



Seasonality and phenology of an epiphytic calcareous red alga, *Hydrolithon boreale*, on the leaves of *Posidonia oceanica* (L) Delile in the Turkish water

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Abstract

Epiphytes on *Posidonia oceanica* play a crucial role for determination of the ecological status of marine environment in time and space besides the seagrasses alone. The study was aimed to estimate the spatiotemporal ecological status linked to variation in biometry of an epiphytic micro-calcareous red alga, *Hydrolithon boreale*, found on leaves of the meadow with the exclusive environmental parameters along the entire Turkish coast of the Mediterranean Sea. Collection of *Posidonia oceanica* samples was conducted at 64 stations in winter (December 2018–January 2019) and 112 stations in summer (June–July 2019) by SCUBA (0.4×0.4 m of a quadrat frame) in the infralittoral zone along the entire Turkish Mediterranean coast surrounded by the siliciclastic Taurus Mountain Range which favor growth of epiphytic micro-calcareous red algae. Percent occurrence of the epiphyte changed seasonally—lower in winter (25%) than in summer (44%). The epiphyte which is an indicator and sensitive to undisturbed marine area grew up well to 5 mm in diameter, 0.35 mm in thickness of the crust size, and was populated up to 1006 ind/m² in summer owing to the increased utilization of the carbonate by the epiphyte with the increased water temperature. The size was contrasted to the density (abundance and biomass) in space. The biometry was significantly dependent on the siliciclastic-carbonate deposition as inferred from SiO₄-Si of the water in relation to the leaf area index (LAI) of *P. oceanica*. Therefore, this deposition induced specimens to grow in size, followed by the reduced density concerning the N-based nutrient of the water. Further major environmental parameters which negatively affected the biometry were pH and total suspended matter of the water, analogous to turbidity. Of the trace elements, Ni was negatively correlated with the biometry, whereas the LAI was however positively correlated with all the anthropogenic-sourced trace elements (V, Cu, Zn, As, Cd, and Pb) in the leaves. Of the bottom types, the calcite rock had a higher density than the other soft bottoms in contrast to the size of the epiphyte. Future studies could be based on the present study for determination of the ecological status regarding two dominant epiphytes on leaves of two seagrasses (*H. boreale* on *P. oceanica* and partly *Pneophyllum fragile* on *Cymodocea nodosa*) found in the different environments and substrates in space and time.

Keywords Epiphyte · Biometry · Meadow · Environmental correlation · Turkish Mediterranean coast

Introduction

Posidonia oceanica is an endemic species to Mediterranean Sea, and its meadows are extending to about 40 m deep (Colantoni et al. 1982; Marbà et al. 2002); its distribution is limited by low salinity and/or high temperature (Vacchi et al. 2017). Coarsely, seagrass shoot density alone determines the ecological status of the Mediterranean marine environment (UNEP/MAP-RAC/SPA 2015; Gobert et al. 2009). Beds of *P. oceanica* comprise the climax community in a spatial expansion process of the organisms' establishment (Den Hartog 1977). The meadows responded differently to the different environmental parameters depending on

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their different parts such as below-ground or above-ground parts, e.g., leaf, leaf-related parts, and roots. Besides the water salinity, temperature, and light (Vacchi et al. 2017) as an ecological indication and interaction, the sea surface water nitrogen negatively affected the leaf width and positively affected the number of leaves per shoot (Mutlu et al. 2022). Seasonal nutrient deficiency, which reduced growth, was more pronounced in autumn, and nutrient limitations occurred in late spring and summer (Alcoverro et al. 1997; Lepoint et al. 2002). The light reaching the leaves was further blocked through the shelf-shading of the leaves and epiphytes (Via et al. 1998). The climate affects the meadows in various ways depending on both physical and chemical variables inducing changes in sea water temperature, sea level rise, modification of wave frequency and height, and ocean acidification (Bianchi et al. 2012; Planton et al. 2012; Vacchi et al. 2017). Climatic anomalies declined meadow vitality (Pergent et al. 2014). All environmental variables aforementioned are related to presence and absence of epiphytes and their diversity on the meadows (Sfriso et al. 2007; Nesti et al. 2009).

The epiphytes on the seagrass suggest ecological indications and status for the marine environments. As occurs at every taxon, the epiphytes have sensitive and tolerant species to the levels of disturbance in the marine environment (Sfriso et al. 2007, 2009). Therefore, their density (abundance and biomass) and species composition showed direction and levels of the ecological conditions. One of the sensitive seagrasses in the Mediterranean Sea is a meadow, *Posidonia oceanica*, and is covered by diverse epiphytes hosted on its rhizomes and leaves (Nesti et al. 2009). The epiphytes and *P. oceanica* together are a good combination to assess and monitor the ecological conditions in the Mediterranean Sea. The epiphytes are composed generally of their different species in the meadow (Lepoint et al. 2000, 2006). Overall, the epiphytes are an indication and intensity level of, i.e., eutrophication, productivity, herbivory, trace chemical elements, acidification, ambiance, anthropogenically, seasonality, turbidity, warming, sedimentation, hydrodynamics, and natural land sourcing around the marine environments in time and space (Bedini et al. 2003; Balata et al. 2008; Jacquemart and Demoulin 2008; Jaschinski and Sommer 2008; Baggett et al. 2010; Brahim et al. 2020). One of the epiphyte taxa which are noticed and paid attention to the calcareous species is acted as processors in the sediments (Walker and Woelkerling 1988). The most dominant encrusting species were *Hydrolithon* and *Pneophyllum* species as epiphytes on the seagrass in the Mediterranean Sea (Jacquemart and Demoulin 2008; Piazzzi et al. 2000). Only these two genera species predicted reasonably most of the ecological indications (Mann 2001; Lepoint et al. 2007; Peterson

et al. 2007; Tsirika et al. 2007; Mabrouk et al. 2013; Bermejo et al. 2016; Mabrouk et al. 2017; Prado 2018; Sfriso et al. 2014, 2016, 2020) since they are very sensitive to change in the environments and common in undisturbed areas (Piazzzi et al. 2002; Martinez-Crego et al. 2010; Bedini and Piazzzi 2012; Brahim et al. 2020). The main indication of the encrusting micro calcareous has been focused on the acidification process in relation of the carbonate to the pH in the Mediterranean Sea (e.g. Cox et al. 2015; Mutalipassi et al. 2020; Sfriso et al. 2020) due to the global warming. The targeted species in the present study, *Hydrolithon* spp, had the highest coverage (18–69%; Martin et al. 2008) on seagrass at a water pH of 8.1 (8.0–8.2) while there were no such epiphytes at 7.7 pH (Martin et al. 2008; Mutalipassi et al. 2020). In an undisturbed site where the NO_3 and NO_2 were lower and $\text{Si}(\text{OH})_4$ was higher, some species (*Hydrolithon farinosum* (J.V.Lamouroux) Penrose & Y.M.Chamberlain 1993, *Fosleilla* spp. and *Pneophyllum fragile* Kützing, 1843) of epiphytic red algae were dominant (Mabrouk et al. 2013).

Compared to the other waters of the Mediterranean Sea, meadows are less-known for their distribution and are abundant in Turkish waters (Giakoumi et al. 2013; Vacchi et al. 2017). Besides, there are some studies on their distribution on small scale from the Turkish Levant coasts, Sea of Marmara, and Black Sea (Gücü and Gücü 2002; Çirik et al. 2006; Boudouresque et al. 2012; Mutlu et al. 2022). *Hydrolithon* spp and *P. fragile* are sensitive species for undisturbed areas (Sfriso et al. 2007, 2009). A species of the present study, *Hydrolithon boreale* (Foslie) Y.M.Chamberlain, 1994 is one of the larger specimens of the microcalcareous red algae in terms of size of its crust (up to 2–5 mm in diameter; Reyes and Afonso-Carrillo 1995; Bradassi 2011) and has been reported here for the Turkish Mediterranean Sea. Research on invasion success and mechanisms can guide scientists to understand regulation by a complex set of factors, including biotic and abiotic features of recipient systems, disturbance regimes, and invader life traits (Sol et al. 2012). Therefore, this brings the following present study.

Regarding the ecological importance of calcareous seaweed in the marine environment and the historical lack of comprehensive information on their distribution and ecology in the Turkish waters, this study aims to provide the first baseline information on bathymetric and seasonal distribution and biometrical patterns (density and plant traits) of the *H. boreale* recently appeared on the leaves of *P. oceanica* in the infralittoral of the Turkish pristine coast, a region of the most ultra-oligotrophic waters (Sisma-Ventura et al. 2017) of the Mediterranean Sea, and to determine biometrical dynamics and the species-environment relation of the biggest microcalcareous species emphasizing the siliciclastic-carbonate deposition.

Material and methods

Study area

The study area was located in the infralittoral zone regionally limited by a bottom depth of 30 m extending occasionally to 40–43 m hereby along the southern coast of Turkey (Mutlu et al. 2020a). The area was between Taşucu Bay, Mersin through Antalya and Datça Bay, Muğla, along three provinces (Fig. 1). The study area was restricted by Taşucu Bay in the eastern Turkish coast since there are no further locations of a meadow, *P. oceanica* beyond Taşucu Bay to the eastern end of the eastern Mediterranean Sea (Ergün Taşkın who researches the presence of the meadows and macrophytes by SCUBA, pers. comm.). The study area has a coastline length of about 1100 km (Fig. 1a).

The eastern half of Mersin Bay is nutritionally fed by three major (Seyhan, Ceyhan, and Göksu) rivers and is partially under influence of the Nile River (Fig. 1b). Owing to few brooks having a moderate flow rate, Antalya Bay is oligotrophic compared to Mersin Bay. Muğla's bays and coves are devoid of rivers and brooks but are partially fed by local creeks and have undergone the effect of the Aegean Sea from east to west (Fig. 1).

The prevailing surface rim current of the Turkish Mediterranean coast was cyclonically circulated from İskenderun Bay (the easternmost Mediterranean Sea), flowed off Mersin Bay reaching Taşucu Bay, and crossed off Antalya Gulf (cape to cape, Fig. 1f) then to Rhode Island where the current is bifurcated northerly and southerly (El-Geziry and Bryden 2010). The current velocity was faster than 20 cm s^{-1} typical for the entire Mediterranean Sea but was generally about 50 cm s^{-1} on average along the Turkish Mediterranean coast (Poulain et al. 2013).

There are three main rivers with high flow rates in the easternmost of the Turkish Mediterranean coasts, which influence the coastal zone till Anamur Cape from the east by diluting the rate westward. There are many small-scale brooks along Antalya's coast, and some creeks along Muğla's coast (Fig. 1b). Springs of the streams were sourced through the Taurus mountain range parallel to the Turkish Mediterranean coast (Fig. 1b). The study area has been influenced by the geological structure of the mountain. The geological chronology showed that the mountain had mixed siliciclastic-carbonate during the Paleozoic, carbonate deposition during Jurassic-Cretaceous, and then shallow-water carbonates inducing deeper-water deposits during Paleocene-Eocene (Duman et al. 2017). Therefore, the streams and groundwater feed and enhance the study area with the siliciclastic-carbonate and drains of anthropogenic sources around the beds of the streams as well

(Fig. 1). The flow rates of the streams and groundwater have decreased in time due to climate change and global warming.

Anthropogenic effects were present with a variety of sources as follows: marine litter, tourism, fisher, maritime activities, and trace elements (Gündoğdu and Çevik 2017; Olguner et al. 2018; Mutlu et al. 2020b; Öztürk et al. 2021). Furthermore, the study area is under influence of intensive coastal agricultural activities, particularly throughout the coast of Mersin and Antalya providences (Fig. 1f).

Sampling and field measurements

Collection of *Posidonia oceanica* samples was conducted in winter (December 2018/January 2019) and summer (June/July 2019) along the entire Turkish Mediterranean coast (Fig. 1) since the biometrics of the meadows was at minima in winter and at maxima in summer. Referring to the echogram of the echosounder to see absences/presence of *P. oceanica* on the seafloor, 64 stations were sampled by a van Veen grab (ca. 0.1 m^2 at 13 stations) and SCUBA ($0.4 \times 0.4 \text{ m}$ of a quadrate frame at 51 stations, and a total of 49 stations was inhabited by *P. oceanica*) in winter, and 112 stations (6 by a van Veen grab and 106 by SCUBA, and 103 by *P. oceanica*) in summer. The stations were triplicate-sampled.

Sampling bottom depth varied between 5 and 50 m but generally between 10 and 30 m at 5-m intervals because of the safety of R/V "Akdeniz Su" with a draft of 3.7 m at the shallowest waters, sometimes extending to 35–40 m. Each cruise lasted 1.5–2 months to complete the field-work (Fig. 1).

Some environmental parameters of water columns were measured and sampled from the surface (prefix S) and near-bottom (prefix N) waters of the stations on the board. These parameters were physical (T; temperature in °C, pH; pH, S; salinity, and O; oxygen in mg/l) using multi-parameter probes (YSI, HiTech), chemical (nutrients; $\text{NO}_2 + \text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and PO_4 , $\text{SiO}_4\text{-Si}$, chl *a*, and TSM; total suspended matter). The oxygen was measured only in winter since the oxygen probe malfunctioned in summer and the chemical parameters were sampled only in summer due to the low occurrence of the epiphyte in winter (Figs. 2 and 3). One liter of the water was filtered through CF/C for each, of the nutrients, and total suspended matter and through CF/F filters for chl *a*, and then all was kept in a freezer having -20 °C on board during the field survey. Onboard, samples of the meadow were preserved in borax-buffered formaldehyde (3%) in plastic jars on the deck of the R/V "Akdeniz Su."

