Research Article

Mediterranean Marine Science
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
www.hcmr.gr
DOI: https://doi.org/10.12681/mms.36616

Wave attenuation by *Cystoseira sensu lato* in two shallow Mediterranean coastal waters

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Contributing Editor: Panayota KOULOURI

Received: 23 January 2024; Accepted: 02 August 2024; Published online: 18 September 2024

Abstract

Coastal protection from erosion is an important ecosystem service provided by marine vegetation. Seaweeds and seagrasses can attenuate wave action in coastal areas and increase sediment retention. Here we investigated for the first time the effects of stipitate *Cystoseira sensu lato* forests in attenuating the wave energy in two Mediterranean shallow areas (Greece and Tunisia). The hydrodynamic effects were measured using the dissolution rate of gypsum cones (f_d). Experiments were carried out in Greece on the species *Ericaria barbatula*, and in Tunisia on the species *E. brachycarpa* and *Cystoseira crinitophylla*. Wave attenuation was directly related to percent cover of these macroalgal forests under different spatial and temporal conditions. On average, *Cystoseira s.l.* forests with 100% cover reduced the wave action by 38% more than the control (0% cover). This study shows that *Cystoseira s.l.* forests under specific conditions play a key role in protecting the Mediterranean coasts from erosion, and can present a nature-based solution as an alternative to unsustainable and costly artificial constructions.

Keywords: Canopy-forming seaweeds; dissolution rate of gypsum; ecosystem service.

Introduction

Human activities have led indirectly or directly to climatic and environmental changes increasing air and ocean temperatures, declining ocean pH and sea-level rise, and increasing intensity and frequency of climate-driven episodic events, which are critical for the survival of many organisms, and the people themselves (Sanò *et al*., 2011; Toimil *et al*., 2020). There are two main consequences in the coastal zone, demanding the introduction of sustainable measures to cope with this problem: sea-level rise and intense storms that intensify coastal erosion and floods, and cause changes in the geomorphology of the coasts (Duarte *et al*., 2013; Masselink & Russell, 2013; Maza *et al*., 2015).

In response to these threats, more and more sea walls and breakwaters are being built (Morris *et al*., 2018). These structures are becoming less sustainable, both ecologically and economically, since they are usually temporary (as impacted by wave action), expensive, and can further alter hydrodynamic conditions (Kindeberg *et al*., 2023; Van Rijn, 2011). Moreover, a large number of non-indigenous organisms proliferate on artificial structures, threatening native populations (Dafforn *et al*., 2009). Non-indigenous species, through strong competition for resources and habitat, reduce native biodiversity and alter the ecosystem (Dafforn *et al*., 2009). In parallel, over time, these coastal infrastructures and protection measures can have the opposite effect of what they were designed for, resulting in habitat fragmentation and exacerbating the problems of erosion in areas adjacent to the structures (Masselink & Russell, 2013). Therefore, alternative nature-based solutions are preferred, due to their effectiveness, lower cost and lack of negative impact on the ecosystem. These ecological protection techniques also called ‘natural and nature-based infrastructure’ (Sutton-Grier *et al*., 2018), include the habitat restoration of marine vegetation for coastal protection, while maintaining other coastal ecosystem services (Duarte *et al*., 2013; Morris *et al*., 2018).

Marine vegetation, including seagrasses, mangroves, saltmarsh habitats, and seaweeds, such as the large brown algae (kelps and fucoids), provide valuable ecosystem services (Schiel & Foster, 2006), and play a pivotal role in coastal areas by producing primary biomass and providing nursery areas (Steneck *et al*., 2002). Amongst other ecosystem services, they provide coastal protection from hydrodynamism and erosion (Koch *et al*., 2006; Morris *et al*., 2018). Indeed, marine vegetation determines energy flow dissipation from hydrodynamic parameters such as wave conditions (height and period) and currents (Duarte *et al*., 2013; Maza *et al*., 2015). Many macrophyte species significantly affect the patterns of local currents and surface waves by exerting drag in the water column through morphological characteristics such as stiffness, cover, density, height of the vegetation, and biomass (Maza *et al*., 2015). Marine vegetation reduces wave energy and bottom current flow velocity, decreasing sediment resuspension and promoting sedimentation (Duarte *et al*., 2013). The significant role of shore conditions (substratum type, exposition of wave action, inclination, roughness, depth, etc.) combined with the vegetation characteristics (cover-%, biomass, height, etc.) and wave conditions (height and period) determine the protection of the area (Morris *et al*., 2020).

