the local seawater temperature. In the timeline, the coldest and the warmest months have been reported, which correspond to dark and light bands of growth. Elements/Ca in the missing bands have been calculated as the means of the values measured in warm or cold periods. Monthly means of temperature have been extracted by ORAS5 reanalysis.

445

The estimated growth rate of *L. corallioides* was 0.13 ± 0.02 mm/yr and it was supposed to decrease with increasing depth as a direct consequence of a lower light availability (Halfar et al., 2011); indeed, the growth rate of the sample from Pontian Isl. was the lowest (0.10 mm/yr). As already suggested~~proved~~ by previous studies on both synthetic and biogenic calcite, B incorporation is likely affected by growth rate (Gabitov et al., 2014; Mavromatis et al., 2015; Noireaux et al. 2015; Uchikawa

450 et al., 2015; Kaczmarek et al., 2016). Indeed, in the cultured calcareous red alga ~~CA~~ *Neogoniolithon* sp. the B/Ca increases with increasing growth rate (Donald et al., 2017). In Pontian Isl., the slow growth rate could have~~probably~~ contributed to the low B/Ca values. T~~On the contrary, t~~he mean annual growth rate of the shallowest sample (Morlaix) was equal to the one in Aegadian Isl. (0.13 mm/yr). In Morlaix, the alga probably significantly slowed down the growth in cold months, when the monthly mean seawater temperature was the lowest of all the sampling sites ~~(8.28 °C)~~ (Table 1~~2~~). Nevertheless, its growth rate

455 likely speeded up in the warm season due to the abundant light availability at shallow depth and the warming of seawater (Table 1~~2~~), contributing to the significantly higher B/Ca values in long cells (Fig. 10~~8~~). According to this interpretation~~Thus~~, the effect of the growth rate on B/Ca might be significant across depth and geographical regions (Fig. 11)~~appeared evident from the shallowest to the deepest samples (Fig. 9), because of the positive correlation between growth rates and mean B/Ca values.~~

460 ~~Our results suggest that temperature is, in a way, related to B/Ca ratio in *L. corallioides*. Indeed, B/Ca ratio decreased with ΔT across depth (Fig. 7), with the exception of the Elba sample.~~ In Morlaix, B/Ca showed higher values in comparison with Aegadian Isl. and Pontian Isl. ~~(726.9 ± 102.8 µmol/mol)~~, and a positive correlation with temperature proxies (Mg/Ca, Li/Ca and Sr/Ca; Fig. 8~~6~~). A positive correlation between B/Ca and Mg/Ca was already observed in planktonic foraminifera (Wara et al., 2003; Yu et al., 2007).

465 In the sample from the Pontian Isl., the seasonal ΔT ~~(3.37°C)~~, Mg/Ca ~~(216.1 ± 21.9 mmol/mol)~~ and B/Ca ~~(462.8 ± 49.2 µmol/mol)~~ values were the lowest among sites. In particular, B/Ca was significantly low (Fig. 9~~7~~), differing more from the other samples than the results on Mg/Ca (Fig. 4)~~.,~~ This suggests~~ing~~ that in this sample the B incorporation should~~could~~ be influenced by ~~other~~ factors other than those affecting Mg. In general, the poor correlation with seawater temperature (Fig. 11~~9~~), and most of all the lack of distinct seasonal oscillations in B/Ca across the algal thallus (Fig. 12),~~especially in deep-water~~

470 ~~samples,~~ excludes the suitability of B/Ca as a temperature proxy and suggests a closer relationship with growth rate rather than temperature.

Knowing the biogeochemistry and the variation of the environmental parameters of seawater is crucial for a more comprehensive picture of the reliability of geochemical proxies, like the ones we investigated in this paper (Mg, Li, Sr/Ca and B/Ca). Boron incorporation in marine carbonates is still debated, rising questions about the boron isotopic fractionation, the

475 mechanisms of boron incorporation into marine carbonates, the so-called "vital effects" (i.e. the metabolic activities that can bias the isotopic signal), and the seawater isotopic composition. Moreover, t~~The~~ paucity of B/Ca measurements from coralline algae~~CA~~ and, most of all, the complete absence of these data on ~~wild deep-water~~ specimens grown in nature makes it difficult to compare our B/Ca data with the literature. This evidence takes stock of the significance of our results and emphasizes the importance of collecting more representative B/Ca data in coralline algae.~~CA. Nevertheless, Elba and Morlaix samples~~

480 ~~appeared to have extremely out of range B/Ca values (Fig. 7), compared to the range measured by Donald et al. (2017) and Anagnostou et al. (2019), suggesting the presence of diverse factors.~~

Further studies on *L. corallioides* and other calcareous red algae~~CA~~ should be carried out to clarify the environmental factors influencing the B/Ca~~substitution of boron within the calcite lattice of~~ in these organisms, and to ensure the reliability of this~~prior to adopting boron-based~~ proxy~~ies~~ for paleoclimate reconstructions.