Fig. 1 Study area (a; red frame) and the streams flowing to the Turkish Mediterranean waters (b, from <http://www.beycan.net/eklenen/nehirler/Akarsular-2068x1051.png>) and sampling stations classified by the bottom types and bottom depth (red circle; min: 5 m and max: 52 m) in December 2018/January 2019 (c and d, respectively) and June/July 2019 (e and f, respectively) and anthropogenic sources from the land: p; small-capacity hotel, and pension, a; intensive agriculture on land, h; very high capacity of the hotel, b; metropolitan beach activities, y; intensive activities of yachting and pleasure crafts, m; very coastal intensive agriculture of banana in the crossed-area along the Turkish Mediterranean Sea coast

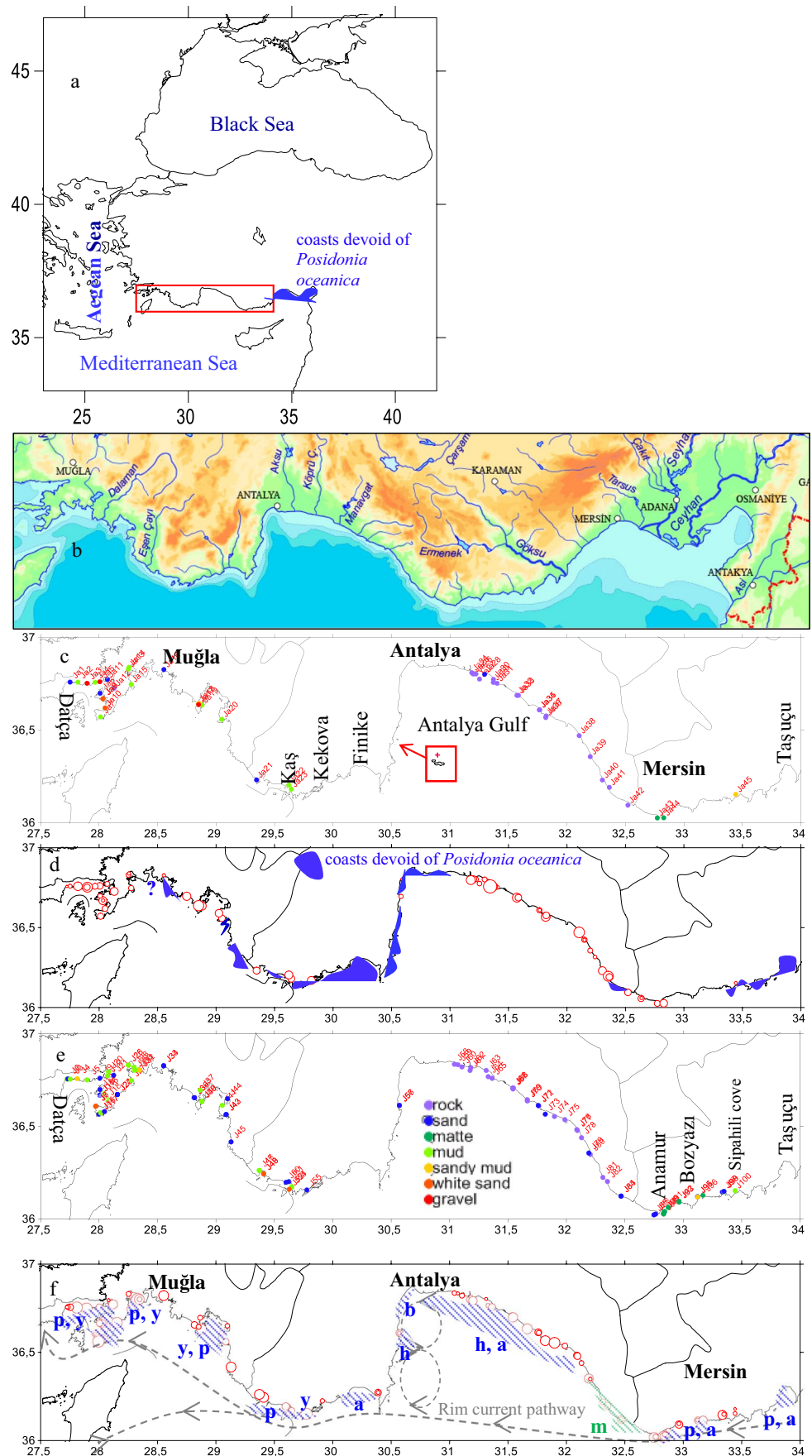


Fig. 2 Temporal distribution of the biometrics of *Pneophyllum fragile* found on leave, and LAI of *Cymodocea nodosa* in January–August of the year 2012, and November 2011

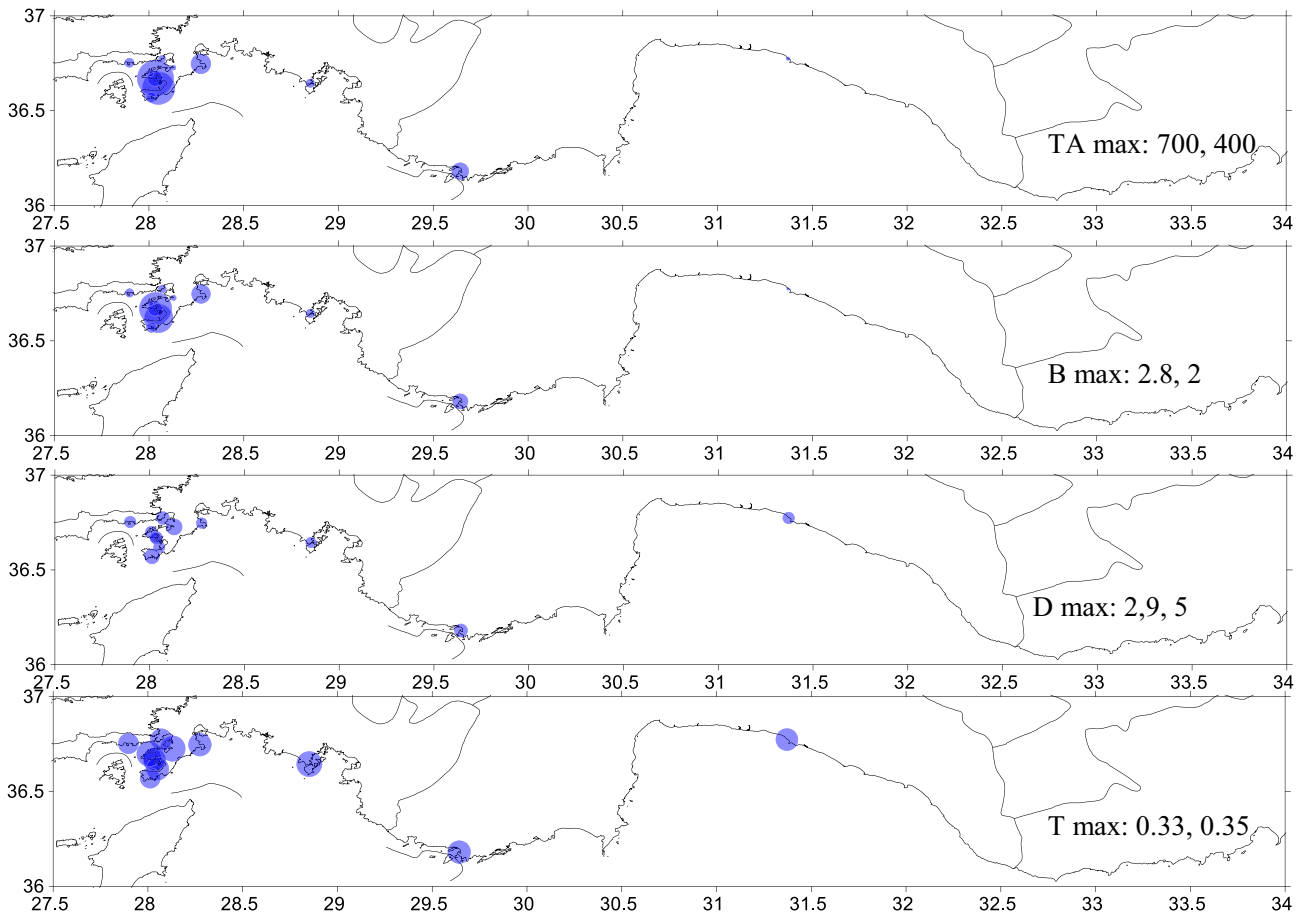
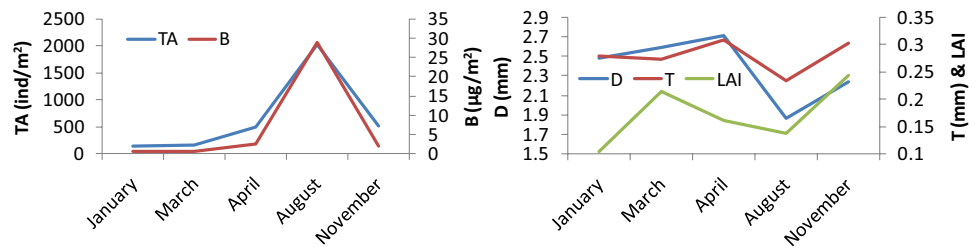


Fig. 3 Biometrical distribution of *Hydrolithon boreale*; abundance (TA; ind/m²), biomass (B; µg/m²), crust diameter (D; mm), and thickness (T; mm) in winter. Maximum values were the maximum values

of the winter survey, and the scaling value for the circles in both winter and summer in Fig. 4, respectively

Laboratory analyses

Biological materials

A total of 45 and 100 stations were analyzed for the biometry of a calcareous epiphyte, *H. boreale*, in winter and summer, respectively. A total of 2928 and 5028 shoots, and 11,662 and 24,509 leave of the meadows were measured for scanning the epiphyte in winter and summer, respectively. It is hereby worthy to note that sampling more than 1000 shoots is considered a destructive sampling to

this sensitive species, *P. oceanica*. Of the epiphytes, *H. boreale* was majorly recorded on the leave of *P. oceanica* (Tables 3, 4 in Appendix). Crust diameter (D) and thickness (T, height of about cylindrical crust) of *H. boreale* were measured using an ocular micrometer scale under a binocular microscope. All measurements were converted to mm. The crust weight was estimated from the crust volume (cylinder) and density of calcium carbonate (2.711 kg/m³). Abundance (TA, ind/m²) and biomass (B, µg/m²) of *H. boreale* were calculated to value per square meter.

Environmental materials

In the laboratory, nutrients were measured following the standard procedures (APHA 1999): Ammonium (mg NH_4/l), nitrate (mg NO_3/l), nitrite (mg NO_2/l), phosphate (mg PO_4/l), and silicon dioxide (mg SiO_2/l) were measured using the methods of 4500- $\text{NH}_4\text{-B}$, 4500 $\text{NO}_3\text{-E}$, 4500 $\text{NO}_2\text{-B}$, 4500-P E, and 4500-SiO 2 Silica, respectively (APHA 1999). The values of the nutrients were converted to a unit μM .

For estimation of total suspended solids the filtered material with the membrane was dried in an oven at 60 °C for 24 h, and then weighed. The weight of the dried empty membrane was subtracted from the total dry material weight to get the net total suspended solids. Chlorophyll *a* (chl-*a*) was measured using a method described by Lorenzen (1967). Secchi disk depth was recorded once at each station.

Statistical analyses

Of the univariate analyses, Spearman rank correlation and partial correlation were subjected to data between biometry of the epiphyte and the environmental data to estimate the hidden environmental variables. The Spearman correlation was applied between trace elements (mg/kg) in blades of *P. oceanica* and its sediments (Öztürk et al. 2021), the biometrics of the epiphyte, and LAI of *P. oceanica* to estimate the effect of anthropogenic trace elements on the biometrics. The Generalized Additive Model (GAM) was used to estimate the effect of the predicted environmental parameters (all physics, chemists and optics, and each physics, and chemists separately) on the response biometrical variables of the epiphyte for the summer survey. The univariate statistical analyses were performed using the statistical tools of MatLab (vers. 2021a, Mathworks Inc).

The following statistical analyses were designed according to the results of the univariate statistical analyses. Of the multivariate analyses, multiple regression was used to test the relationship and correlation between the biometrics of the epiphyte and LAI of *P. oceanica* concentration of sea surface $\text{SiO}_4\text{-Si}$ using the MatLab statistical tool. Principal Coordinate Analyses (PCO) were applied to a triangular Euclidean distance matrix of the biometry to figure out the best variable with the variation on the component, and then the PCO configuration on the axes was correlated with the environmental variables using the Spearman rank correlation for summer survey. The multivariate analyses were performed using PRIMER 6 (vers. 6.1.13)+PERMANOVA+(1.0.3.).

