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Characterization of a *Cymodocea nodosa* (Ucria) Ascherson Meadow in the Northern Adriatic Sea: Phenology, Reproduction and Epiphytic Assemblages

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Abstract

The little Neptune grass *Cymodocea nodosa* (Ucria) Ascherson is common in shallow coastal areas, lagoons and estuaries in the Mediterranean Sea. As a pioneer and habitat-forming macrophyte, it plays an important ecological role and deserves attention for conservation, especially in areas affected by anthropogenic stressors. A *C. nodosa* meadow located in a marina of the northern Adriatic Sea (Porticciolo di Torrette, Ancona, Italy) was monitored during its seasonal development (May–October 2024). Structural parameters (shoot density, leaf length and width, percentage of leaves with broken apices), plant fertility and composition of the epiphytic community were assessed across five sampling dates. This population exhibited the typical Mediterranean developmental pattern, with a fully developed canopy in summer (July–September). Female flowers were rarely found, whereas male flowers and fruits were not observed, suggesting that the meadow is likely to rely mainly on clonal propagation. Epiphytic communities displayed low diversity; encrusting corallines and filamentous red algae (*Ceramium* sp.) were the main algal epiphytes, whereas serpulid polychaetes and ascidiaceans were the main animal epiphytes. Overall, structure, phenology and epiphytic assemblages of the studied meadow are similar to those of other Mediterranean *Cymodocea* meadows, suggesting that this meadow has persisted under long-term urban conditions despite multiple anthropogenic pressures (not directly tested in the present study).

Keywords: benthos; epiphytes; morphometry; phenology; seagrasses; urbanization

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1. Introduction

Seagrasses are a group of 82 monocot angiosperms distributed throughout tropical and temperate waters [1] in intertidal and shallow subtidal habitats, usually on soft substrata and mainly from 0 to 30/35 m depth [2]. Seagrass meadows are one of the most valuable coastal ecosystems, offering a wide range of ecological services that significantly contribute to human well-being [3–5]. Despite such valuable benefits, seagrass meadows are increasingly threatened worldwide by numerous anthropogenic stressors acting at both local and global scales [4,6,7]. Over the past decades, these ecosystems have experienced a

notable decline, losing approximately 29% of their total area, equivalent to about 3370 km^2, with an average loss of 110 km^2 per year since 1980s [6].

Four seagrass species are native to the Mediterranean Sea, where they live in lagoons, estuaries, and shallow coastal waters: *Posidonia oceanica* (Linnaeus) Delile; *Cymodocea nodosa* (Ucria) Ascherson; *Zostera marina* Linnaeus; and *Nanozostera noltei* (Hornemann) Tomlinson & Posluszny. *C. nodosa* is a fast-growing species widely distributed in the Mediterranean and adjacent Atlantic regions [1]. In the Mediterranean, this species often occurs in shallow, sheltered, and semi-exposed coastal habitats, including lagoons and estuaries, forming monospecific or mixed meadows with other seagrasses, such as *P. oceanica* and *N. noltei* [8–11]. Some populations occur at sites located within or in proximity of urban areas [12,13], where they are subjected to multiple anthropogenic stressors that may cause their regression [13].

Mediterranean populations of *C. nodosa* show optimal growth at 24.5 °C and maximum photosynthetic activity between 30 °C and 32 °C [14]. High thermal tolerance (up to 34/35 °C) and a broad salinity range (10–50) highlight a strong euryecious nature and a remarkable adaptability of the species [15,16]. Phenotypic plasticity enables this seagrass to adjust its morphology and physiology in response to environmental variability and tolerate anthropogenic stress [8,17–20]. In the Mediterranean basin the species follows a seasonal growth pattern: rapid growth in late spring, fully developed canopy in late summer, and subsequent leaf loss as temperatures declines in autumn [14,21–23]. In the Mediterranean basin, flowering of *C. nodosa* occurs in spring and early summer (April–June), fruiting from July to October, and seed germination in the subsequent spring, although in several localities, sexual reproduction has not been documented [24–26].

Given its importance as a habitat-forming species, *C. nodosa* is listed as strictly protected flora species in Appendix I of the Bern Convention [27]. It is also included in the list of endangered and threatened species in the Annex II of the SPA/RAC Protocol of the Barcelona Convention [28], while its typical habitats, i.e., sandbanks, estuaries and coastal lagoons, are protected under the EU Habitat Directive, as habitat types of community interest 1110, 1130 and 1150, respectively [29], and *C. nodosa* beds are classified as 11.331 CORINE biotope [30]. Monitoring and conservation actions are recommended to preserve the extant *C. nodosa* meadows, to identify threats and, when necessary, guide restoration actions. Up to 2011, *C. nodosa* populations were considered generally stable and the species was listed as "Least Concern" by the IUCN [31,32]. However, the recent decline of some populations has been documented and attributed to a variety of anthropogenic impacts, in part related to urbanization [13]. For this reason, populations of *C. nodosa* affected by urban impacts require special attention and their status should be carefully assessed and monitored.

One such population occurs in the Porticciolo di Torrette, a marina located in a coastal suburb of Ancona, a large port city of the northern Adriatic Sea. This is the only seagrass meadow in the area [33], and its highly impacted condition makes it vulnerable to regression [34]. Planning measures for its conservation is currently impossible, due to the complete lack of information about its phenological traits and associated biodiversity. The aim of this study was to characterize this *C. nodosa* meadow over a seasonal cycle considering the following aspects: (I) structural morphometric parameters of the plant; (II) flowering; and (III) taxonomic composition of the epibiota colonizing the leaves.

2. Materials and Methods

2.1. Study Area

The Porticciolo di Torrette is a wave-sheltered basin located about 2 km from the city of Ancona, on the Adriatic coast of Italy. Wave breakers enclose a marina extending

on a surface of about 40,000 m^2, used since the 1960s for docking and mooring by local fishermen. The bottom ranges in texture from coarse gravel to muddy and in depth from 0.5 to 2.5 m (mostly 1–1.5 m). Artificial substrata (boulders of the marina breakers, wood and metal poles, concrete surfaces of piers) represent the only hard substrata in the area. Water turbidity is generally high, due to a high sediment load (which, however, is typically much lower within the *Cymodocea* meadow, due to the barrier posed by the seagrass canopy). The *C. nodosa* meadow is fragmented in four main patches, one of which is partially distributed under a stilt structure housing a restaurant. The meadow is subjected to several anthropogenic impacts, including boat traffic, temporary mooring, the proximity of the Port of Ancona with the associated activities, a nearby railway and artificial light at night produced by public lighting (see Supplementary Materials, Figure S1). The study focused on two patches of the meadow, hereafter referred to as Site A (43°36′32.17″ N, 13°27′48.05″ E) and Site B (43°36′31.64″ N, 13°27′51.20″ E), located approximately 50 m from each other (Figure 1; map generated by using QGIS version 3.40.9-Bratislava [35] with Google Satellite as basemap), with perimeters of approximately 260 m and 155 m and areas of 1620 m^2 and 887 m^2, respectively. The meadow extends from nearly water surface (30–40 cm) to approximately a 2 m depth. The bottom on which the seagrass grows is muddy, as a result of the accumulation and decomposition of the detached leaves. According to local fishermen, the meadow has been present in the marina for at least 50 years.