The species of the genera *Cystoseira*, *Ericaria*, and *Gongolaria* (*Cystoseira sensu lato*) dominate many shallow rocky coasts of the world's temperate seas. In the Mediterranean Sea, *Cystoseira s.l.* forests grow in shallow and mesophotic rocky reefs representing one of the most endangered habitats (Verlaque *et al*., 2019) due to local anthropogenic stressors such as coastal development, habitat destruction, and pollution (Fabbrizzi *et al*., 2020; Orfanidis *et al*., 2021; Verdura *et al*., 2023) and/or regional stressors, such as grazing and heat waves (Mulas *et al*., 2022; Sala *et al*., 2011). However, *Cystoseira s.l.* provide many essential ecosystem goods and services, such as carbon burial, nutrient cycling, nurseries for fish stocks, bioindicatorss (Smith *et al*., 2023, and references therein), but their effect in attenuating coastal erosion has never been studied. Here we investigated the effects of *Cystoseira s.l.* forests in attenuating wave action in two Mediterranean coastal areas of Greece and Tunisia, using the dissolution rate of gypsum cones (f_d) as a relative measure of hydrodynamism. The dissolution rate of gypsum has been widely used in aquatic sciences to characterize water motion because its dissolution is mass-transfer limited, i.e. faster moving water will remove dissolved gypsum ions from the surface of the cone more quickly (Falter *et al*., 2005). The aim of this study was to explore the use of canopy-forming seaweeds as an alternative biostructure to coastal protection from wave action.

Material and Methods

Species and study area

The experiments were conducted on *Cystoseira s.l.* forests in Greece and Tunisia. The experiments in Greece took place along the Elaiohori coast (40.793328° N, 24.247631° E), located in the northern Aegean Sea, between the Strymon and Kavala Gulfs (Fig. S1). The area was chosen due to the fucalean forests abundance, exposure to wave action, and accessibility. The coast consists of hard substrate at an intermediate depth (max. 1.2 m deep), with patchy *Ericaria barbatula* forests. *E. barbatula* thalli are characterized by a holdfast from which 3-7 erect main axes start, and their height reaches 30 to 40 cm (Berov *et al*., 2015; Orfanidis *et al*., 2017). *E. barbatula* is endemic to the Mediterranean Sea, inhabiting the upper sublittoral zone (1-1.5 m depth) of rocky shores. It is mainly fertile from April to July (Papadimitriou *et al*., 2022).

The experiments in Tunisia were conducted at two sites (up to 1 m depth) along the Rimel coast (1st site: 37.252333° N, 9.942628° E and 2nd site: 37.252794° N, 9.944739° E), northwest of the Gulf of Tunis in the southern Mediterranean Basin (Fig. S2) and concerned the species *Ericaria brachycarpa* and *Cystoseira crinitophylla*. *E. brachycarpa* is an endemic Mediterranean species that forms dense populations on hard substrata of the upper sublittoral zone (1-20 m depth). Its height reaches 20 to 25 cm (Bellissimo *et al*., 2014; Esposito *et al*., 2022). It is fertile all year round except in summer in some areas. *C. crinitophylla* grows on shallow rocky bottoms to 1 m depth and forms dense forests in the Mediterranean Sea (Bouafif *et al*., 2014). It is fertile seasonally from October to March, while its habitat requirements are similar to *E. crinita* (Montesanto & Panayotidis, 2001). It has a thick thallus, a multi-axis base with several main axes, and its height extends up to 30 cm (Bouafif *et al*., 2014).

Experimental design

The experiments of protection from coastal erosion were based on the use of gypsum cones (plaster). Initially, artistic gypsum and tap water were mixed in a plastic bucket in a ratio of 60% and 40%. After good mixing, the liquid mixture was transferred to plastic cups (140 ml volume) with an aluminum screw, and was allowed to solidify for 24 hours. Then the gypsum cones were placed in an oven at 50°C for 8 hours. Afterward, the gypsum cones were weighed and numbered with a waterproof marker.