Results

Plant phenology

Understanding the biometrical dynamic of an encrusting red alga, *P. fragile* on a seagrass, *C. nodosa* in time, data from a

previously unpublished study (Mutlu et al. 2014) were examined since they were sampled at 5 months a year (Fig. 2). This guides in filling the gap of their temporal dynamic between winter and summer samplings conducted in the present study. The abundance and biomass increased slightly from January to April, and then peaked in August, followed by the occurrence of decrement in November (Fig. 2). The size was distributed in contrast to the temporal density of the epiphyte, and the LAI of *C. nodosa* did the same distribution as well (Fig. 2). However, any individual calcareous red alga on leaves of *P. oceanica* in the Gulf of Antalya was not encountered during 2011–2012 (Mutlu et al. 2014). Coverage of *P. fragile* was 6.4% of the leaf surface of *C. nodosa* on average and varied between 1.6% in March and 16.0% in August.

Hydrolithon boreale on leaves of *P. oceanica* occurred at 25% of the total stations in winter and 44% in summer during the present study (Fig. 3). Average coverage of *H. boreale* was 0.12% (max: 0.75%) of the leaf surface of *P. oceanica*. Most occurrences took place along the westernmost coast of the study area, Muğla's coast in winter, and all coasts of three provinces in summer (Figs. 3 and 4).

An average abundance of 41 and 49 ind/m² in the study area (163 and 112 ind/m² on stations where the epiphyte occurred) was estimated in winter and summer, respectively (Table 1). In winter, maximum abundance and biomass were recorded in a particular area of Muğla's coast where there used to be fish farms in the 2000s (c.a. 2000–2005). In summer, the abundance and biomass were maximized in the easternmost location as opposed to the location in winter and were highly variable with the regions along the coast of the study area (Figs. 3 and 4). The lowest biomass and abundance occurred along Antalya's coast with a few exceptions of the locations and a moderate value was along Muğla's coasts.

The diameter of *H. boreale*'s crust was less in winter than that in winter on average, almost similar to around 2.5–2.9 mm in all stations in winter, while the diameter was very different in the regions of the study area (Table 1). The maximum diameter almost doubled the winter values in summer in contrast to the abundance and biomass in summer with exception of Antalya's Gulf where the meadows were found only on the rocks (Figs. 1, 2, 3, and 4). This contrast seemed to be more pronounced on soft bottom (sand and mud) and dead *matte* at about 2 m high.

Similar to the diameter, the thicker crust of *H. boreale* was observed on Muğla's coast in both winter and summer. This trend was more apparent in summer. The thickness was in a similar range between winter and summer (Table 1).

Of the environmental parameters, sea surface $\text{SiO}_4\text{-Si}$ concentration was however straight-proportionally overlapped on the size of the epiphyte, but reversely on the density (abundance and biomass) depending on the size of

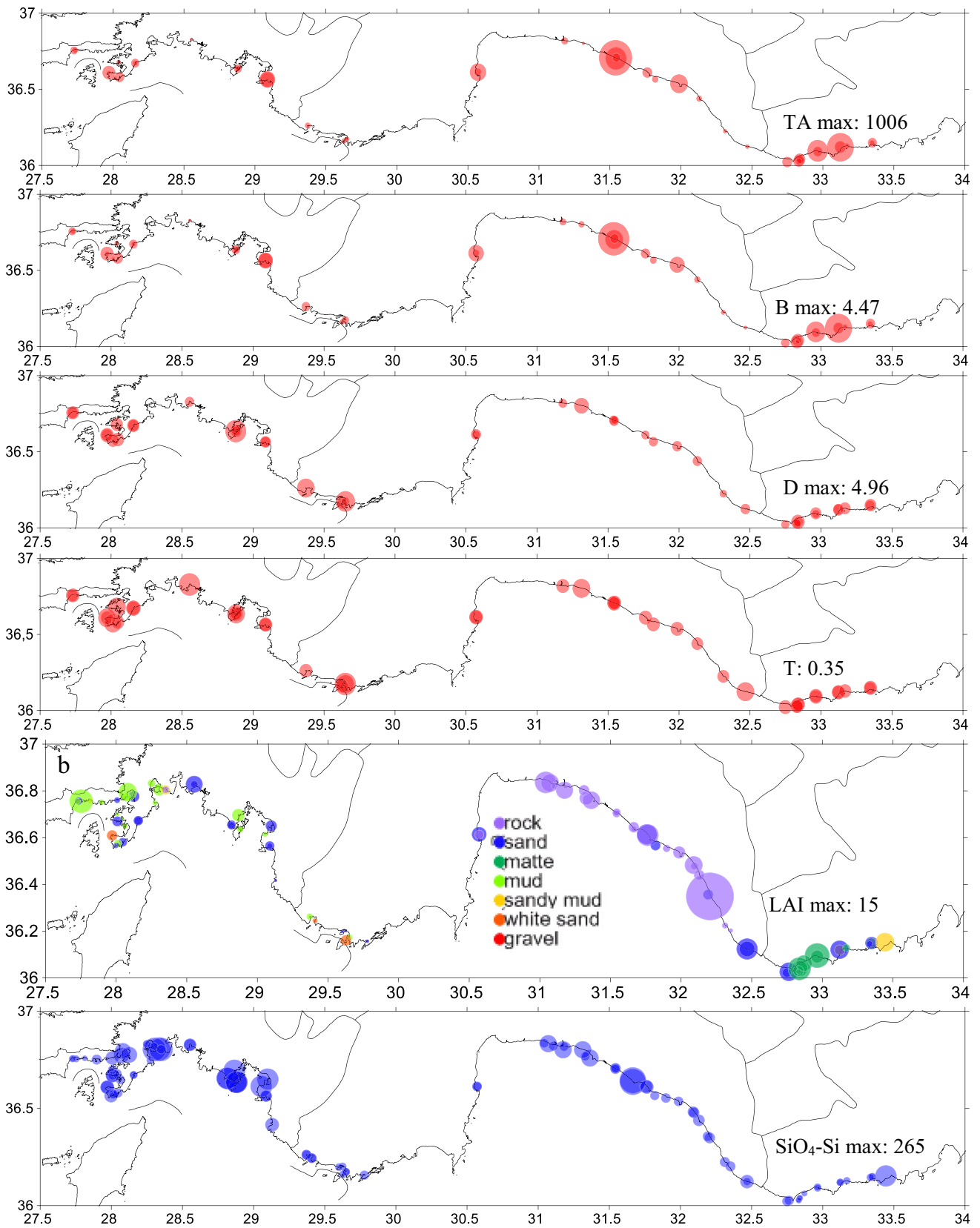


Fig. 4 Biometrical distribution of *Hydrolithon boreale*; abundance (TA; ind/m²), biomass (B; μg/m²), crust diameter (D; mm), and thickness (T; mm), and LAI of *Posidonia oceanica* and sea surface con-

centration of SiO₄-Si (μM) in summer. The maximum value was the maximum value of the summer

Table 1 Average (Avg) and standard deviations (SD) of the biometrics of *Hydrolithon boreale* and LAI of *Posidonia oceanica* for all stations and the stations where *Hydrolithon boreale* was present in winter and summer (Bold statistics, Avg and SD for only summer)

	On all stations					On only presence			
	TA ind/m ²	D mm	T mm	B μg/m ²	LAI	TA ind/m ²	D mm	T mm	B μg/m ²
Avg	41	0.57	0.074	0.171	1.48	163	2.23	0.290	0.671
SD	134	0.99	0.128	0.528	0.95	231	0.30	0.022	0.895
Avg	49	1.11	0.131	0.232	3.11	112	2.52	0.297	0.529
SD	136	1.34	0.148	0.618	2.18	188	0.70	0.017	0.847

epiphyte and LAI of *P. oceanica* in summer (Fig. 3). The larger epiphyte carried less abundance on a given LAI.

However, there was a significant correlation between the biometrics and bottom type (Table 2 in Appendix). However, there was a significant correlation between the biometrics and bottom type (Table 2 in Appendix).

Environmental parameters

Overall, sea surface temperature is at minima in December–February (14–17 to 21 °C), at maxima in July (19–28 °C)–August (28–30, and to 31 °C), and decreased from eastern to western coasts of the present study area. During the present study, the salinity varied seasonally between 38 and 39 (~40 in August–early September). Sea surface temperature varied between 14 and 21 °C in winter and 19 and 28.8 °C in summer and salinity between 18 and ~40 in winter and 24 and 38.8 in summer. Maximum Secchi disk depth was recorded as 29 m in winter and 32 m in summer. Sea surface dissolved oxygen was measured in a range of 8 to 11 mg/l in winter. The pH was recorded to be 8 and 9.1 in winter and 8.5 and 9.5 in summer.

Summer sea surface nutrients were measured as follows: The nitrite varied between 0.02 and 3.96 μM (0.47 ± 0.56 μM on average ± SD), the nitrate between 0.18 and 0.03 μM (0.12 ± 0.03 μM), the ammonium between 2.44 and 531.2 μM (126.4 ± 127.2 μM), the reactive silicate between 1 and 402 μM (32.2 ± 53.4 μM), and ortho-phosphate between 0.58 and 4.87 μM (2.91 ± 1.07 μM). The total suspended matter ranged from 0.02 to 1.43 mg/l and was averaged to be 0.08 ± 0.18 mg/l, and the chl-*a* from 0.08 to 2.87 μg/l and 0.51 ± 0.38 μg/l on average.

Anthropogenic effect of trace elements in *Posidonia* blades and its sediments in the present study area; the highest bioaccumulation factor in *P. oceanica* was calculated for Cd. Coastal waters were heavily exposed to trace elements, and significant positive correlations were detected between the anthropogenic trace element pollutants (As, Cd, Cu, Zn, Pb, and V) and natural sourced trace elements (Ni and Cr). The Mediterranean Sea coast of Turkey did not have significant levels of Zd, Cd, Cu, and Pb pollution, whereas 65% of the stations were heavily polluted with As.

Biometrics of the epiphyte was correlated negatively with sea surface temperature and positively dissolved oxygen concentrations of the near-bottom water in winter at $p < 0.05$. Sea surface temperature was negatively correlated with the diameter and oxygen positively with density variables of the epiphyte in winter.

In summer, near-bottom temperature correlated positive-significantly the density variables (abundance and biomass) of the epiphytes in contrast to that in winter. Interestingly, the biometrics was negative-significantly correlated with sea surface concentration of the SiO₄–Si but positively with the salinity of the near-bottom water (Table 3 in Appendix). The PO₄–P of the near-bottom water was positively correlated with only crust diameter at $p < 0.05$ (Table 3 in Appendix).

There was an obvious relationship between the density and diameter of the epiphyte and the sea surface silicate (SiO₄–Si) and LAI of the meadow in summer (Fig. 4). However, biometrics of the epiphyte was not significantly correlated with the LAI of *P. oceanica* at $p < 0.05$, which has brought about the multiple-regression between the variables aforementioned.

Statistics of the linear multiple regression were given in Table 4 in Appendix for the relationship between biometrics of the epiphyte and the sea surface silicate (SiO₄–Si) and LAI of the meadow in summer. To extract out the hidden variables of the LAI and SiO₄–Si in linear relation to the biometrics, Spearman partial correlations showed that none of the variables was correlated with the biometrics at $p < 0.05$. Multiple linear regression showed that there was however a significant correlation only between the thickness and the LAI and SiO₄–Si at $p < 0.05$ in Table 4 in Appendix. Regarding the *b* value, the LAI affected biometrics positively, but the SiO₄–Si negatively (Table 4 in Appendix).

Based on all environmental variables, the abundance of the epiphyte was not partial-correlated with any of the environmental parameters. The nutrients were not partial-correlated with any of the biometrics (Table 5 in Appendix). Diameter, thickness, and biomass were positively partial-correlated with six of the environmental parameters at $p < 0.05$ (Table 5 in Appendix). The LAI of *P. oceanica* was highly correlated with the biometrics of the epiphyte (Table 5 in Appendix).

The Generalized Additive Model (GAM) performed with all environmental parameters in summer showed that abundance (TA) of the epiphyte was positively affected first with sea surface temperature (ST), followed by the SpH, and total suspended matter (TSM) in a negative way (Fig. 5). The crust diameter (D) was negatively affected by the ST and positively by the bottom depth. The biomass (B) including also contribution of crust thickness (T) was influenced by more variables compared to abundance and diameter; the SpH and NpH affected negatively and positively biomass, respectively. These variables were followed by the $\text{SNH}_4\text{-N}$ under the positive influence, and the SS and NTSM under the negative influence related to the biomass (Fig. 5).

Eliminating this complexity derived from the effects of all the environmental variables on the biometrics, the GAM was solved for the effectiveness of each of the physical and chemical variables separately (Figs. 6 and 7).

Concerning only physical environmental parameters, the abundance was positively affected by the ST, followed negatively by the SS and slightly Sec. The diameter and thickness were mostly influenced by the pH and S; the pH affected positively the size and biomass as a function of the diameter and thickness, but the salinity negatively did (Fig. 6).