5 Conclusion

This paper present~~sed~~ the first measures on trace elements (Mg, Sr, Li and B) from the coralline alga~~CA~~ *L. corallioides* collected across the Mediterranean Sea and in the Atlantic Ocean, at different oceanographic settings and depths (12 m, 40 m, 45 m, and 66 m depth).

LA-ICP-MS records of Mg/Ca, Sr/Ca and Li/Ca have shown a similar trend, primarily controlled by seawater temperatures in the algal habitat. ~~Indeed, higher Mg/Ca values were registered in Morlaix and lower Mg/Ca in Pontian Isl., which had respectively the highest and lowest ΔT.~~

In order to evaluate the control exerted by temperature on B incorporation, we also tested the correlation between B/Ca with Mg/Ca, Li/Ca and Sr/Ca. This led us to provide the first B/Ca data on wild grown coralline algae from across the photic zone depths in different Basins~~deep-water CA~~. The correlation between B/Ca and Mg/Ca in *L. corallioides* was statistically significant only in the shallow Atlantic waters of Morlaix, where seasonality, hence the seasonal temperature variations, during the algal growth was the strongest among sites~~the samples studied (8.90 °C)~~. Accordingly, B incorporation differences between long and short cells of *L. corallioides* strongly depend on ~~the magnitude of temperature fluctuations~~seasonality, being statistically significant just in Morlaix. Nevertheless, in contrast to Mg, Li, and Sr/Ca, B/Ca oscillations across the algal growth showed a poor relationship with seasonal variations in seawater temperature. ~~The extracted carbon data did not explain the low B concentration in the deepest sample, Pontian Isl. (462.8 ± 49.2 µmol/mol), where pH and DIC were high compared to the other sampling sites (8.12; 2.32 mol/m³).~~ We ~~also~~ found high B/Ca values in the Atlantic sample ~~from Morlaix (726.9 ± 102.8 µmol/mol)~~, at shallow depth, where pH and DIC were the lowest ~~(8.09; 2.17 mol/m³)~~. Carbon data did not explain the low B concentration in the Pontian Isl. sample (66 m depth), though, where pH and DIC were similar to the other Mediterranean sites. The estimation of growth rate, that wa~~si~~s low in the ~~deepest sample (~~Pontian Isl. sample, (0.11 mm/yr) and g~~ot~~ets higher in the other Mediterranean samples and in Morlaix ~~samples~~ (~0.13 mm/yr), led us to conclude that B/Ca relates to growth rate rather than seawater temperature. ~~In deep samples, B incorporation decreases with ΔT and depth, as growth rates did. Indeed, no statistically significant correlation can be traced with other temperature proxies.~~

B incorporation is therefore subject to the specific algal growth patterns and rates, whose knowledge is essential in order to assess the reliability of B/Ca in tracing seawater carbon variations.

510 **Appendix A**

Table A1: (a) Statistically non-significant results of tests performed to evaluate (a) the differences of Mg/Ca in *L. corallioides* and (b) the differences of Mg/Ca in the short cells of *L. corallioides* collected in different sampling sites. Test significance at α = 0.05.

(a)	Kruskal-Wallis test (Mg/Ca)		
	Df	χ^2	P
SITE	3	3.799	0.284

(b)	One-way ANOVA test (Mg/Ca)				
	Short cells				
	Df	Sum sq.	Mean sq.	F value	Pr(>F)
SITE	2	788.1	394.0	1.4647	0.2496
Residuals	26	6994.5	269.0		
Shapiro-Wilk normality test			P=0.6442		
Bartlett's K-squared			P=0.5856		

515 **Table A2: Results of statistical tests performed to evaluate the differences of Mg/Ca in the warm cells of *L. corallioides* collected in different sampling sites. Statistically significant p-values are given in bold. ANOVA test significance at α = 0.05; Tukey's test significant at p ≤ α.**