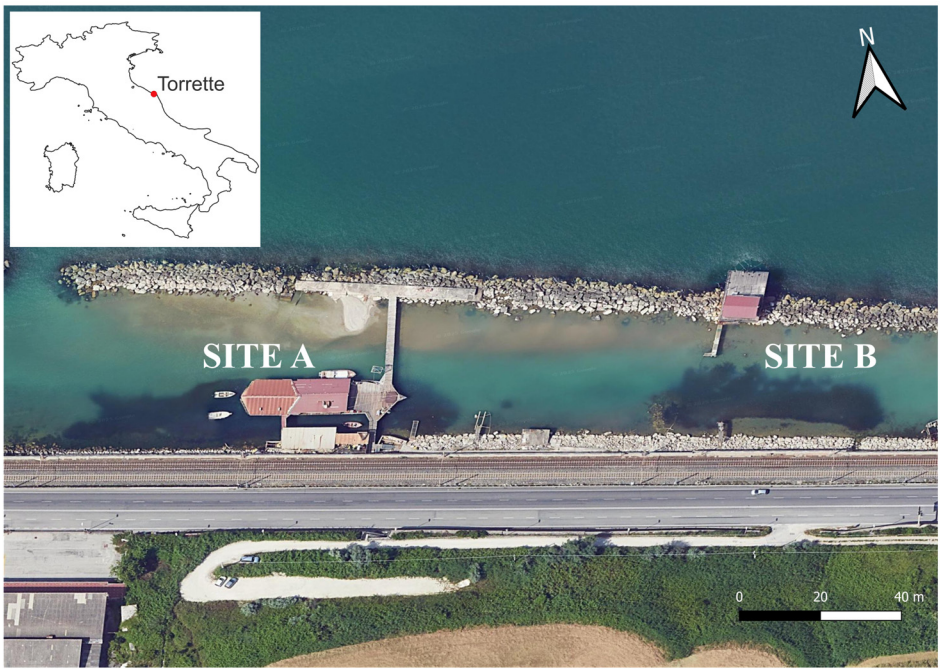

Figure 1. Map of the study area illustrating the two *C. nodosa* studied patches (site A and B).

2.2. Fieldwork

Sampling was conducted on five dates between late spring and autumn 2024, at approximately monthly intervals (Table 1). In the Mediterranean basin, summertime corresponds to the phase of full leaf canopy development of *C. nodosa* and is recognized as the optimal period for the sampling and status assessment of meadows of this species [10,36–38]. Subsequent observations showed that, after the fifth sampling date, the meadow lost most of its leaf biomass and did not support a functional canopy, as is typical for the species in the autumn–winter period. In consideration of this, sampling was not continued.

Table 1. Schedule of sampling dates.

Sampling	Date	Season
1	23 May 2024	Spring
2	27 June 2024	Summer
3	31 July 2024	Summer
4	9 September 2024	Summer
5	12 October 2024	Autumn

Temperature and salinity were measured at both sites on each sampling date using a YSI Model 30 Handheld Salinity, Conductivity and Temperature System (YSI Incorporated, Yellow Springs, OH, USA). Measurements were performed by placing the sensor about 20 cm below the water's surface.

The fieldwork was carried out by snorkeling. In each sampling date, three plots of approximately 2 m × 2 m were randomly selected in both sites, setting a random nested sampling design. Plots were selected independently at each sampling date. Different plots were selected in different sampling dates. So, each plot was sampled only once in the study (i.e., it was not resampled in different dates) and therefore plots do not represent fixed, repeatedly monitored units over time.

Shoot density was estimated at Site A by counting the number of shoots within sampling quadrats. On each sampling date, two quadrats (20 cm × 20 cm) were randomly placed on the seabed within each of the three selected plots. Due to some technical issues, shoot counting could not be carried out in Site B.

The presence or absence of male flowers and fruits—the former consisting of a simple stalk bearing red anthers without petals and the latter being laterally compressed disk-shaped—was noted by visual inspection while snorkeling at Site A.

Samples of *C. nodosa* were collected for measurements of morphometric variables at both sites on each sampling date. On each date, two samples were randomly collected from each of the six selected plots, for a total of 12 samples. Each sample consisted of a fragment of rhizome 10–15 cm long, bearing 1 to 3 shoots. Collection of this type of sample was preferred to the removal of sods, in order to minimize the mechanical impact on the meadow.

Samples were placed in numbered zip-lock bags, which were transferred within 1–2 h to the Laboratory of Marine Botany, Department of Life and Environmental Sciences, Polytechnic University of Marche. For each sample, one shoot was randomly chosen and processed immediately after transferal or stored in a constant temperature room at 4 °C until laboratory analysis (which, in this case, was carried out within the subsequent 1–2 days).

2.3. Laboratory Analyses

For each collected shoot, the number of leaves was counted. Overall, 60 shoots bearing 224 leaves were examined in the study. For each leaf, the following variables were measured: (i) total leaf length; (ii) length of the photosynthetic portion of the leaf, i.e., excluding the sheath; and (iii) averaged leaf width, i.e., calculated as the mean between the measured leaf at the base of the blade and at 1 cm from the apex. Based on these measurements, the total leaf surface and the photosynthetic leaf surface were calculated as in the following Equation (1):

$$X = w \times l, \quad (1)$$

in which X represents total leaf surface or photosynthetic leaf part surface, w is the averaged leaf width, and l corresponds to total leaf length or length of the photosynthetic portion.

Furthermore, the integrity of the leaf apex was assessed by observation under a stereoscope, and the percentage of damaged leaf apices was recorded. Finally, the presence/absence of female flowers, which consist of ovaries stored within the bundle leaf sheath, was also assessed by a detailed stereoscope examination of the leaf sheaths.

The taxonomic diversity of the epiphytic algal and macrofaunal taxa occurring on the leaves was assessed by observation of the leaf surface over its entire length on both sides. The taxa were identified at the lowest possible taxonomic level based on morphological features observed under a stereoscope (Zeiss Stemi 2000-C, Carl Zeiss AG, Oberkochen, Germany) and a light microscope (Zeiss Axioskop HBO 50, Carl Zeiss AG, Oberkochen, Germany), using the relevant taxonomic literature. Algal classification and nomenclature follow AlgaeBase [1], while zoological ones follow WoRMS [39]. Due to the scattered and irregular distribution on the leaves and the small size of the epiphytes, an accurate estimation of percentage cover for individual taxa was not possible.