In terms of the effect of only chemical parameters, the TA was under the negative effect of the NTSM and $\text{NNO}_3\text{-N}$, followed by that under the positive effect of the $\text{SPO}_4\text{-P}$ and $\text{SSiO}_4\text{-Si}$. Overall, N-based nutrients affected negatively the abundance (Fig. 7). The $\text{NNO}_2 + \text{NO}_3\text{-N}$, $\text{SSiO}_4\text{-Si}$, and $\text{NNO}_2\text{-N}$ increased the diameter of the epiphyte, and the

size was reduced by the $\text{NNO}_3\text{-N}$ and $\text{SNO}_2\text{-N}$ (Fig. 7). As occurred in the abundance, NTSM decreased the biomass, but the $\text{SSiO}_4\text{-Si}$ and $\text{SNH}_4\text{-N}$ increased the biomass of the epiphyte (Fig. 7).

A significant part (97.5%) of the total explained variance occurred on the PCO1 to estimate the first component-based and launched on the biometrics well-correlated with $\text{SSiO}_4\text{-Si}$ (Table 6 in Appendix and Fig. 8). The density (B and TA) of the epiphyte increased with the NS and ST and decreased with the $\text{SSiO}_4\text{-Si}$ (Table 6 in Appendix and Fig. 8a, b, d). The distribution of the crust diameter (D) was exactly contrasted to the density of the epiphytes on the PCO (Fig. 8a–c).

The best descriptive trait of the biometric in direct correlation with the $\text{SSiO}_4\text{-Si}$ was the diameter of the epiphyte (Fig. 8c, d) since the other biometrics changed dependently on the LAI of its host, *P. oceanica*, and thickness. The enlargement of the diameter was accelerated after a threshold of about $80 \mu\text{M}$ of the $\text{SSiO}_4\text{-Si}$ to about $210 \mu\text{M}$ which inhibited the occurrence of the epiphyte (Fig. 8c, d*). This threshold could be due to action as a limiting factor for SiO_2 on the growth of the epiphyte.

Of the trace elements on the blades of the meadow, the Ni originated by the nature was negatively correlated with the crust biometrics of the epiphyte and LAI of *P. oceanica* at $p < 0.05$ (Table 7 in Appendix). Of the anthropogenic-sourced trace elements (V, Cu, Zn, As, Cd, and Pb) in the blades, Zn was negatively correlated only with the diameter of the epiphyte. In the sediments, the Ni was affected

Fig. 5 The GAM solution to estimate effective variables from all environmental parameters (see Table 6 in Appendix for the abbreviations) on the biometrics (abundance, TA; crust diameter, D; and biomass, B) of the epiphyte in summer

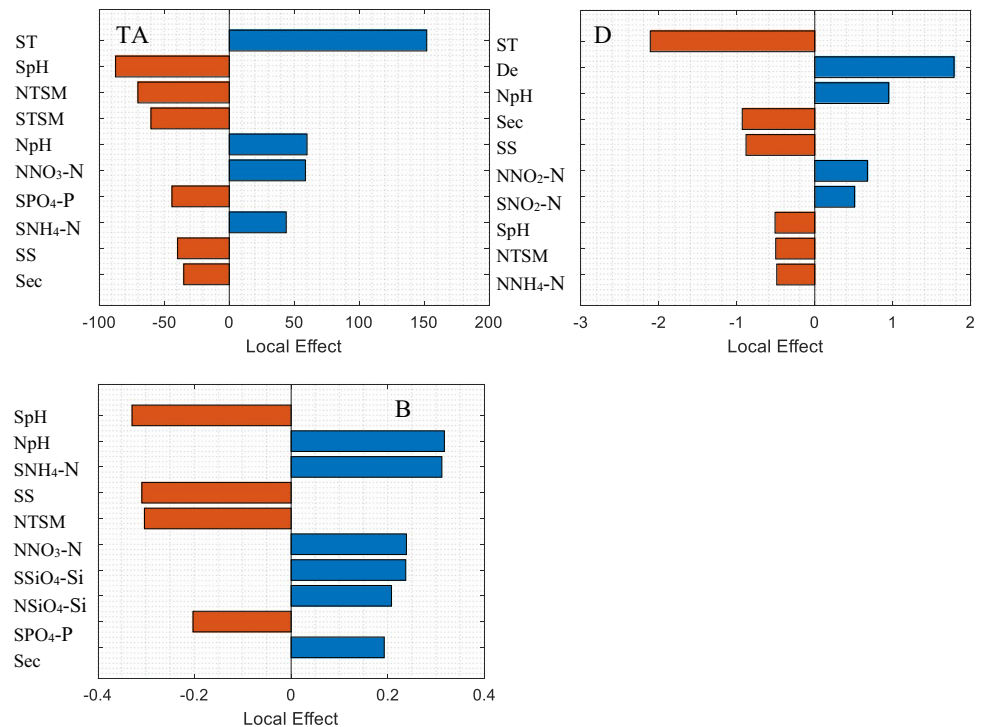


Fig. 6 The GAM solution to estimate effective variables from only physical environmental parameters (see Table 6 in Appendix for the abbreviations) on the biometrics (abundance, TA; crust diameter, D; and biomass, B) of the epiphyte in summer

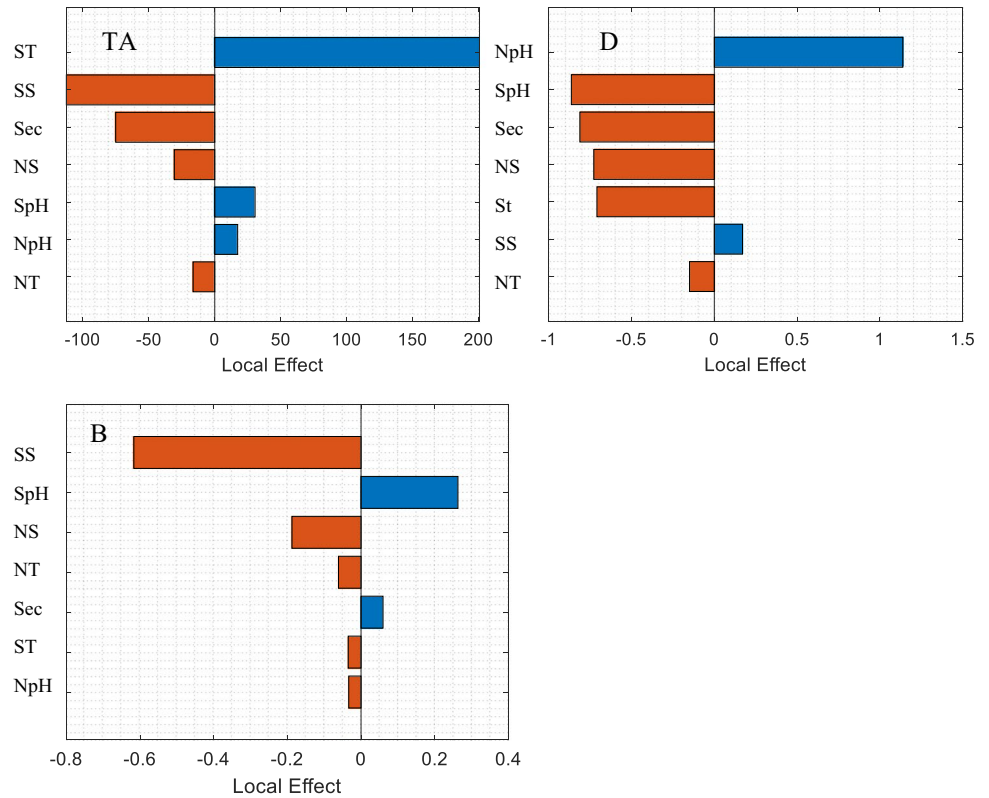
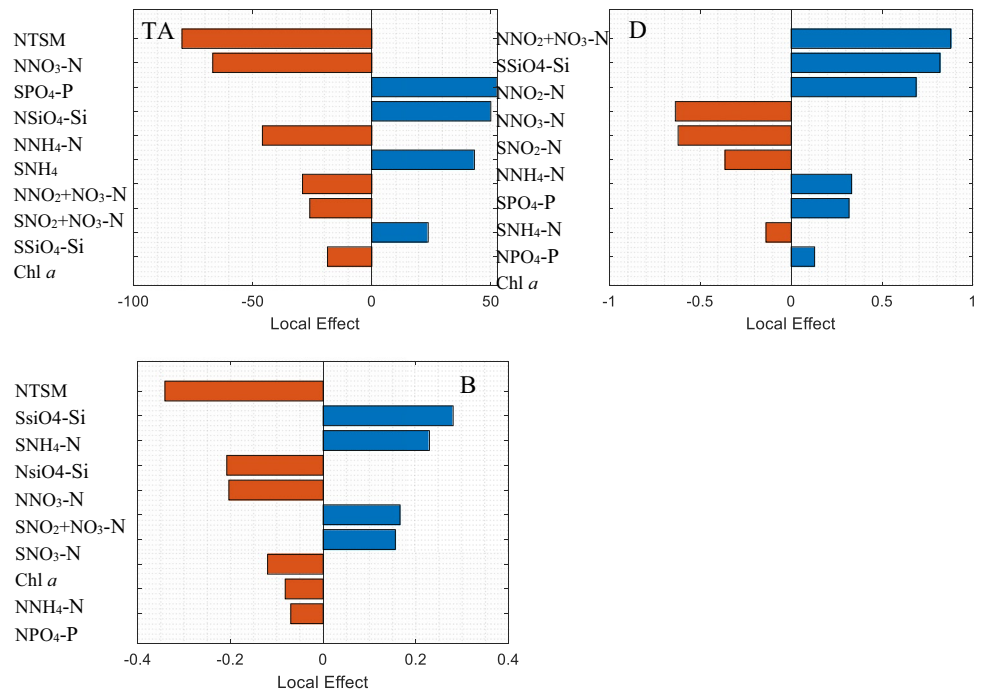


Fig. 7 The GAM solution to estimate effective variables from only chemical environmental parameters (see Table 6 in Appendix for the abbreviations) on the biometrics (abundance, TA; D, crust diameter; and biomass, B) of the epiphyte in summer

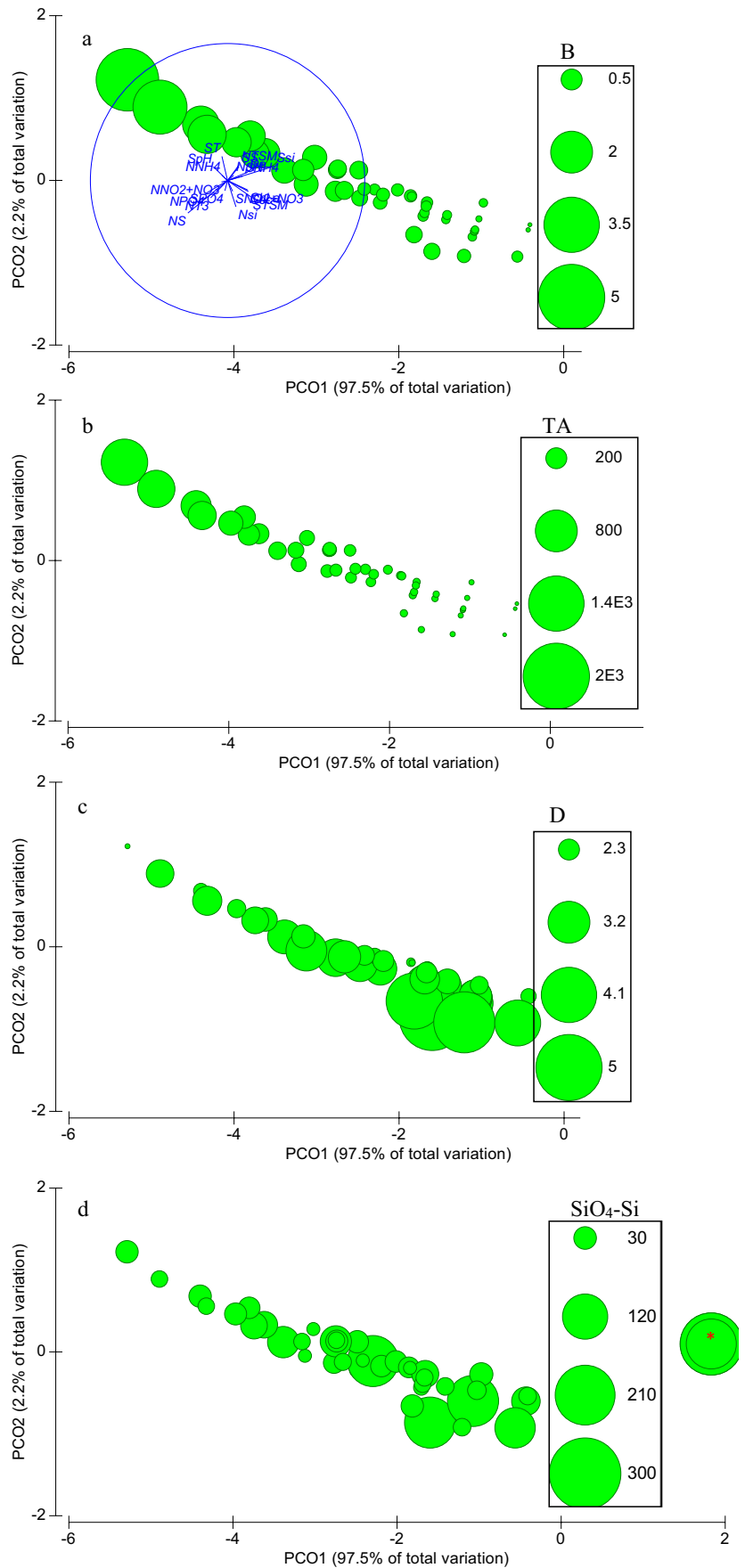


negatively by the TA, T, and B of the epiphyte. However, the LAI was positively correlated with all the anthropogenic-sourced trace elements. The As was positively correlated with the diameter of the crust (Table 7 in Appendix).