One-way ANOVA test (Mg/Ca)					
Warm cells					
	Df	Sum sq.	Mean sq.	F value	Pr(>F)
SITE	2	10897.7	5448.9	16.413	**0.0001**
Residuals	20	6639.8	332.0		
Shapiro-Wilk normality test			P=0.1440		
Bartlett's K-squared			P=0.5826		
Tukey's test					
Multiple comparisons of means					
SITE	Mean difference	95% confidence interval		P. adjusted	
	SITE	lower bound	upper bound		
Morlaix-Aegadian Isl.	38.32918	15.09816	61.56019	**0.00130**	
Pontian Isl.-Aegadian Isl.	-10.84361	-35.48382	13.79661	0.51716	
Pontian Isl.-Morlaix	-49.17278	-72.40380	-25.94177	**0.00009**	

Table A3: Results of statistical tests performed to evaluate the differences of B/Ca in *L. corallioides* collected in different sampling sites. Statistically significant p-values are given in bold. Kruskal-Wallis test significance at α = 0.05; Dunn's test significant at p ≤ α/2.

Kruskal-Wallis test (B/Ca)			
	Df	χ^2	P
SITE	3	79.816	**<2.2e-16**
Dunn's test			
Comparisons by SITE (Bonferroni)			
Z P. adjusted	Aegadian Isl.	Elba	Morlaix
Elba	-4.64580 **0.00000**		
Morlaix	-3.07755 **0.00630**	1.17249 0.72300	
Pontian Isl.	2.80564 **0.01510**	8.38673 **0.00000**	6.15663 **0.00000**

Table A4: Results of statistical tests performed to evaluate the differences of B/Ca in the warm cells of *L. corallioides* collected in different sampling sites. Statistically significant p-values are given in bold. ANOVA test significance at α = 0.05; Tukey's test significant at p ≤ α.

One-way ANOVA test (B/Ca)					
Warm cells					
	Df	Sum sq.	Mean sq.	F value	Pr(>F)
SITE	2	428364	214182	33.066	**0.0000**
Residuals	20	129546	6477		
Shapiro-Wilk normality test			P=0.5527		
Bartlett's K-squared			P=0.5470		
Tukey's test					
Multiple comparisons of means					
SITE	Mean difference SITE	95% confidence interval lower bound	 upper bound	P. adjusted	
Morlaix-Aegadian Isl.	190.11730	87.50374	292.73094	**0.00040**	
Pontian Isl.-Aegadian Isl.	-135.42490	-244.26303	-26.58672	**0.01342**	
Pontian Isl.-Morlaix	-325.54220	-428.15581	-222.92862	**0.00000**	

Table A5: Results of statistical tests performed to evaluate the differences of B/Ca in the cold cells of *L. corallioides* collected in different sampling sites. Statistically significant p-values are given in bold. ANOVA test significance at α = 0.05; Tukey's test significant at p ≤ α.

One-way ANOVA test (B/Ca)					
Cold cells					
	Df	Sum sq.	Mean sq.	F value	Pr(>F)
SITE	2	216232	108116	35.360	**0.0000**
Residuals	26	79497	3058		
Shapiro-Wilk normality test				P=0.1699	
Bartlett's K-squared				P=0.0576	
Tukey's test					
Multiple comparisons of means					
SITE	Mean difference	95% confidence interval		P. adjusted	
	SITE	lower bound	upper bound		
Morlaix-Aegadian Isl.	43.09640	-19.61932	105.81212	0.22146	
Pontian Isl.-Aegadian Isl.	-156.90170	-223.66771	-90.13574	**0.00001**	
Pontian Isl.-Morlaix	-199.99810	-260.58727	-139.40898	**0.00000**	

530 **Data availability**

Data resulting from this study have been submitted to the open access~~are available~~ PANGAEA repository~~from the authors upon request to the corresponding author~~.

Environmental data were provided by E.U. Copernicus Marine Service Information.

DIC data in the Mediterranean:

535 https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=MEDSEA_ANALYSIS_FORECAST
_BIO_006_014

DIC data in the Atlantic Ocean:

https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=IBI_ANALYSISFORECAST_BGC_0
05_004

540 pH data:

https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_BIO_001_
029

Temperature data: https://icdc.cen.uni-hamburg.de/daten/reanalysis-ocean/easy-init-ocean/ecmwf-oras5.html

Author contributions

DB, VB, and GP conceptualized the research question and study design. AL, DB, and VB conducted the experimental work; AM and GP the environmental data extraction. GP performed the data analysis and prepared the draft of the paper. All authors contributed to the editing and reviewing of the paper.

Competing interests

The authors declare that they have no conflict of interest.

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