2.4. Statistical Analyses

Statistical analyses were performed in R software version 4.5.2 [40]. The considered variables were: (i) apical leaf width, (ii) base leaf width, (iii) averaged leaf width, (iv) length of photosynthetic part of leaf, (v) total leaf length, (vi) surface of photosynthetic part of leaf, (vii) total leaf surface, (viii) percentage of broken apices per shoot, and environmental variables (salinity and temperature). Normality of data for the selected variables was assessed by Shapiro–Wilk test using the shapiro.test function from the stats package [40], while the homoscedasticity was checked using Bartlett and Levene tests with the bartlett.test and leveneTest functions from stats and car packages, respectively [40,41]. Since assumptions of normality and homoscedasticity were not met, non-parametric tests were applied. Kruskal–Wallis tests (kruskal.test function from the stats package [40]) were performed to test hypotheses for differences among sampling dates, considering both sites (A and B) combined and separately. Dunn's test was used for post hoc pairwise comparisons using the dunnTest function from the FSA package [42], with Benjamini–Hochberg correction, to further explore differences among dates, also accounting for sites individually. To describe the relationship between salinity and temperature, Spearman's rank correlation was applied using the cor.test function with the spearman method from the stats package [40]. The same test was used to evaluate correlations between environmental parameters and phenological variables [40].

To formally test the effect of the hierarchical sampling structure, we additionally fitted generalized linear mixed-effect models (Gamma distribution, log link; [43,44]) for each of the seven leaf morphometric variables, with sampling date and site as fixed effects and plot and shoot included as nested random effects (plot nested within site, shoot nested within plot). The site was included as a fixed rather than random effect due to the limited number of levels (n = 2). Model residuals were evaluated using simulation-based diagnostics [45].

Three quantitative morphometric variables (i.e., total leaf length, averaged leaf width, and total leaf area) were included in a Non-metric Multidimensional Scaling (nMDS) analysis using the function metaMDS from the vegan package, with Bray–Curtis set as a dissimilarity index [46] and plotted to visualize leaves' variability and potential spatio-temporal patterns. The other leaf variables were excluded to avoid data redundancy. To analyze epiphytic community composition, data from leaves belonging to the same plot were pooled. The two distinct communities (macroalgae and animals) were analyzed and visualized separately using a nMDS with metaMDS (vegan package), applying a presence–absence Jaccard distance matrix [46]. Analysis of Similarities (ANOSIM; permutation: free, number of permutations: 9999) and Permutational Multivariate Analysis of Variance (PERMANOVA; permutation: free, number of permutations: 9999) were used to test significant

differences among morphometric variables and epiphytic communities investigated by previous nMDS analyses. ANOSIM and PERMANOVA were conducted using anosim and adonis2 functions, respectively, from the vegan package [46]. The betadisper function, from the same package, was used to test the homogeneity of multivariate dispersion for each grouping factor considered in the ANOSIM/PERMANOVA analyses.

3. Results

3.1. Environmental Parameters

The abiotic parameters (i.e., temperature and salinity) were significantly negatively correlated with each other (rho = −0.59, $p < 0.001$). Temperature recorded during the samplings reached the maximum value on date 3 (28.7 °C at the site B) and the lowest on date 1 (19 °C at the site A), with mean values of 23.62 °C ± 1.68 °C and 24.88 °C ± 1.88 °C, in site A and B, respectively. Salinity ranged between 29.6 at site A on date 2 and 35.1 at site B on date 1, respectively (more details in Table 2), with a mean value of 33.02 ± 0.95 and 33.1 ± 0.62 in site A and B, respectively.

Table 2. Measured temperature (°C) and salinity (ppt) values.

	Site A		Site B	
Sampling Date	**Temperature (°C)**	**Salinity**	**Temperature (°C)**	**Salinity**
1	19	35	20.1	35.1
2	24.7	29.6	27.7	29.9
3	27.6	33.2	28.7	33.3
4	26.4	32.7	27.4	33.1
5	20.4	34.6	20.5	34.5

3.2. Shoot Counting

Shoot counting results are shown in Figure 2. No significant differences in shoot countings were found among sampling dates ($p > 0.05$). The mean number of shoots per quadrat, however, varied between a maximum value of 75.5 ± 10.6 shoots and a minimum of 22.5 ± 6.4 shoots, both recorded on the first sampling date.

3.3. Leaf Variables

Overall, 224 leaves were sampled throughout the study (Table S1). The total number of leaves recorded per sampling date showed a decreasing trend in time: 51, 49, 48, 42, and 34 from date 1 to date 5. Consistently, the mean number of leaves per shoot showed the same temporal pattern: 4.25 ± 0.75 on date 1, 4.08 ± 0.52 on date 2, 4.0 ± 0 on date 3, 3.50 ± 0.52 on date 4, and 2.83 ± 0.84 on date 5.

Table S2 details measurements of the leaf parameters for each sampling site and date. The morphometric variables investigated (excluding the leaf width) displayed generally higher values ($p < 0.001$) on sampling dates 3 and 4 (in averaged leaf width, high values were also exhibited on sampling date 2; $p < 0.01$), indicating full leaf development in mid- and late summer (Figure 3), while the percentage of broken apices displayed higher ones ($p < 0.05$) in the two last sampling dates. Heatmaps showing significance levels (p-values) of leaf variables across sampling dates, in all sites combined and separately, are shown in Figure S2.

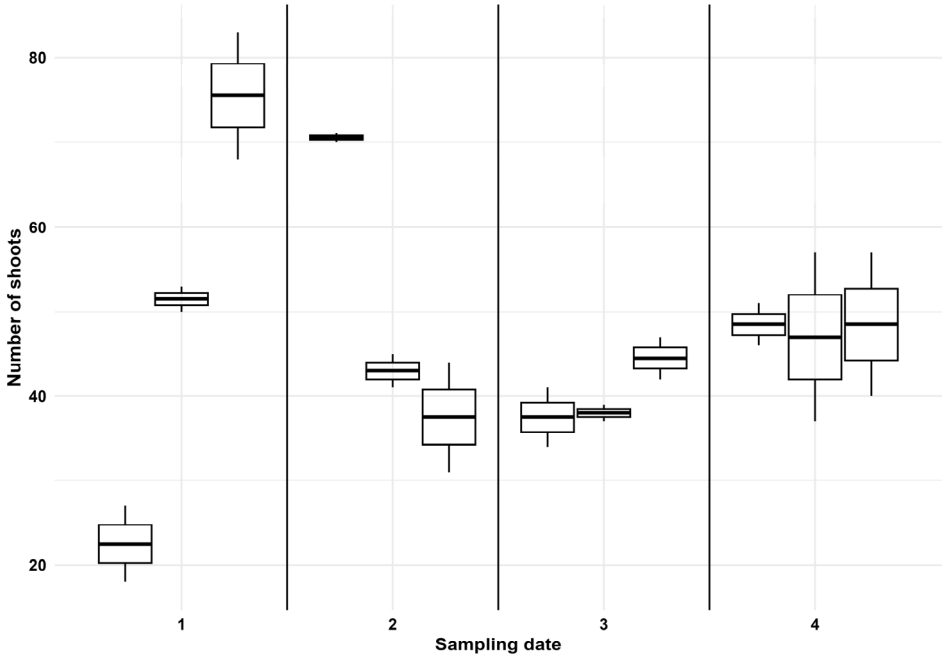

Figure 2. Shoot counting results. Each boxplot results from the number of shoots counted in the two quadrats sampled within each of the three plots across sampling dates in site A. Note: on sampling date 5, the counting could not be performed due to high turbidity and rough sea.