Discussion

Of the epiphytes on *P. oceanica*, encrusting algae were significantly different in their distribution between leaves

Fig. 8 The PCO solution of the biometrics and correlation with the environmental parameters. Distribution of the biomass (B, $\mu\text{g}/\text{m}^2$), abundance (TA, ind/m^2), crust diameter (D, mm) of the epiphyte, and $\text{SSiO}_4\text{-Si}$ (μM) of the environmental parameter overlapped on the ordination of the PCO in summer. * denotes locations where the epiphyte is absent (a–d)



(Figs. 9, 10, 11 in Appendix), and rhizomes of *P. oceanica* and species belonging to genus *Pneophyllum* and *Hydrolithon* spp were found generally on the leaves (Nesti et al. 2009). The epiphytic assemblages were indicators of various types of natural and anthropogenic disturbances (Table 8, Figs. 12, 13 in Appendix) and occurred to grow to detect the moderate nutrient level (Balata et al. 2008). *Hydrolithon* spp and *P. fragile* are sensitive species for undisturbed areas (Sfriso et al. 2007, 2009). Average leaf coverage on *P. oceanica* was estimated more than 1% by the encrusting coralline algae comprising mostly *H. farinosum* and *Pneophyllum* spp (Prado et al. 2007) higher than our estimates (< 1% on average).

Plant phenology

Similar to our estimates in summer 2–threefold higher than in winter (Peterson et al. 2007; Mabrouk et al. 2015, 2017), Sfriso et al. (2020) estimated an occurrence of 41.6% of a total of 107 stations for microcalcareous epiphytic seaweeds composed majorly of *Hydrolithon*, *Pneophyllum*, and *Melobesia* species in the Italian coasts. In summer, the epiphytes were increased on seagrass owing to the low concentration of the nutrient induced by the leaf turnover of the seagrass which was minima in winter (Peterson et al. 2007). This brought about a difference of 20% in the occurrence of epiphytes between winter and summer (Peterson et al. 2007) similar to the difference estimated in the present study.

Encrusting algae (generally belonging to the genera *Hydrolithon* and *Pneophyllum*) dominate the epiphytic communities and occur as patches of crusts up to 3.5 mm in diameter, which vary in thickness between thin, monostromatic crusts several tens of microns thick (Beavington-Penney Simon et al. 2004): *H. boreale* up to 2–5 mm in diameter and up to 0.02 mm thick (Bradassi 2011; Reyes and Afonso-Carrillo 1995) and *P. fragile* crusts up to 700 µm and 2 mm in diameter (Kjølsterud 1997; Bradassi 2011). Our measurements fell within the above range of the crust size of the epiphyte. The epiphyte, *H. boreale*, was not found on blades of *P. oceanica* during 2011–2012 in Antalya Gulf, but *P. fragile* was determined on leaves of *C. nodosa* on an isolated island within the study area (Fig. 1c). Therefore, *C. nodosa* had LAI enough only for *Pneophyllum fragile* considering the leaf width of *C. nodosa*. On contrary, the richness of rhodophyta epiphytic algae was high in winter and low in spring–autumn around Canary Island where *P. fragile* and *H. farinosum* were permanent species on leaves of *C. nodosa* (Reyes and Sanson 1997) and on the different coasts of the Mediterranean Sea (Jacquemart and Demoulin 2008; Mabrouk et al. 2014).

With respect to the depthwise distribution of crustose macroalgae, their coverage decreased from the shallowest to the deepest station during both winter and summer (Tsirika et al. 2007). As the depth increased, increased diameter of the epiphyte limited increase in the density of epiphyte in a given LAI of *P. oceanica* in a matter of carrying capacity of the leaf during the present study.

Phenology-environment relation

Sensitive epiphytes were positively correlated with water transparency and the %DO (Bermejo et al. 2016) with salinity (Sfriso et al. 2017). Nevertheless, the nutrient concentrations both in the water column and surface sediments and Chl-*a* were negatively correlated with the sensitive taxa (Sfriso et al. 2017).

In the Mediterranean Sea, overall the decomposition of thionitrophilous taxa reduced pH values which slowed down the growth of small calcareous species such as *P. fragile* and *Hydrolithon* spp which cannot grow in poor-bad conditions (Sfriso et al. 2007, 2009, 2014). The epiphyte was affected by the pH of the water. Sfriso et al. (2020) fixed a range of pH from > 7.93 (Martin et al. 2008; Cox et al. 2015) to 8.35 for the occurrence of the calcareous seaweeds due to inhibition of utilization of HCO₃ via CO₂ in higher pH (Mann 2001; Martin et al. 2008; Fragoso et al. 2010; Mutalipassi et al. 2020) for growth of calcareous seaweeds in the Mediterranean Sea (Sfriso et al. 2020).

Regarding the essential nutrient concentrations, especially N-components to the marine flora, the nutrients had concentrations 2–threefold more in 2011–2012 (absent of *H. boreale* on leaves) than those in 2019 during the present study area (Table 8 in Appendix). The microcalcareous epiphytic seaweeds reappeared in a location classified as bad ecological conditions and status which were then recovered to healthy conditions (Sfriso et al. 2020). Besides, nutrientphilic epiphytes were producing high biomass (Balata et al. 2008). On contrary, Mabrouk et al. (2013) compared qualification and quantification of the epiphytes between the control with high water transparency and NH₄-N and disturbed sites with low NO₃-N and NO₂-N and high Si(OH)₄-Si; epiphytic red algae especially coralline algae as *H. farinosum*, *Fosleilla* spp., and *P. fragile* were dominant in the disturbed area in contrast to the green epiphytic algae as agreed by the other studies (Lepoint et al. 2007; Ben Brahim et al. 2010; Balata et al. 2010). Such epiphytes had tolerance to low light intensity, mostly in a shaded area (Boudouresque et al. 1984), and rapid absorption of nutrients (Lepoint et al. 2007).

The silicate was a prominent compound for the growth of the microcalcereous epiphytic seaweed on the leaves of aquatic angiosperms (Sfriso et al. 2020). The geological chronology of the study area showed that the mountain had mixed siliciclastic-carbonate, carbonate deposition, and then deeper-water deposits derived from the shallow-water carbonates in the easternmost (e.g., Duman et al. 2017), center (Ediger et al. 1997) shelf of the Turkish Mediterranean coast and the streams can bring the carbonates (Walsh-Kennedy et al. 2014; Radeff et al. 2017). The total carbonate content of the sediment in Antalya Gulf varied between 30 and 80% in both winter and summer (Fig. 13 in Appendix, from Mutlu et al. 2014). The highest carbonate contents were measured around locations where the calcite rock was found. In Finike Bay, *P. oceanica* did not inhabit the bottom since sediments of the Bay had low carbonate content (Appendix 12). Inherently, crustose coralline algae at low pH (mean pH 6.9) were significantly smaller and exhibited altered skeletal mineralogy (high Mg calcite to gypsum, hydrated calcium sulfate, Kamenos et al. 2016).

Besides, the trace element concentrations (As, Cd, Cr, Cu, Ni, and Pb) differentiated the density (shoot and LAI) of *P. oceanica*. Epiphyte biomass of mostly *P. fragile* and *H. farinosum* predominated; the higher concentration of the trace elements caused the lower density and biomass (Bedini and Piazzini 2012). Anthropogenic-sourced trace elements increased the density of *P. oceanica*, and a natural trace element, Ni, decreased the density and size of the epiphyte based on measurements of trace elements by Öztürk et al. (2021). Such epiphytes are classified as good ecological

indicators based on the elements (Martinez-Crego et al. 2010). However, leaf epiphytes are known to be less sensitive to chemical impacts (Piazzini et al. 2004).

Conclusions

One of the sensitive species to the environmental disturbance, *H. boreale* recently and dominantly occurred on the blades of a Mediterranean meadow, *P. oceanica* along the entire Turkish Mediterranean coast. Crusts of *P. fragile* on leaves of *C. nodosa* grew up to 2.7 mm in diameter, while crust of *H. boreale* on leaves of *P. oceanica* up to 2.9 mm in winter and 4.96 mm in summer depending on space on the leaf surface. Average coverage of *H. boreale* was 0.12% (up to 0.75%) of the leaf surface of *P. oceanica*. The epiphytes were predominant in summer. The size and density (abundance and biomass) of the epiphyte were contrasted. Primarily SiO₄-Si (generally landward sourced from the mountains surrounding the study area) of the water accelerated their occurrence and growth in their size, but reduced their density. Furthermore, the pH, nutrients, (especially NO₂ + NO₃-N), chl-*a*, TSM, and salinity of the water affected the quantification of these sensitive epiphytes. Besides natural and anthropogenic trace elements, bottom types significantly affected the phenological biometrics of the epiphyte. Organically loaded coastal bottom caused being devoid of the epiphyte (Fig. 12 in Appendix). Future studies could be based on the present study for water and ecological status.

Appendix

Table 2 Spearman correlation between the biometrics of epiphyte and physical environmental parameters (see Table 6 in Appendix for the abbreviations), and bottom depth (De) and type (BT) in winter

	TA		D		T		B	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
SS	-0.211	0.155	-0.188	0.205	-0.156	0.295	-0.213	0.151
ST	-0.279	0.057	-0.309	0.035	-0.267	0.069	-0.279	0.058
SpH	0.129	0.388	0.101	0.498	0.12	0.42	0.126	0.399
SO	0.303	0.038	0.278	0.059	0.281	0.056	0.302	0.039
NS	0.057	0.702	0.038	0.802	0.062	0.678	0.058	0.698
NT	-0.29	0.048	-0.305	0.037	-0.298	0.042	-0.29	0.048
NpH	-0.047	0.755	-0.065	0.664	-0.065	0.666	-0.052	0.726
NO	0.301	0.04	0.313	0.032	0.292	0.047	0.3	0.04
Sec	0.13	0.383	0.136	0.363	0.164	0.272	0.133	0.374
De	-0.119	0.427	-0.103	0.489	-0.117	0.434	-0.121	0.419
BT	0.4216	0.0032	0.3431	0.0182	0.3643	0.0118	0.4206	0.0032

The bold values are significantly correlated at $p < 0.05$

Table 3 Spearman correlation between the biometrics of epiphyte and physical and chemical environmental parameters (see Table 6 in Appendix for the abbreviations), and bottom depth (De) and type (BT) in summer

	TA		D		T		B	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
SS	-0.081	0.424	-0.113	0.262	-0.108	0.284	-0.096	0.344
ST	0.049	0.626	-0.098	0.33	-0.011	0.915	0.046	0.653
SpH	0.106	0.295	0.038	0.704	0.079	0.437	0.107	0.289
NS	0.29	0.003	0.358	0	0.318	0.001	0.283	0.004
NT	0.235	0.019	0.151	0.134	0.188	0.061	0.237	0.018
NpH	-0.043	0.672	-0.059	0.558	-0.017	0.87	-0.029	0.771
Sec	-0.156	0.12	-0.08	0.428	-0.096	0.341	-0.144	0.153
De	-0.146	0.146	-0.18	0.073	-0.156	0.122	-0.169	0.093
BT	-0.0114	0.91	0.1476	0.1428	0.0614	0.5437	-0.0097	0.9239
SSiO ₄ -Si	-0.342	0.000	-0.309	0.002	-0.287	0.004	-0.321	0.001
SNO ₃ -N	-0.075	0.459	-0.074	0.463	-0.026	0.794	-0.059	0.560
SPO ₄ -P	0.020	0.841	-0.002	0.981	-0.022	0.831	0.011	0.912
SNO ₂ -N	-0.006	0.955	0.040	0.690	0.064	0.525	0.004	0.966
SNH ₄ -N	-0.108	0.283	-0.088	0.383	-0.081	0.423	-0.111	0.270
SNO ₂ +NO ₃ -N	-0.036	0.722	0.009	0.925	0.035	0.728	-0.023	0.817
NSiO ₄ -Si	-0.061	0.545	0.054	0.594	0.031	0.759	-0.050	0.623
NNO ₃ -N	-0.130	0.196	-0.051	0.618	-0.116	0.249	-0.123	0.223
NPO ₄ -P	0.152	0.131	0.212	0.034	0.148	0.143	0.150	0.136
NNO ₂ -N	0.079	0.433	0.091	0.367	0.124	0.218	0.085	0.403
NNH ₄ -N	0.042	0.679	0.086	0.395	0.095	0.347	0.043	0.673
NNO ₂ +NO ₃ -N	0.043	0.673	0.054	0.592	0.084	0.403	0.047	0.640
STSM	-0.170	0.091	-0.127	0.208	-0.116	0.252	-0.172	0.087
NTSM	-0.083	0.412	-0.146	0.148	-0.195	0.052	-0.088	0.385
Chl <i>a</i>	-0.147	0.146	-0.135	0.182	-0.094	0.352	-0.145	0.150