In Greece, ten (10) experiments were conducted from July to August 2020 using ten gypsum cones in each one (100 gypsum cones in total, Fig. S3). The cover (%) of *E. barbatula* in each experiment ranging from 0 (control) to 100%, was estimated using a quadrat with a metallic frame (25 x 25 cm). For thalli height (cm) and perimeter (cm) measurements, a thin non-elastic thread (fishing line) was laid along or around the branches, always at the same position and under maximum tension. Then the thread was placed on a measuring tape, and the length between two points held by the thumb and finger of each hand was measured. Furthermore, for each 24-hour experimental period, the sea conditions (wave height H, wind speed, seawater depth) were recorded from the "Windy" (https://www.windy.com) weather forecast site (Table S1), while wind speed and direction was also recorded from the Hellenic National Meteorological Service.

In Tunisia, three (3) experiments were conducted from September to November 2022 using 20 gypsum cones in each one (60 gypsum cones in total, Fig. S4). The same protocol as the Greek experiment was used where the gypsum cones were transported to the site and put in different cover (%) of *Cystoseira s.l.* species, ranging from 0 (control) to 100%. However, in contrast to the Greek experiment, only the dissolution rate of gypsum cones in relation to the *Cystoseira s.l.* cover (%) was studied. Meteorological data for the experimental period was collected from the Copernicus catalogue from the WIND_GLO_WIND_L3_NRT_OBSERVATIONS_012_002 product.

The dissolution rate of the gypsum cones

After 24 hours in the field, the cones were transferred to the laboratory, where they were left to dry for 48 hours in a drying oven at 50°C and weighed. To calculate the dissolution rate and examine the difference before and after their exposure to the field. The following equation was applied.

$$f_{\mathrm{d}}\ (Dissolution\ rate\ of\ gypsum\ cones) = \frac{Ma - Mb}{Ma * t} * 100\%$$

where M_a is the initial dry mass of the gypsum cones before the experiment, M_b is the dry mass at the end of the experiment, and t is the duration, in hours, of the experiment.

Data analysis

Percentage of water column occupied by *Cystoseira s.l.* thalli was calculated by dividing the thalli height to the depth at each sampling point. Spearman's rank-order correlation and a Principal Components Analysis (PCA) were used to assess the relationships between f_{d} and abiotic [wave height (m), wind speed (km/h), and depth (m)] and biotic [thallus cover (%), height (cm), and perimeter (cm)] variables. The software Origin Pro v.9. (www.originlab.com) and CANOCO 5 (Microcomputer Power, Ithaca, NY, USA) were used, respectively. We performed a linear regression to test whether the linear relationship was significant and strong enough to model the relationship between f_{d} and thallus cover (%), height (cm) and perimeter (cm).

Results

Prevailing wind conditions were similar in the two areas throughout the field experiments, with slightly stronger winds in Tunisia (Fig. 1). The average wind speed in Greece was 19.7 ± 0.4 km/h with NNE direction, while in Tunisia 17.4 ± 3.3 km/h with SSE direction.

Ericaria barbatula's thalli length and periphery in Greece ranged from 7 to 27 cm (mean value ± SE 19.69 ± 1.02 cm) and from 8.5 to 40 cm (29.20 ± 1.64 cm), respectively. When present (cover > 0%), thalli occupied 38.49 ± 1.23% of the water column. Thalli cover (%) of *Cystoseira s.l.* in both countries ranged from 0 to 100%,