Positive correlations were found between temperature and all the leaf morphometric variables represented in Table 3 ($p < 0.001$), while negative correlations were observed with salinity ($p < 0.001$). Correlations were stronger in absolute terms for temperature than for salinity, as highlighted from rho values reported in Table 3.

Table 3. Correlation coefficients among morphometric variables and environmental parameters. *p*-values were always <0.001, reported as *** in the table.

Phenological Parameter	Temperature (°C)	Salinity
Averaged leaf width	0.54 ***	−0.38 ***
Apical leaf width	0.46 ***	−0.26 ***
Base leaf width	0.52 ***	−0.43 ***
Photosynthetic leaf part length	0.51 ***	−0.27 ***
Total leaf length	0.52 ***	−0.32 ***
Photosynthetic leaf part surface	0.59 ***	−0.38 ***
Total leaf surface	0.61 ***	−0.28 ***

The nMDS (Figure 4) performed on morphometric data (i.e., total leaf length, averaged leaf width and total leaf surface) shows a large overlap among different sampling dates, although a temporal progression can be observed. Leaves sampled on dates 1 and 5, characterized by a lower length and surface, are distributed mainly in the left half of the plot. Conversely, leaves sampled on dates 3 and 4, corresponding to the phase of full vegetative development, are mostly grouped in the right half of the plot.

The ANOSIM performed with sampling dates as a grouping factor indicated a significant temporal variability in leaves' morphometric variables, although with only moderate separation among sampling dates (R statistic = 0.291; $p < 0.001$). This result reflects the seagrass seasonal cycle, as morphometric traits vary relatively continuously overtime. PERMANOVA analysis confirmed the same trend, revealing significant differences in leaf morphometric parameters among dates ($R^2 = 0.435$; $F = 42.096$; $p < 0.001$), with temporal variation accounting for the 43% of the variability in leaf parameters.

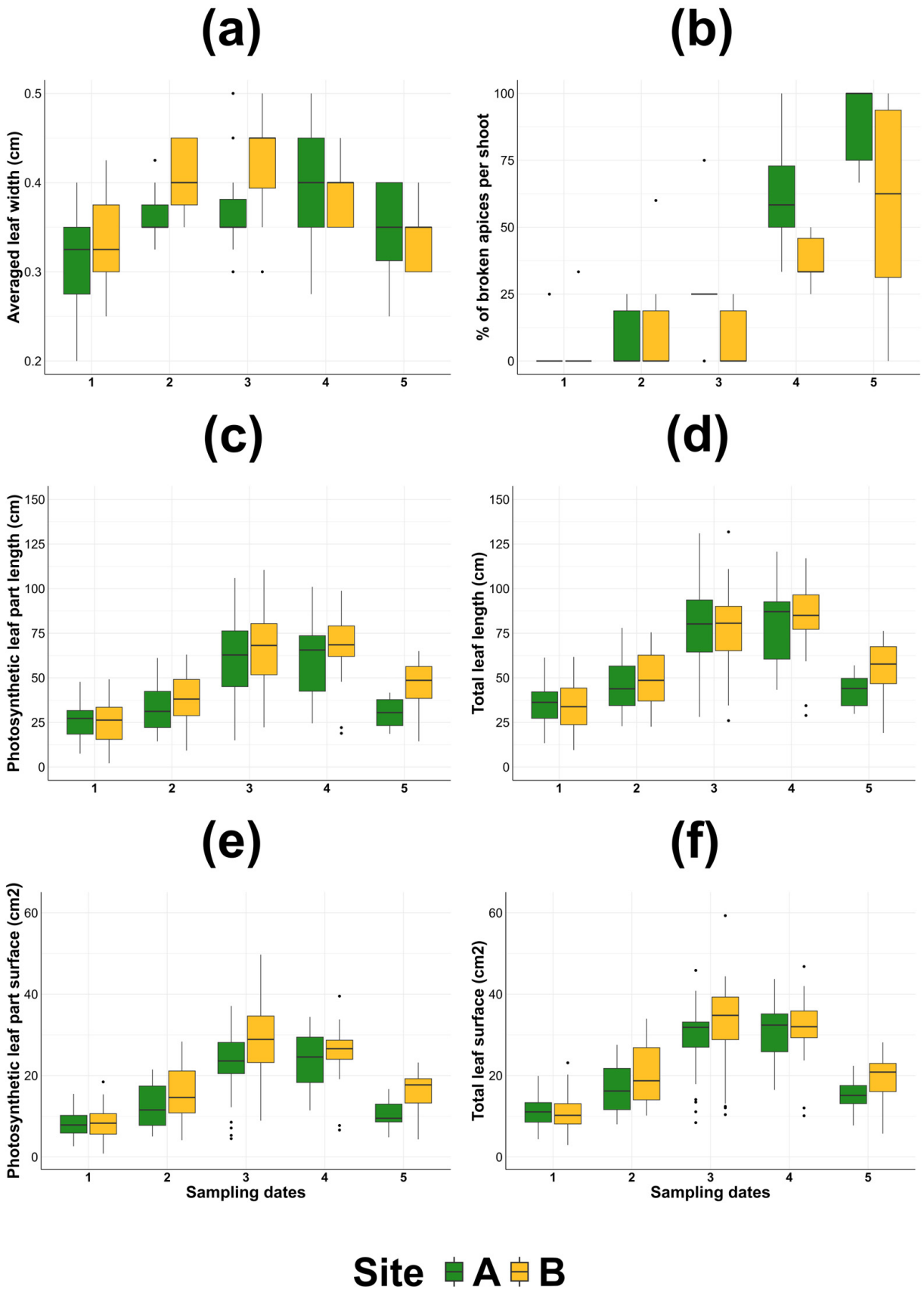

Figure 3. Boxplots of the leaf parameters across sampling dates and sites: (**a**) averaged width; (**b**) percentage of broken apices per shoot; (**c**) photosynthetic leaf part length; (**d**) total leaf length; (**e**) photosynthetic leaf part surface; and (**f**) total leaf surface.