The bold values are significantly correlated at *p* < 0.05

Table 4 Linear multiple-regression constants (*a*; intercept, *b*; slope) between the biometrics of epiphyte and LAI of *Posidonia oceanica* and sea surface SiO₄-Si in summer

	<i>a</i>	<i>b</i> (LAI)	<i>b</i> (SiO ₄ -Si)	Adjusted <i>R</i> ²	<i>p</i>
TA	63.863	2.629	-5.526	0.01	0.228
D	1.447	-0.013	-0.071	0.03	0.091
T	0.170	0.0005	-0.010	0.06	0.021
B	0.304	0.011	-0.025	0.01	0.227

Bold *a* and *b* values were significantly represented for the relationship, and *p* value was significantly correlated (*R*²) for the multiple correlations at *p* < 0.05

Table 5 Partial correlation coefficients between biometrics and the environmental parameters (see Table 6 in Appendix for the abbreviations) for summer samplings

	D	T	B
SpH	0.206	0.243	0.235
NS	0.229	0.218	0.200
NpH	0.211	0.253	0.246
STSM	0.302	0.335	0.327
NTSM	0.299	0.335	0.328
Chl <i>a</i>	0.282	0.320	0.309
LAI	0.920	0.929	0.928

Values are only correlation coefficients that were significantly partial-correlated at *p* < 0.05

Table 6 Spearman correlation coefficients between the environmental parameters and the PCO solution of the biometrics. Bold value denotes significant correlation at $p < 0.05$

Environmental variables	Abbreviations	PCO1	PCO2
Sea surface salinity	SS	0.084	0.102
Sea surface temperature (°C)	ST	-0.041	0.177
Sea surface pH	SpH	-0.103	0.101
Near-bottom water salinity	NS	-0.289	-0.237
Near-bottom water pH	NpH	0.044	0.038
Near-bottom water temperature (°C)	NT	-0.124	-0.127
Secchi disk depth (m)	Sec	0.152	-0.080
Bottom depth (m)	De	0.148	0.062
Sea surface SiO ₄ -Si (μM)	SSiO ₄ -Si	0.342	0.105
Sea surface PO ₄ -P (μM)	SPO ₄ -P	-0.019	-0.075
Sea surface NH ₄ -N (μM)	SNH ₄ -N	0.111	0.032
Sea surface NO ₂ +NO ₃ -N (μM)	SNO ₂ +NO ₃ -N	0.037	-0.078
Near-bottom water SiO ₄ -S (μM)	NSiO ₄ -Si	0.061	-0.192
Near-bottom water PO ₄ -P (μM)	NPO ₄ -P	-0.157	-0.094
Near-bottom water NH ₄ -N (μM)	NNH ₄ -N	-0.042	0.039
Near-bottom water NO ₂ +NO ₃ -N (μM)	NNO ₂ +NO ₃	-0.045	-0.011
Sea surface total suspended matter (mg/l)	STSM	0.170	-0.119
Near-bottom water total suspended matter (mg/l)	NTSM	0.086	0.117
Sea surface chlorophyll <i>a</i> (mg/l)	Chl <i>a</i>	0.148	-0.070

Table 7 Spearman correlation coefficients between the trace elements in blades of *Posidonia oceanica* and its sediments, and the biometrics of the epiphyte and LAI of *P. oceanica* in summer

	V	Cr	Ni	Cu	Zn	As	Cd	Pb
TA	-0.051	-0.076	-0.318	-0.197	-0.167	0.080	-0.065	0.006
D	-0.154	-0.143	-0.338	-0.281	-0.302	0.003	-0.170	-0.016
T	-0.092	-0.092	-0.359	-0.228	-0.210	0.056	-0.099	0.041
B	-0.041	-0.065	-0.317	-0.187	-0.162	0.090	-0.057	0.027
LAI	-0.045	-0.076	-0.326	-0.168	-0.205	-0.177	-0.081	-0.052
TA	0.092	-0.184	-0.418	-0.026	0.020	0.237	0.149	0.018
D	0.211	0.031	-0.199	0.084	0.101	0.350	0.279	0.197
T	0.179	-0.087	-0.322	0.060	0.088	0.292	0.240	0.094
B	0.101	-0.176	-0.405	-0.020	0.024	0.232	0.165	0.035
LAI	0.463	0.110	-0.171	0.361	0.429	0.384	0.401	0.358

Bold coefficients are significant at $p < 0.05$



Fig. 9 Through an unusual habitat, a sponge stuck to the rocks, *Hydrolithon boreale* on the tips of leaves of *Posidonia oceanica*

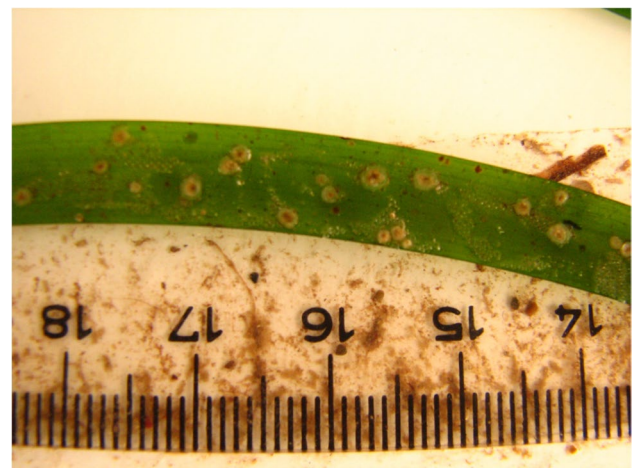


Fig. 10 A leaf of *Posidonia oceanica*, invaded by *Hydrolithon boreale* preserved in the formalin solution

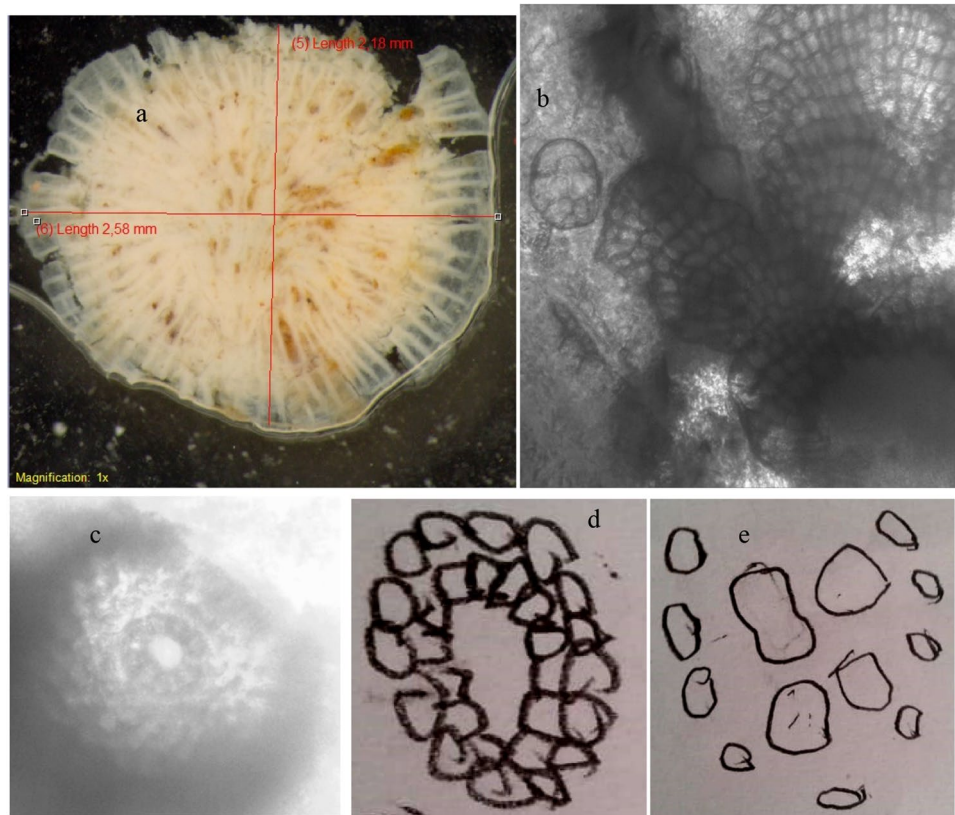


Fig. 11 *Hydrolithon boreale*: its crust preserved in the formalin solution (a), surface view of the thallus (b), carposporangial conceptacles surrounded by superficial vegetative cells (c), details draft—drawings of an inner and outer ring of pore filaments with uncounted cells sequence (d), and spore germination disk with a 4-celled central element and 4-celled laterally (8 cells) (e). **Brief description:** specimen preserved in the formalin is pinkish creamy in color (a), a disk with the center is thicker than the margin of the crust in shape. A thin and flat germination disk with cells sequenced curly perpendicular to the center (b). Carposporangial conceptacles are surrounded by superficial vegetative cells with 11 cells of the outer ring (c). Spore germination disk; four central cells in semi-rectangle or square in shape; two

larger than the other two, surrounded by 4 small cells on each lateral of the central cells (e) (Reyes and Afonso-Carrillo 1995). **Remarks to differentiate the other similar and common species in the Mediterranean Sea:** *Pneophyllum fragile* has an 8-celled central element on the spore germination disk (Reyes and Afonso-Carrillo 1995; Kjøsterud, 1997). *Hydrolithon farinosum* with spore germination disks consisting of a 4-celled central element in quarter oval-shaped, surrounded by 12 cells; central and lateral cells almost in the same size (Penrose and Chamberlain 1993). *Hydrolithon cruciatum*; spore germination disk consisting of a 4-celled central element in quarter oval-shaped, surrounded by 8 cells; central and lateral cells almost in the same size (Reyes and Afonso-Carrillo 1995; Kjøsterud 1997)

Table 8 Average essential nutrients (μM) distribution between a period of 2011–2012 in the Antalya Gulf (a) and 2019 in the present area (PSA) and Antalya Gulf (AG) (see Table 6 in Appendix for the abbreviations)

a	$\text{SNO}_3 + \text{NO}_2\text{-N}$	$\text{SNH}_4\text{-N}$	$\text{SPO}_4\text{-P}$	$\text{NNO}_3 + \text{NO}_2\text{-N}$	$\text{NNH}_4\text{-N}$	$\text{NPO}_4\text{-P}$		
Dec-2011	22.87	174.07	2.00	21.20	170.75	2.00		
Jan-2012	18.61	210.66	1.90	12.59	215.65	1.79		
Jul-2011	17.59	71.51	0.95	15.46	71.51	1.26		
Aug-2012	5.74	516.12	3.26	5.74	455.14	3.37		
b	$\text{SNO}_2 + \text{NO}_3\text{-N}$	$\text{SNH}_4\text{-N}$	$\text{SPO}_4\text{-P}$	$\text{NNO}_2 + \text{NO}_3\text{-N}$	$\text{NNH}_4\text{-N}$	$\text{NPO}_4\text{-P}$	$\text{SSiO}_4\text{-Si}$	$\text{NSiO}_4\text{-Si}$
PSA	2.39	137.83	8.77	1.81	185.94	7.51	61.47	34.85
AG	2.19	125.50	8.35	1.51	108.12	4.59	75.23	33.50

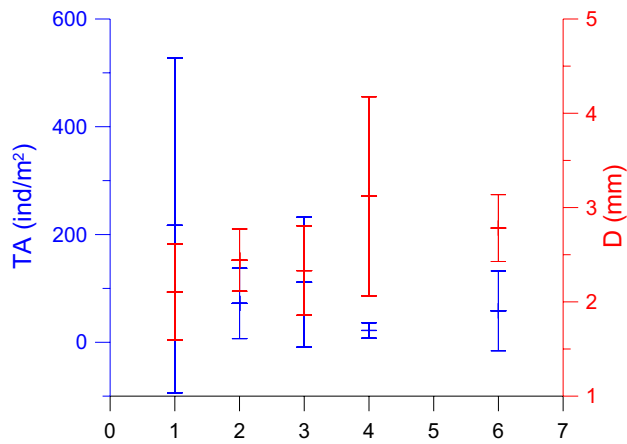
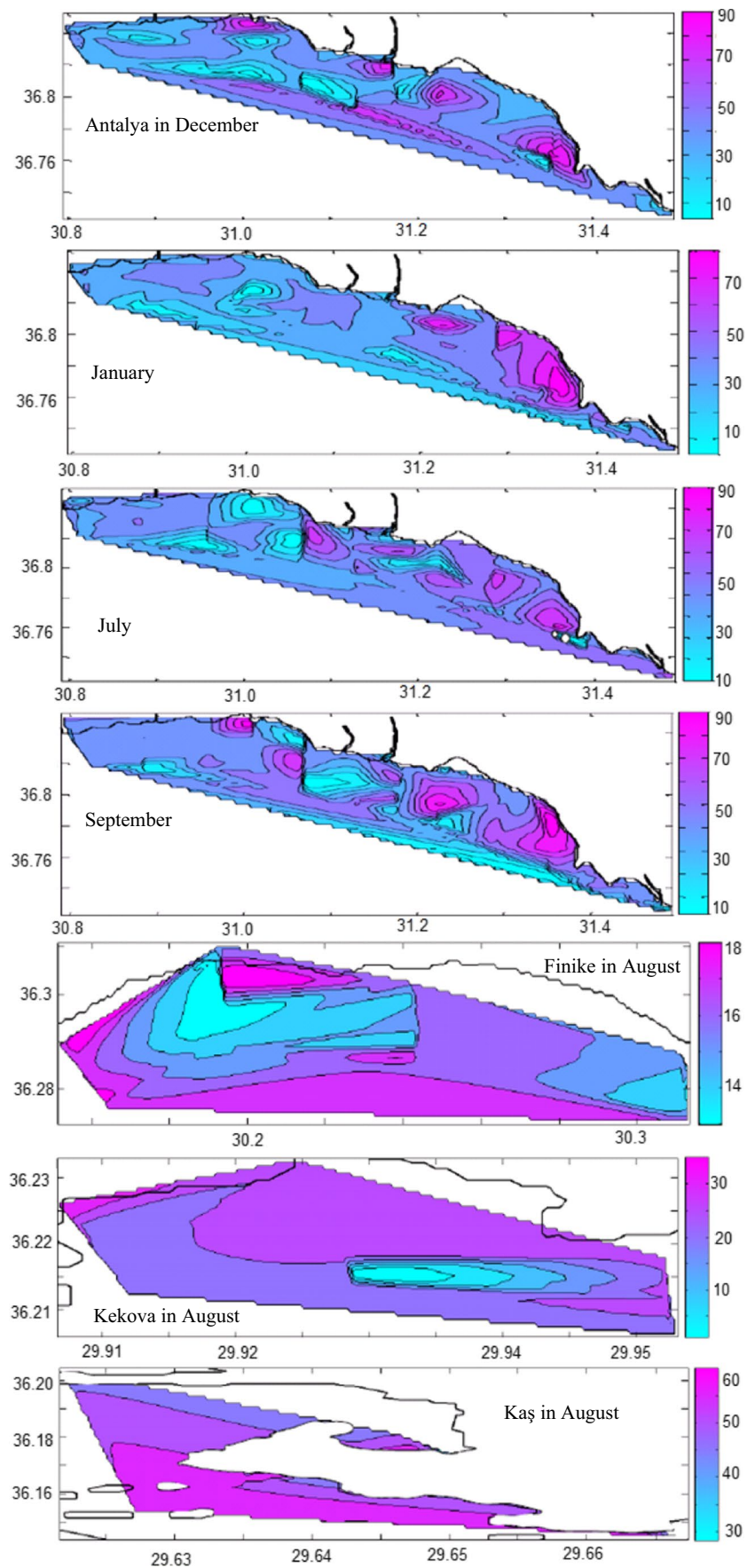


Fig. 12 Abundance (TA) and diameter (D) of the crust of *Hydrolython boreale* on leaves of *Posidonia oceanica* found on the different bottom types (1; rock, 2; sand, 3; matte, 4; mud, 5; coastal sandy mud, organically loaded; 6; white sand in summer (see Fig. 1 for the locations))

Fig. 13 Temporal total carbonate content (% on scale bar) of the surface sediment in Antalya Gulf and westerly adjacent bays found within the present study area (Mutlu et al. 2014) (see Fig. 1 for the locations)



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Data availability The data are not shared but the data will be available if requested by the journal.

Code availability All software used in the present study was used with the license of each code.

Declarations

Ethics approval The authors declare that all applicable guidelines for sampling, care, and experimental use of animals in the study have been followed.

Consent to participate All authors declare their participation in the study and the development of the manuscript herein.

Consent for publication All authors have read and approved the final version of the manuscript herein for publication in “Environmental Science and Pollution Research.”

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References

- Alcoverro T, Romero JCM, Duarte N, Lopez L (1997) Spatial and temporal variations in nutrient limitation of seagrass *Posidonia oceanica* growth in the NW Mediterranean. *Mar Ecol-Prog Ser* 146:155–161. [10.3354/meps146155](https://doi.org/10.3354/meps146155)
- APHA (1999) Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington DC
- Baggett LP, Heck KL, Frankovich TA, Armitage AR, Fourqurean JW (2010) Nutrient enrichment, grazer identity, and their effects on epiphytic algal assemblages, field experiments in subtropical turtlegrass *Thalassia testudinum* meadows. *Mar Ecol Prog Ser* 406:33–45
- Balata D, Bertocci I, Piazzini L, Nesti U (2008) Comparison between epiphyte assemblages of leaves and rhizomes of the seagrass *Posidonia oceanica* subjected to different levels of anthropogenic eutrophication. *Estuar Coast Shelf Sci* 79:533–540. <https://doi.org/10.1016/j.ecss.2008.05.009>
- Balata D, Piazzini L, Nesti U, Bulleri F, Bertocci I (2010) Effects of enhanced loads of nutrients on epiphytes on leaves and rhizomes of *Posidonia oceanica*. *J Sea Res* 63:173–179. <https://doi.org/10.1016/j.seares.2009.12.001>
- Beavington-Penney Simon J, Paul WV, Woelkerling Wm J (2004) Recognising macrophyte-vegetated environments in the rock record: a new criterion using ‘hooked’ forms of crustose coralline red algae. *Sediment Geol* 166:1–9. <https://doi.org/10.1016/j.sedgeo.2003.11.022>
- Bedini R, Canali Mg, Bertuccelli M (2003) Epiphytic communities on *Posidonia oceanica* (L.) Delile leaves along the north Tyrrhenian coasts (N.W. Mediterranean Sea, Italy). *Medit Mar Sci* 4(2):99–114. <https://doi.org/10.12681/mms.233>
- Bedini R, Piazzini L (2012) Evaluation of the concurrent use of multiple descriptors to detect anthropogenic impacts in marine coastal systems. *Mar Biol Res* 8(2):129–140. <https://doi.org/10.1080/17451000.2011.615324>
- Ben Brahim M, Hamza A, Hannachi I, Rebai A, Jarboui O, Bouain A, Aleya L (2010) Variability in the structure of epiphytic assemblages of *Posidonia oceanica* in relation to human interferences in the Gulf of Gabes, Tunisia. *Mar Environ Res* 70(5):411–421. <https://doi.org/10.1016/j.marenvres.2010.08.005>
- Bermejo R, Fuente G de la, Ramírez-Romero E, Vergara JJ, Hernández I (2016) Spatial variability and response to anthropogenic pressures of assemblages dominated by a habitat forming seaweed sensitive to pollution (northern coast of Alboran Sea). *Mar Poll Bull* 105(1):255–264. <https://doi.org/10.1016/j.marpolbul.2016.02.017>
- Bianchi CN, Morri C, Chiantore M, Montefalcone M, Parravicini V, Rovere A (2012) Mediterranean Sea biodiversity between the legacy from the past and a future of change. In: Science N (ed) *Life in the Mediterranean Sea: a look at habitat changes*, Stambler N. Publishers, New York, pp 1–55
- Boudouresque CF, Bernard G, Bonhomme P, Charbonnel E, Diviacco G, Meinesz A, Pergent G, Pergent-Martini C, Ruitton S, Tunesi L (2012) Protection and conservation of *Posidonia oceanica* meadows. RaMoGe and RAC/SPA, Tunis
- Boudouresque CF, Jeudy de Grissac A, Meinesz A (1984) Relations entre le sédimentation et l’allongement des rhizomes orthotropes de *Posidonia oceanica* dans la baie d’Elbu (Corse). In: Boudouresque CF, Jeudy de Grissac A, Olivier J (eds) *International workshop on Posidonia oceanica beds*. GIS Posidonie Publishers, Marseille, p 185–191
- Bradassi F (2011) Determining a threshold in effect of ocean acidification on crustose coralline algae (including a case study to teach at school). PhD Thesis. Università Degli Studi Di Trieste, 144 pp.
- Brahim MB, Mabrouk L, Hamza A, Jribi I (2020) Comparison of spatial scale variability of shoot density and epiphytic leaf assemblages of *Halophila stipulacea* and *Cymodocea nodosa* on the Eastern Coast of Tunisia. *Plant Biosyst* 154(3):413–426. <https://doi.org/10.1080/11263504.2019.1674399>
- Çirik Ş, Akçalı B, Özalp HB (2006) Çanaklake Boğazı ve Marmara Denizi’nde İşaretleme Yöntemi ile *Posidonia oceanica*’nın Sınırlarının Belirlenmesi. *E.U. J Fish Aquat Sci* 23:45–48
- Colantoni P, Gallignani P, Fresi E, Cinelli F (1982) Patterns of *Posidonia oceanica* (L.) DELILE Beds around the Island of Ischia (Gulf of Naples) and in adjacent waters. *PSZNI Mar Ecol* 3(1):53–74. <https://doi.org/10.1111/j.1439-0485.1982.tb00105.x>
- Cox TE, Schenone S, Delille J, Díaz-Castañeda V, Alliouane S, Gattuso J-P, Gazeau F (2015) Effects of ocean acidification on *Posidonia oceanica* epiphytic community and shoot productivity. *J Ecol* 103:1594–1609. <https://doi.org/10.1111/1365-2745.12477>
- Den Hartog C (1977) Structure, function, and classification in seagrass communities. In: McRoy CP, Helfferich C (eds) *Seagrass ecosystems: a scientific perspective*. Marcel Dekker, New York, pp 89–121
- Duman TY, Robertson AHF, Elmacı H, Kara M (2017) Palaeozoic–Recent geological development and uplift of the Amanos Mountains (S Turkey) in the critically located northwesternmost corner of the Arabian continent. *Geodin Acta* 29(1):103–138. <https://doi.org/10.1080/09853111.2017.1323428>
- Ediger V, Evans G, Ergin M (1997) Recent surficial shelf sediments of the Cilician Basin (Turkey), northeastern Mediterranean. *Continental Shelf Res* 17(13):1659–1677