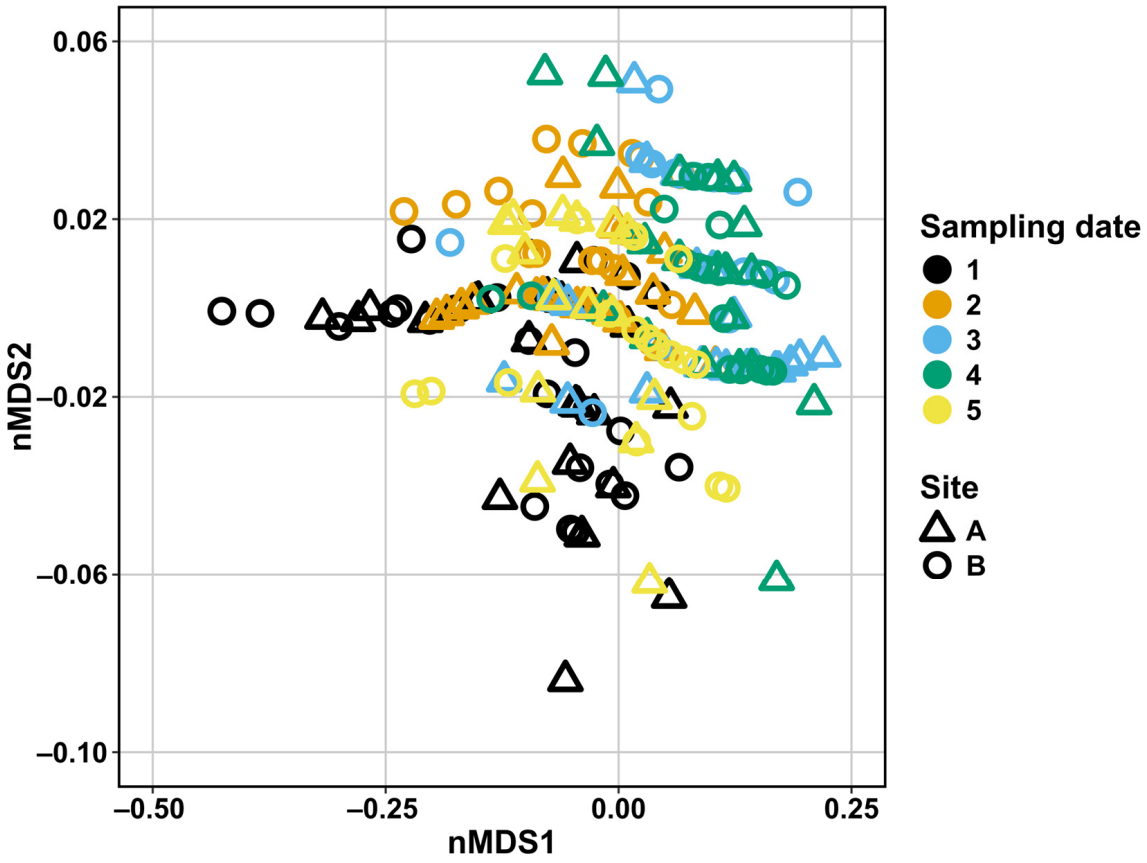

Figure 4. Non-metric Multidimensional Scaling plot based on averaged leaf width, total leaf length, and total leaf surface. Stress value: 0.018.

The ANOSIM performed with sampling sites as a grouping factor did not detect significant spatial differences in the morphometric variables (R statistic −0.001; *p*-value > 0.05), indicating high similarity between sites A and B. Similarly, PERMANOVA confirmed that small-scale spatial variability was not significant for the leaf variables (R^2 = 0.002; F = 0.5461; $p > 0.05$).

Homogeneity of multivariate dispersion did not differ significantly among sampling dates or between sites for the leaf morphometric variables ($p > 0.05$ in both cases), supporting the reliability of the results.

Nested mixed-effect models confirmed a significant effect of sampling date on all seven leaf morphometric variables after explicitly accounting for the hierarchical sampling structure ($p < 0.001$ in all cases), consistent with the Kruskal–Wallis results reported above. A significant effect of the site was detected for three of the seven variables—apical leaf width ($p < 0.05$), averaged leaf width ($p < 0.05$), and photosynthetic leaf surface ($p < 0.01$)—while the remaining four variables showed no significant spatial difference between sites ($p > 0.05$). Variance partitioning of the nested random effects (plot and shoot) indicated that residual variability was distributed unevenly between the two levels across variables: for most traits (total leaf length, photosynthetic part length, photosynthetic leaf surface, total leaf surface), the majority of residual variance (65–100%) occurred among shoots within the same plot, whereas for base width, averaged width, and apical width, plot-level variability was comparatively more relevant (82–100% of residual random variance).

3.4. Reproductive Phenology

During the fieldwork, no male flowers or fruits were observed, despite a careful search conducted by snorkeling on all sampling dates (except the last one, when the sea conditions

did not allow accurate observation). Ovaries were found within the sheaths of three leaf bundles after the dissection of the leaf sheaths in the laboratory. Two were recorded in site A on date 1, and one at site B on date 2.

3.5. Leaf Epiphytes

Overall, 12 algal taxa were recorded as epiphytes of *Cymodocea* leaves throughout the study (Table 4). Algal epiphytes mainly occurred in the apical portions of the leaves. Red algae (Rhodophyta) were the dominant group, followed by green algae (Chlorophyta) and brown algae (Heterokontophyta, Phaeophyceae). Finally, Cyanobacteria, represented by filamentous forms typical of the order Oscillatoriales, were also observed in some samples.

Table 4. List of identified algae, animals and eggs found on the seagrass leaves reported per site across sampling dates. Higher taxonomic levels are indicated in bold.

Site			**A**					**B**		
Sampling Date	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Algal epiphytes										
Chlorophyta										
Chaetomorpha cf. *ligustica*	X			X	X				X	X
Cladophora spp.			X	X	X	X		X	X	X
Ulva spp.		X	X	X	X	X	X	X	X	X
Rhodophyta										
Ceramium cf. *siliquosum* var. *zostericola*	X	X	X	X	X	X		X	X	X
Colaconema cf. *daviesii*					X					X
Crustose corallines	X	X	X	X	X	X	X	X	X	X
Erythrotrichia carnea					X					X
Hypnea cf. *cervicornis*			X	X				X		X
Stylonema alsidii					X					X
Heterokontophyta										
Cladosiphon cf. *cylindricus*	X									
Feldmannia mitchelliae					X					X
Cyanobacteriophyta										
Oscillatoriales				X	X				X	X
Animal epiphytes										
Anellida										
Polychaetes Spirorbinae	X	X	X	X	X	X	X	X	X	X
Bryozoa			X						X	X
Cndiaria										
Hydrozoa		X	X	X	X		X	X		X
Crustacea										
Cirripedia Thoracica	X									
Mollusca										
Gastropoda eggs	X	X	X	X		X	X	X	X	
Gastropoda Trochidae					X				X	
Bivalvia Mytilidae	X	X			X	X			X	
Tunicata										
Ascidiacea	X	X	X	X	X	X	X	X	X	X

Most algal epiphytes were small-sized, with either a crustose or filamentous morphology. In many cases, this made a reliable identification at the species level impossible and only the genus was determined; this was the case, in particular, for green algae of the genera *Cladophora* and *Ulva*. Crustose coralline algae were the most common macroalgal epiphytes and were recorded from most of the leaves examined in the laboratory. These algae formed thin calcified crusts in which species of different genera (*Hydrolithon*, *Pneophyllum*, *Titanoderma*) were mixed. Separation and detailed identification of individual coralline

specimens by stereoscope and microscope observation were not possible, so these algae were considered collectively as a group (Table 4). The nMDS based on the algal epiphytes data is shown in Figure 5a. A temporal progression in the epiphytic community is evident, with samples of the first and second sampling dates found in the left part of the plot, and samples of the fourth and fifth dates in the right part.