- El-Geziry TM, Bryden IG (2010) The circulation pattern in the Mediterranean Sea: issues for modeller consideration. *J Oper Oceanogr* 3(2):39–46. <https://doi.org/10.1080/1755876X.2010.11020116>
- Fragoso D, Ramírez-Cahero F, Rodríguez-Galván A, Hernández-Reyes R, Heredia A, Rodríguez D, Aguilar-Franco M, Bucio L, Basiuk VA (2010) Characterization of the CaCO₃ biomineral in coralline red algae (Corallinales) from the Pacific coast of Mexico. *Cienc Mar* 36(1):41–58
- Giakoumi S, Sini M, Gerovasileiou V, Mazor T, Beher J, Possingham HP, Abdulla A, Cinar ME, Dendrinis P, Gucu AC, Karamanlidis AA, Rodic P, Panayotidis P, Taskin E, Jaklin A, Voultsiadou E, Webster C, Zenetos A, Katsanevakis S (2013) Ecoregion-based conservation planning in the Mediterranean: dealing with large-scale heterogeneity. *PLoS ONE* 8(10):e76449
- Gobert S, Sartoretto S, Rico-Raimondino V, Andral B, Chery A, Lejeune P, Boissery P (2009) Assessment of the ecological status of Mediterranean French coastal waters as required by the water framework directive using the *Posidonia oceanica* rapid easy index: PREI. *Mar Pollut Bull* 58(11):1727–1733. <https://doi.org/10.1016/j.marpolbul.2009.06.012>
- Güçü G, Gücü AC (2002) Ecological significance of sea grass meadows (*Posidonia oceanica* (L.) Delile) in Bozyazı-Kızilliman Marine Protected Area. Proceeding of the second international conference on oceanography of the Eastern Mediterranean and Black sea: similarities and differences of two interconnected Basins, METU Cultural and Convention Center Ankara, Turkey 1:924–32
- Gündođdu S, Çevik C (2017) Micro- and mesoplastics in Northeast Levantine coast of Turkey: the preliminary results from surface samples. *Mar Poll Bull* 118(1–2):341–347. <https://doi.org/10.1016/j.marpolbul.2017.03.002>
- Jacquemart J, Demoulin V (2008) Comparison of the epiphytic macroflora of *Posidonia oceanica* leaves in different meadows of the western Mediterranean. *Flora Mediterr* 18:393–420
- Jaschinski S, Sommer U (2008) Top-down and bottom-up control in an eelgrass-epiphyte system. *Oikos* 117:754–762
- Kamenos NA, Perna G, Gambi MC, Micheli F, Kroeker KJ (2016) Coralline algae in a naturally acidified ecosystem persist by maintaining control of skeletal mineralogy and size. *Proc R Soc B* 283(1840):11–59. <https://doi.org/10.1098/rspb.2016.1159>
- Kjøsterud AB (1997) Epiphytic coralline crusts (Corallinales, Rhodophyta) from South Norway. *Sarsia* 82(1):23–37. <https://doi.org/10.1080/00364827.1997.10413635>
- Lepoint G, Cox AS, Dauby P, Poulicek M, Gobert S (2006) Food sources of two detritivore amphipods associated with the seagrass *Posidonia oceanica* leaf litter. *Mar Biol Res* 2:355–365
- Lepoint G, Jacquemart J, Bouquegneau J-M, Demoulin V, Gobert S (2007) Field measurements of inorganic nitrogen uptake by epiphyte components of the seagrass *Posidonia oceanica* (Monocotyledons, Posidoniaceae). *J Phycol* 43:208–218. <https://doi.org/10.1111/j.1529-8817.2007.00322.x>
- Lepoint G, Millet S, Dauby P, Gobert S, Bouquegneau JM (2002) Annual nitrogen budget of the seagrass *Posidonia oceanica* as determined by *in situ* uptake experiments. *Mar Ecol-Prog Ser* 237:87–96. <https://doi.org/10.3354/meps237087>
- Lepoint G, Nyssen F, Gobert S, Dauby P, Bouquegneau JM (2000) Relative impact of a seagrass bed and its adjacent epilithic algal community in consumer diets. *Mar Biol* 136:513–518
- Lorenzen CJ (1967) Determination of chlorophyll and phaeopigments: spectrophotometric equations. *Limnol Oceanogr* 12(2):343–346
- Mabrouk L, Asma H, Bradai MN (2017) Temporal and bathymetric variation on of epiphyte cover and leaf biomass in a southern *Posidonia oceanica* (L.) meadow: The case of Mahdia coast, Tunisia. *Mar Ecol* 38:e12394. <https://doi.org/10.1111/maec.12394>
- Mabrouk L, Brahim MB, Hamza A, Bradai M-N (2014) Diversity and temporal fluctuations of epiphytes and sessile invertebrates on the rhizomes *Posidonia oceanica* in a seagrass meadow off Tunisia. *Mar Ecol* 35:212–220. <https://doi.org/10.1111/maec.12072>
- Mabrouk L, Brahim MB, Hamza A, Bradai M-N (2015) Temporal and spatial zonation of macroepiphytes on *Posidonia oceanica* (L.) Delile leaves in a meadow off Tunisia. *Mar Ecol* 36:77–92. <https://doi.org/10.1111/maec.12118>
- Mabrouk L, Hamza A, Brahim MB, Bradai M-N (2013) Variability in the structure of epiphyte assemblages on leaves and rhizomes of *Posidonia oceanica* in relation to human disturbances in a seagrass meadow off Tunisia. *Aquat Bot* 108:33–40. <https://doi.org/10.1016/j.aquabot.2013.03.002>
- Mann S (2001) Biomineralization: principles and concepts in bioinorganic materials chemistry. Oxford University Press, New York
- Marbà N, Duarte CM, Holmer M, Martinez R, Basterretxea G, Orfila A, Jordi A, Tintore J (2002) Effectiveness of protection of seagrass (*Posidonia oceanica*) populations in Cabrera national park (Spain). *Environ Conserv* 29(04):509–518. <https://doi.org/10.1017/S037689290200036X>
- Martin S, Rodolfo-Metalpa R, Ransome E, Rowley S, Buia M-C, Gattuso J-P, Hall-Spencer J (2008) Effects of naturally acidified seawater on seagrass calcareous epibionts. *Biol Lett* 4:689–692. <https://doi.org/10.1098/rsbl.2008.0412>
- Martinez-Crego B, Prado P, Alcoverro T, Romero J (2010) Composition of epiphytic community of *Posidonia oceanica* as a tool for environmental biomonitoring. *Estuar Coast Shelf Sci* 88:199–208
- Mutalipassi M, Fink P, Maibam C, Porzio L, Buia MC, Gambi MC, Patti FP, Scipione MB, Lorenti M, Zupo V (2020) Ocean acidification alters the responses of invertebrates to wound-activated infochemicals produced by epiphytes of the seagrass *Posidonia oceanica*. *J Exp Mar Biol Ecol* 530–531:151435. <https://doi.org/10.1016/j.jembe.2020.151435>
- Mutlu E, Balaban C, Gokoglu M, Özvarol Y, Olguner MT (2014) Acoustical density-dependent calibration of the dominant sea meadows and seagrasses and monitoring of their distribution. TUBITAK project, grant no: 110Y232, Final report, The Scientific and Technological Research Council of Turkey, Ankara, p 368
- Mutlu E, Özvarol Y, Şahin A, Duman GS, Karaca D (2020a) Acoustical determination of biomass quantities and monitoring of distribution of *Posidonia oceanica* meadows on the Turkish entire coasts in the Eastern Mediterranean. TUBITAK project, grant no: 117Y133, Final report, The Scientific and Technological Research Council of Turkey, Ankara, p 190
- Mutlu E, Özvarol Y, Şahin A, Duman GS, Karaca D (2020b) Macro litter distribution of the Turkish Mediterranean coasts dominated by pleasure crafts. *Mar Poll Bull* 151:110833. <https://doi.org/10.1016/j.marpolbul.2019.110833>
- Mutlu E, Olguner C, Gökoglu M, Özvarol Y (2022) Seasonal growth dynamics of *Posidonia oceanica* in a pristine Mediterranean gulf. *Ocean Sci J*. <https://doi.org/10.1007/s12601-022-00078-8>
- Nesti U, Piazzoli L, Balata D (2009) Variability in the structure of epiphytic assemblages of the Mediterranean seagrass *Posidonia oceanica* in relation to depth. *Mar Ecol* 30:276–287. <https://doi.org/10.1111/j.1439-0485.2008.00275.x>
- Olguner MT, Olguner C, Mutlu E, Deval MC (2018) Distribution and composition of benthic marine litter on the shelf of Antalya in the eastern Mediterranean. *Mar Pollut Bull* 136:171–176. <https://doi.org/10.1016/j.marpolbul.2018.09.020>
- Öztürk RÇ, Gedik K, Şahin A, Özvarol Y, Mutlu E (2021) Comparative trace element trends in *Posidonia oceanica* and its sediments along the Turkish-Mediterranean Sea coast. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-021-15089-6>
- Penrose D, Chamberlain YM (1993) *Hydrolithon farinosum* (Lamouroux) comb. nov.: implications for generic concepts in the Mastophoroideae (Corallinaceae, Rhodophyta). *Phycologia* 32(4):295–303

- Pergent G, Bazairi H, Bianchi CN, Boudouresque CF, Buia MC, Calvo S, Clabaut P, Harmelin-Vivien M, Mateo MA, Montefalcone M, Morri C, Orfanidis S, Pergent-Martini C, Semroud R, Serrano O, Thibaut T, Tomasello A, Verlaque M (2014) Climate change and Mediterranean seagrass meadows: a synopsis for environmental managers. *Mediterr Mar Sci* 15(2):462–473
- Peterson BJ, Frankovich TA, Zieman JC (2007) Response of seagrass epiphyte loading to field manipulations of fertilization, gastropod grazing and leaf turnover rates. *J Exp Mar Biol Ecol* 34:61–72. <https://doi.org/10.1016/j.jembe.2007.04.012>
- Piazzi L, Acunto S, Cinelli F (2000) Mapping of *Posidonia oceanica* beds around Elba Island (western Mediterranean) with integration of direct and indirect methods. *Oceanol Acta* 23:339–346
- Piazzi L, Balata D, Cinelli F (2002) Epiphytic macroalgal assemblages of *Posidonia oceanica* rhizomes in the western Mediterranean. *European J Phycol* 37(1):69–76. <https://doi.org/10.1017/S0967026201003432>
- Piazzi L, Balata D, Cinelli F, Benedetti-Cecchi L (2004) Patterns of spatial variability in epiphytes of *Posidonia oceanica*. Differences between a disturbed and two reference locations. *Aquat Bot* 79:345–356
- Planton S, Lionello P, Artale V, Aznar R, Carrillo A, Colin J, Congedi L, Dubois C, Elizalde A, Gualdi S, Hertig E, Jacobeit J, Jordà G, Li L, Mariotti A, Piani C, Ruti P, Sanchez-Gomez E, Sannino G, Sevault F, Somot S, Tsimplis M (2012) The climate of the Mediterranean region in future climate projections. In: Lionello P (ed) *The climate of the Mediterranean region, from the past to the future*. Elsevier, Amsterdam, pp 449–502
- Poulain P-M, Bussani A, Gerin R, Jungwirth R, Mauri E, Menna M, Notarstefano G (2013) Mediterranean surface currents measured with drifters: from basin to subinertial scales. *Oceanography* 26(1):38–47. <https://doi.org/10.5670/oceanog.2013.03>
- Prado P (2018) Seagrass epiphytic assemblages are strong indicators of agricultural discharge but weak indicators of host features. *Estuar Coast Shelf Sci* 204:140–148. <https://doi.org/10.1016/j.ecss.2018.02.026>
- Prado P, Alcoverro T, Martínez-Crego B, Vergés A, Pérez M, Romero J (2007) Macrograzers strongly influence patterns of epiphytic assemblages in seagrass meadows. *J Exp Mar Biol Ecol* 350:130–143. <https://doi.org/10.1016/j.jembe.2007.05.033>
- Radeff G, Schildgen TF, Cosentino D, Strecker MR, Cipollari P, Darbaş G, Gürbüz K (2017) Sedimentary evidence for late Messinian uplift of the SE margin of the Central Anatolian Plateau: Adana Basin, southern Turkey. *Basin Res* 29:488–514
- Reyes J, Afonso-Carrillo J (1995) Morphology and distribution of nongeniculate coralline algae (Corallinaceae, Rhodophyta) on the leaves of the seagrass *Cymodocea nodosa* (Cymodoceaceae). *Phycol* 34(3):179–190
- Reyes J, Sanson M (1997) Temporal distribution and reproductive phenology of the epiphytes on *Cymodocea nodosa* leaves in the Canary islands. *Bot Mar* 40:193–201
- Sfriso A, Buosi A, Facca C, Sfriso AA (2017) Role of environmental factors in affecting macrophyte dominance in transitional environments: the Italian lagoons as a study case. *Mar Ecol* 38:e12414. <https://doi.org/10.1111/maec.12414>
- Sfriso A, Buosi A, Wolf MA, Sciuto K, Molinaroli E, Moro I, Mistri M, Munari C, Sfriso AA (2020) Microcalcareous seaweeds as sentinels of trophic changes and CO₂ trapping in transitional water systems. *Ecol Indic* 118:106692. <https://doi.org/10.1016/j.ecoli.2020.106692>
- Sfriso A, Facca C, Bon D, Buosi A (2016) Macrophytes and ecological status assessment in the Po delta transitional systems, Adriatic Sea (Italy). Application of Macrophyte Quality Index (MaQI). *Acta Adriat* 57(2):209–226
- Sfriso A, Facca C, Bonometto A, Boscolo R (2014) Compliance of the macrophyte quality index (MaQI) with the WFD (2000/60/EC) and ecological status assessment in transitional areas: the Venice lagoon as study case. *Ecol Indic* 46:536–547. <https://doi.org/10.1016/j.ecolind.2014.07.012>
- Sfriso A, Facca C, Ghetti PF (2007) Rapid Quality Index, based mainly on macrophyte associations (R-MaQI), to assess the ecological status of the transitional environments. *Chem Ecol* 23(6):1–11
- Sfriso A, Facca C, Ghetti PF (2009) Validation of the Macrophyte Quality Index (MaQI) set up to assess the ecological status of Italian marine transitional environments. *Hydrobiologia* 617:117–141
- Sisma-Ventura G, Bialik OM, Yam R, Herut B, Silverman J (2017) pCO₂ variability in the surface waters of the ultra-oligotrophic Levantine Sea: exploring the air–sea CO₂ fluxes in a fast warming region. *Mar Chem* 196:13–23
- Sol D, Maspons J, Vall-Llosera M, Bartomeus I, Garcia-Pena GE, Pinol J, Freckleton RP (2012) Unraveling the life history of successful invaders. *Science* 337:580–583
- Tsirika A, Skoufas G, Haritonidis S (2007) Seasonal and bathymetric variations of epiphytic macroflora on *Posidonia oceanica* (L.) Delile leaves in the National Marine Park of Zakynthos (Greece). *Mar Ecol* 28(S1):146–153
- UNEP/MAP-RAC/SPA (2015) Guidelines for standardization of mapping and monitoring methods of marine magnoliophyta in the Mediterranean. RAC/SPA Publ, Tunis, p 48
- Vacchi M, De Falco G, Simeone S, Montefalcone M, Morri C, Ferrar M, Bianchi CN (2017) Biogeomorphology of the Mediterranean *Posidonia oceanica* seagrass meadows. *Earth Surf Proc Land* 42:42–54. <https://doi.org/10.1002/esp.3932>
- Via JD, Sturmabauer C, Schonweger G, Sotz E, Mathekowitsch S, Stifter M, Rieger R (1998) Light gradients and meadow structure in *Posidonia oceanica*: ecomorphological and functional correlates. *Mar Ecol-Prog Ser* 163:267–278. <https://doi.org/10.3354/meps163267>
- Walker DI, Woelkerling WJ (1988) Quantitative study of sediment contribution by epiphytic coralline red algae in seagrass meadows in Shark Bay, Western Australia. *Mar Ecol Prog Ser* 43:71–77
- Walsh-Kennedy S, Aksu AE, Hall J, Hiscott RN, Yaltrak C, Çifçi G (2014) Source to sink: the development of the latest Messinian to Pliocene-Quaternary Cilicia and Adana Basins and their linkages with the onland Mut Basin, eastern Mediterranean. *Tectonophysics* 622:1–21

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