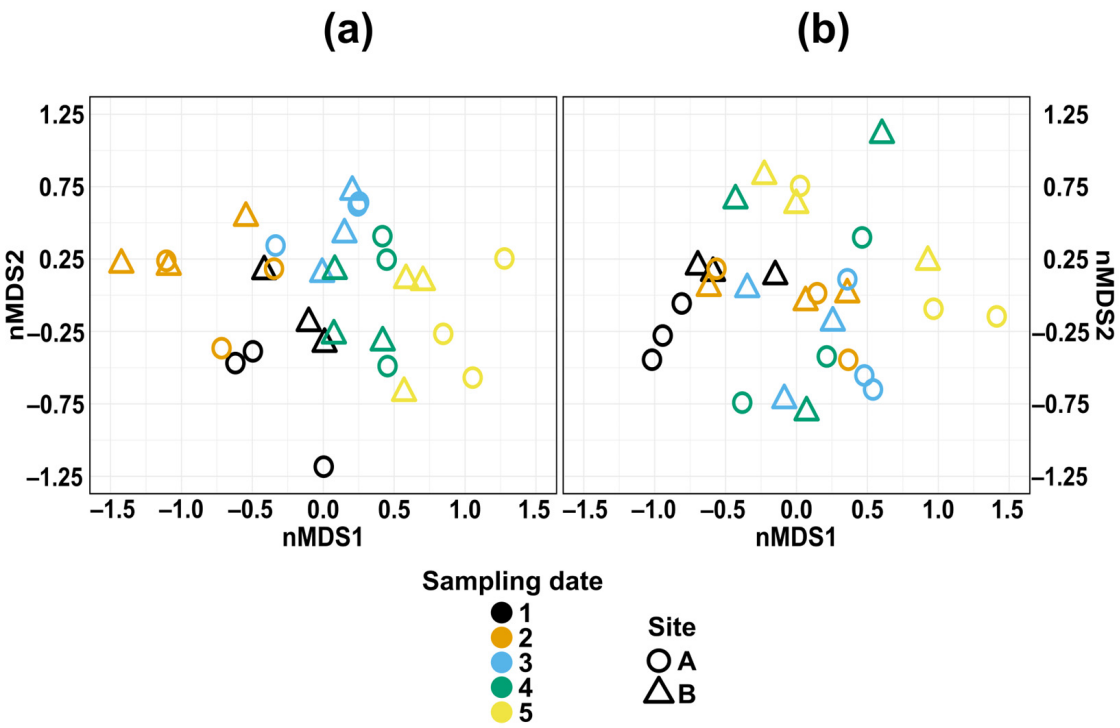

Figure 5. nMDS plots of epiphytic community composition recorded on leaves' surface based on Jaccard distance matrix: (**a**) algal epiphytes (including cyanobacteria) (stress value: 0.106) and (**b**) animal epiphytes including egg clutches (stress value: 0.084).

Temporal variation in the composition of the macroalgal community was also demonstrated by the results of the ANOSIM and PERMANOVA analyses.

ANOSIM with sampling dates as a grouping factor indicated significantly distinct temporal groups (R statistic = 0.734; $p < 0.001$). PERMANOVA results supported this finding, showing that epiphytic community composition varied significantly over time, likely reflecting both the life cycles of individual species and the seagrass phenology ($R^2 = 0.640$; F = 11.122; $p < 0.001$).

The ANOSIM performed with sampling site as a grouping factor revealed that inter-site differences were slightly higher than intra-site differences, but no significant variation on site-scale was detected for the algal community (R statistic = −0.053; p-value > 0.05). PERMANOVA further confirmed that spatial variability had a negligible effect on the algal community distribution ($R^2 = 0.008$; F = 0.2168; $p > 0.05$).

Animal epiphytes were scattered all over the leaf surfaces and could be identified only at high taxonomic levels. Bryozoa occurred in different morphologies, but classification at lower taxonomic levels was not possible due to the absence of useful identification characters. Hydrozoan colonies (phylum Cnidaria) belonged to the family Campanulariidae Johnston, 1836 and included the genus *Clytia* Lamouroux, 1812 and suborder Capitata. For the serpulid polychaetes, all recorded specimens were identified as subfamily Spirorbinae Chamberlin, 1919. The Mollusca phylum both included bivalves belonging to the family Mytilidae Rafinesque, 1815 and gastropods belonging to the family Trochidae Rafinesque, 1815. Some gastropod egg clutches were identified as originating from Nassariidae Iredale,

1916 (1835). Crustacean barnacles belonging to the infraclass Thoracica were also observed. Finally, colonial tunicates of the class Ascidiacea were recorded, with some individual belonging to the family Didemnidae Giard, 1872 and several specimens of *Botryllus schlosseri* (Pallas, 1766).

Overall, eight taxa were recorded, considering both adult individuals and eggs (Table 4). The nMDS analysis of animal epiphytes is shown in Figure 5b. Although less evident than for the algal epiphytes, a temporal progression is also noted for the animal component: samples of the first date occur mainly in the left part of the plot and samples of the fourth and fifth dates mainly in upper right part. ANOSIM indicated a strong temporal overlap, yet significant differences among sampling dates were detected (R statistic = 0.298; $p < 0.001$). PERMANOVA confirmed that sampling date was a significant driver of variation in animal epiphytic diversity over time ($R^2 = 0.359$; $F = 3.4986$; $p < 0.001$). When considering sampling sites, ANOSIM returned weak differences among sites, indicating high similarity (R statistic = 0.115; $p < 0.05$), and PERMANOVA suggested moderate but significant spatial variation among sites ($R^2 = 0.108$; $F = 3.3821$; $p < 0.05$).

For both the macroalgal community and the animal epiphytes, homogeneity of multivariate dispersion did not differ significantly ($p > 0.05$) among sampling dates or between sites.

4. Discussion

In general, the *C. nodosa* meadow in the Porticciolo di Torrette showed a phenology and a seasonal developmental pattern in agreement with reports for other *C. nodosa* meadows in the Mediterranean area.

Findings of the present study agree with the unimodal pattern reported by Mazzella et al. (1993) for *C. nodosa* in the Mediterranean area, with maximum growth in summer [47]. Based on the phenological variables that we measured, the leaf canopy of the Porticciolo di Torrette meadow shows a similar pattern to that reported by Sghaier et al. (2017), who recorded the highest values of shoot density, biomass and leaf length in August–September and the lowest in March for a meadow in Monastir Bay, Tunisia [48]. Sfriso and Ghetti (1998) reported that populations of *Cymodocea* in the Venice Lagoon started growing in standing crop in May and reached the maximum biomass in August (7644 ± 517 g fwt m^{-2}, composed of 73% shoots and leaves, 18% roots and rhizomes and 9% dead parts), a pattern that also agrees with our results [25].

The mean number of leaves per shoot in our meadow varied between 2 and 6, in agreement with Petrocelli et al. (2023) [12] and seasonally, as documented by Rismondo et al. (1997), Cancemi et al. (2002), Guidetti et al. (2002) and Sghaier et al. (2017) [8,21,37,48].

In *C. nodosa* leaves, length, width and sheath length normally reach maximum values in spring–summer and decrease during autumn and winter [48], coinciding with the temperature seasonal trend [49]. Studies by Cancemi et al. (2002), Najdek et al. (2020) and Schäfer et al. (2021) showed that leaf length peaked in summer and decreased in winter/early spring, with a minimum in March [8,50,51]. For the total leaf length, our results agree with those reported by Petrocelli et al. (2023) for *C. nodosa* meadows of Mar Piccolo (Taranto), an area in which the species is also subject to anthropogenic stressors [12]. Average leaf width similar to our results was also reported by Petrocelli et al. (2023), while Cancemi et al. (2002) argued that this variable showed a definite seasonal trend, with maximum values in August [8,12]. Both the nMDS plot based on the three analyzed leaf morphometric parameters and consequent results from ANOSIM and PERMANOVA reflect the seasonal cycle of the seagrass, with these traits varying relatively continuously over time. The temporal pattern observed in leaf morphometric traits was confirmed even when explicitly accounting for the hierarchical sampling structure, supporting seasonal development as the main driver of variability in this meadow. A modest degree of spatial

heterogeneity between the two sites emerged for a subset of morphometric traits, though it was not detected when leaf variables were considered jointly, suggesting that any spatial differentiation between the two patches of the meadow is limited compared to the marked seasonal signal.

Leaf surface in seagrasses determines not only the availability of substrate for epibiota settlement, but it also influences irradiance, water movements and nutrient concentration on rhizome layers [52]. In the population from Grado (northern Adriatic Sea) studied by Guidetti et al. (2002), the green surface area of *C. nodosa* leaves reached 21.6 cm^2 per shoot in summer, similarly to our results [37]. In meadows from the Canary Archipelago, the leaf surface displayed a notably reduced size range, from 1.38 to 10.1 cm^2 [20]. Results of Conte et al. (2023) highlighted small leaf surfaces in analyzed monospecific meadows of Crete compared to this study, while similar results emerged from Petrocelli et al. (2023) [12,53]. Peralta et al. (2021) reported that, even in Cadiz Bay, the leaf traits of *C. nodosa* showed a marked seasonality, with maximum values in summer and minimum in winter for demographic (biomass, shoot density and shoot size) and dynamic attributes (leaf growth rate, leaf loss rate) [54].

The percentage of broken apices is a valuable structural descriptor: a low percentage indicates an undisturbed meadow, while higher values are attributed to mechanical damage, due to either or both natural disturbances (e.g., intense wave motion and grazing) and human impacts causing breakage of apices. In our site A, increasing values of the percentage of broken apices per shoot were recorded over time. One of the main causes was certainly temporary boating activity, since site A is located in the proximity of a small pier that local fishermen use for landing. However, strong hydrodynamics likely contributed to the high values recorded in the last sampling date. Indeed, in the last sampling date, the sea conditions were rough and imposed mechanical stress on the meadow. This effect was probably increased by the fact that, at this stage, the plant was at the end of its developmental period, and the leaves were senescent and easily breakable.

To assess the environmental status of *Cymodocea* meadows, specific indicators can be used, such as the CYMOX index [55], MediSkew index [38], trace elements biomonitoring [56], CymoSkew^m [57] and Leaf Area Index [20]. Assessing the acoustic impact of the railway through bubble production monitoring [58] can also provide more specific information on the health status. We are planning to extend future monitoring activities to include some of these indicators.

The scarcity of flowers and the apparent absence of fruits in the *Cymodocea* meadow of Torrette suggest that, in this area, the seagrass primarily relies on vegetative propagation and clonal integration. This agrees with the general scarcity of flowering and fruiting events generally reported for the species [59] and documented for *C. nodosa* meadows in other Mediterranean areas, such as the Venice Lagoon [25], Montazah Bay, Alexandria, Egypt [49], the Egadi Archipelago [23], and some extra-Mediterranean regions (e.g., the coast of Senegal, [60]). It cannot be excluded, however, that flowering and fruiting in this species take place more frequently than the literature reports suggest. Flowers of *C. nodosa* are small-sized and inconspicuous, not easily observable in the field. This is especially the case for female flowers, which are sessile, with ovaries enclosed within the leaf sheaths. Fruits are also small-sized, 6–8 mm in diameter [9,61]. Therefore, flowers and fruits in the field can be easily overlooked and their observation requires accurate and time-consuming surveys, which are not always possible in field-based investigations.

Reproductive events are reported to occur annually in the Western Mediterranean Sea: flowering is known to take place between mid-May and late June, varying according to local conditions and depth, while fruits develop during the summer and release seeds in October [24]. Our sampling period covered this time span but, despite very detailed

observation in the field and in the laboratory, no male flowers and fruits were observed. Repeated monitoring in future years will be necessary to understand whether this pattern was specific to the environmental conditions of spring/summer 2024 or is due to the genetic structure of the meadow. Genetic analyses, which were not performed in the present study, would be very helpful to clarify this aspect. Population genetic studies carried out in other regions have unraveled different situations. Studies for *Cymodocea* populations from the Canary Islands [62] showed that sexual reproduction strongly contributed to population maintenance. Conversely, for meadows in Cadiz and Alfacs Bay (Spain), clonal propagation contributed as a dispersal vector within meadows at least as much as sexual reproduction; indeed, meadows in both localities were dominated by few, large clones and the species followed a repeated seedling recruitment strategy [63]. At present, we cannot exclude that a similar situation occurs in our meadow, which might be formed by one or few individuals extending by clonal propagation.

The epiphytic community discovered on the leaves of *Cymodocea nodosa* in the Porticciolo di Torrette was characterized by relatively low diversity, although the impossibility of reliably identifying many small-sized specimens may have resulted in a partial underestimation. Its composition appears to be similar to those previously reported for other meadows of this species ([10,49,64–68]; see Supplementary Table S3), and most of the taxa that we recorded are probably common to other *Cymodocea* meadows, although the difficult identification of small-sized specimens partially complicates this comparison.

Among the macroalgal epiphytes, red algae were the dominant group, being represented mainly by thin crustose corallines (genera *Hydrolithon*, *Pneophyllum* and *Titanoderma*) and specimens of the filamentous genus *Ceramium*. Crustose corallines are the most widespread seagrass epiphytes and have been reported in almost all studies documenting *C. nodosa* leaf epiphytes (Table S3), both in the Mediterranean and in the Atlantic. In the Torrette meadow, they represented the dominant group throughout the study period, since they occurred in most of the leaves examined in the laboratory and were notably more abundant in the apical portions. Species of *Ceramium* have also been recorded as *Cymodocea* epiphytes in many locations, such as Canary Islands [64], Tunisia [66], northern Adriatic Sea [10], and Aegean Sea [67,68], although with different species identifications. Even for these algae, a higher abundance in the apical parts of the leaves was noted. Although we did not make a quantitative assessment of the abundance of different epiphytic taxa, the epiphyte distribution on our leaves appeared to conform with the pattern reported by Reyes et al. (1998), who described three developmental stages based on the position along the oldest leaves in Atlantic meadows: stage of initiation (earlier stages settled on leaf basal parts with lowest taxonomic diversity); transition (increase in number on central leaf segments, with both crustose and erect forms); and maturity (apical leaf segments are mainly dominated by ceramialean red algae) [64].

Distribution and abundance of epiphytic autotrophs are strongly influenced by biotic and abiotic factors, such as environmental variables, substratum availability and stability, development of larvae and propagules, or grazing [47,66]. Grazers, such as gastropods and herbivore fishes, may control the epiphytic biomass in at least two main ways: both selectively by removing algae, with alterations on the assemblage structure if competitive dominant species are removed, and indirectly by feeding on the seagrass, their host substrate [69].

The composition of the epiphytic animal community also found correspondence with previous studies in the Mediterranean Sea [10,70]. Among the animals colonizing *Cymodocea nodosa* leaves, Campanulariidae hydroids, particularly those belonging to *Clytia* genus, bivalves (Mytilidae) and polychaetes (*Spirorbis* genus) were also described in the locality of Valsaline (Croatia) by Bračun et al. (2020) [10]. Sessile tube-building polychaetes of

the family Serpulidae were present in a large part of the leaves investigated, although calcareous algae overgrowth can affect their aperture and the feeding activity, as highlighted by Bračun et al. (2021) [11]. Specimens of the ascidiacean *Botryllus schlosseri* were observed both with orange and the characteristic "black–white flower" morphologies and they are widespread in the study area, even on different substrates. A remarkable record for the Torrette meadow was the presence of barnacles, which were not found as *Cymodocea* leaf epiphytes in other studies (Table S3). The inability to determine the identity of eggs at the species level, except for those of gastropods from the family Nassariidae (due to their characteristic shape), is attributed to the wide range of potential candidates: over 480 species were identified as gastropods egg depositors on the leaves in the Thermaikos Gulf, Aegean Sea [71]. Bračun et al. (2020) found 12 potential families of gastropod ovipositors: Cerithiidae J. Fleming, 1822; Chitonidae Rafinesque, 1815; Columbellidae Swainson, 1840; Conidae J. Fleming, 1822; Mangeliidae P. Fischer, 1883; Muricidae Rafinesque, 1815; Nassariidae Iredale, 1916 (1835); Neritidae Rafinesque, 1815; Plakobranchidae J. E. Gray, 1840; Pyramidellidae J. E. Gray, 1840; Rissoidae J. E. Gray, 1847; and Trochidae Rafinesque, 1815 [10]. Young leaves are generally less colonized than older ones and, thanks to their central position within the shoot, epiphytic animals and their eggs are exposed to a lower predation pressure [11]. Borowitzka et al. (2006) suggested that the earliest seagrass leaf colonizers are r-strategists, such as bacteria and diatoms, followed by secondary colonizers, particularly crustose coralline algae, hydrozoans, and bryozoans, and once established, these organisms persist throughout the lifespan of their substrate [69]. nMDS, ANOSIM and PERMANOVA analyses revealed a temporal succession of the epiphytic community, likely in relation to both the life cycles of individual species and seagrass phenology, while significant differences between the two sites were observed only for the animal epiphytic component.

Overall, these findings indicate that the *Cymodocea nodosa* meadow of Porticciolo di Torrette displays structural, phenological and epiphytic characteristics comparable to those reported for other Mediterranean populations. However, because monitoring was limited to a single growing season within a single year and sampling was restricted to two sites within the meadow, further monitoring in the future will be necessary to better characterize spatial and temporal patterns. The goal of the present study was to provide a general characterization of the studied meadow; so, we did not aim at defining its environmental status and assessing quantitatively anthropogenic impacts (which would have required a comparison with at least two meadows located in pristine sites in the area of Ancona). However, ongoing collaborative work including other northern Adriatic meadows (lagoon of Grado and Marano in Italy and Pomer Bay in Croatia) will provide data that will be useful to better characterize our meadows also in terms of environmental quality.

5. Conclusions

The *Cymodocea nodosa* meadow investigated in this study is located within an urban area and subject to several anthropogenic stressors. Despite this, its phenology, developmental patterns and epiphytic communities are similar to those of other meadows of the same species of the Mediterranean area, including meadows not affected by urban impacts. These findings indicate that the Torrette meadow has persisted under long-term urban conditions while maintaining ecological characteristics comparable to those reported for other Mediterranean populations. A more extensive, multi-year monitoring strategy should be adopted in the future to provide further insights into the structure and health status of this meadow and to better evaluate the effects of urbanization. We suggest that the combination of additional phenological indicators with non-invasive, innovative tools,

such as drone remote monitoring, may be a valid strategy for this and other meadows in similar environmental conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18141719/s1, Figure S1: The seagrass *Cymodocea nodosa* in Torrette marina: (a) view on the meadow and (b) on the dense leaf canopy both from the pier at site A, (c) underwater photograph showing the seagrass leaves; Table S1. Number of leaves per shoot examined; Table S2: Mean ± standard deviation of leaf parameters; Figure S2: Heatmaps showing the 4 significance levels from Dunn's post hoc pairwise comparisons of leaf variables across sampling dates: (a) both sites combined; (b) site A only; and (c) site B only. Significance levels: ns ($p > 0.05$); * ($0.05 > p > 0.01$); ** ($0.01 > p > 0.001$); *** ($p < 0.001$); Table S3: Comparison of the epiphytic vegetation and macrofauna recorded in this study with results reported in other studies.

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