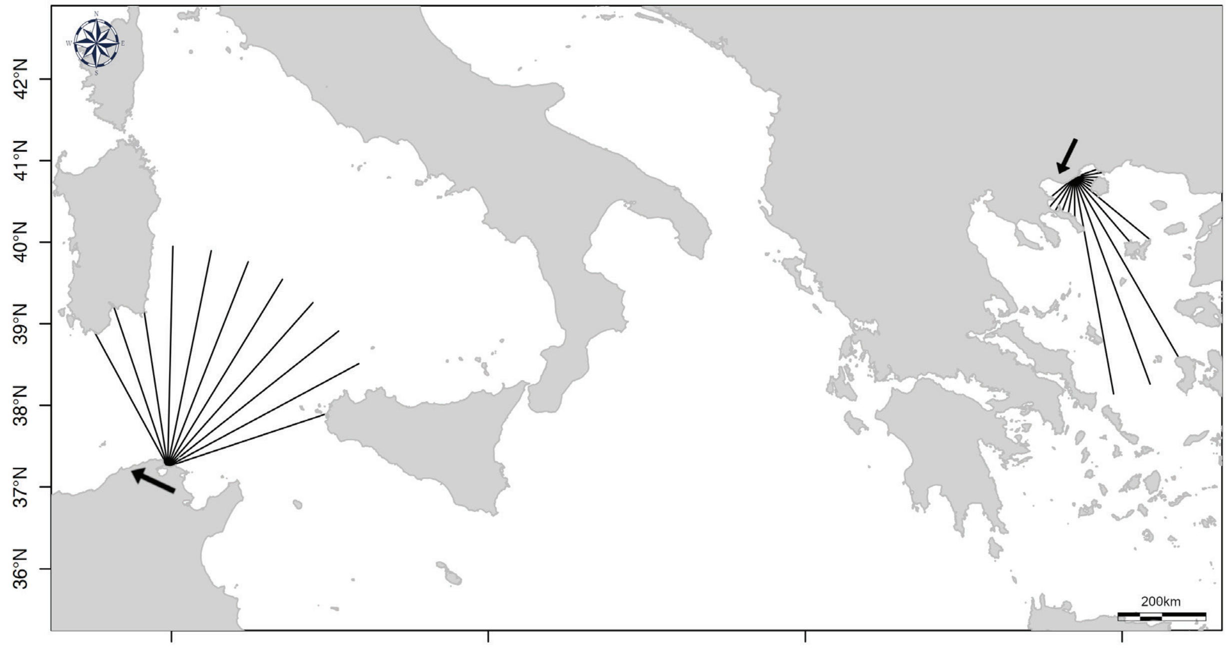

Fig. 1: Study sites and fetch vectors in Greece and Tunisia coastal waters. Arrows show the prevailing wind direction in the experimental period and their length is relative to wind speed.

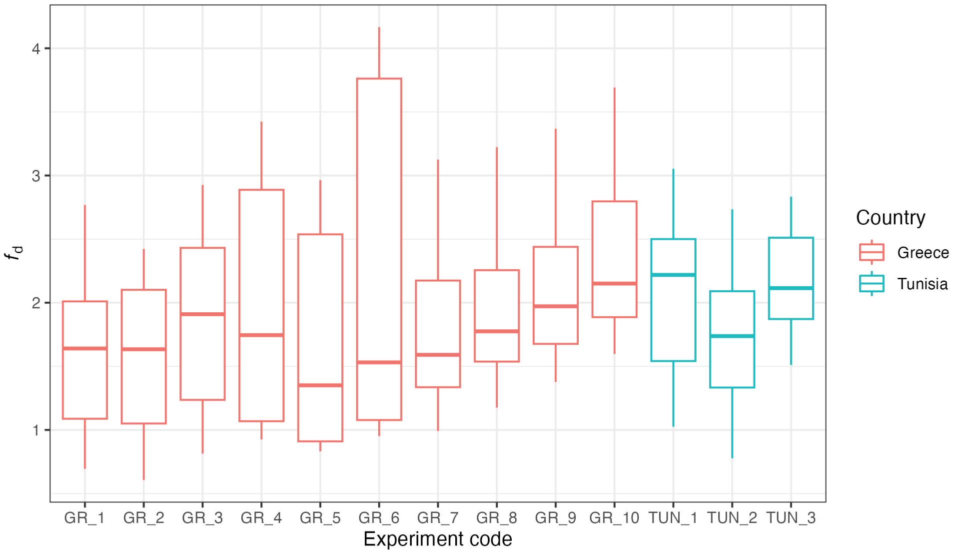

Fig. 2: Box plot of dissolution rate of gypsum (f_d) across the experiments between the two countries. While the numbers correspond to different experiments, GR and TUN are the acronyms for Greece and Tunisia, respectively.

with mean values of 55.55 ± 7.37% and 52 ± 7.83% in Greece and Tunisia, respectively.

No statistically significant difference was found for the f_d between the two experimental areas (wilcox *W = 2669, p = 0.24*), with values in Tunisia being slightly higher (2.01 ± 0.07%) than in Greece (1.94 ± 0.09%). The parameter's variability is shown in Figure. 2 with higher variability in Greece, ranging from 0.61 to 4.17 and lower in Tunisia, ranging from 2.01 to 3.05.

Based on a PCA for the metrics measured in the Greek area, they were divided into two groups, associated with the two axes (Fig. 3). The first axis accounted for 52.2% of the variation and clearly represented the biotic variables and f_d, while the second axis accounted for 27.7% of the variation caused by the three abiotic variables. The third axis accounted for 14.1% of the total variation, while the fourth axis for 4.1%. Among the biotic metrics, cover (%) had the strongest correlation with axis 1 and the strongest negative correlation to f_d (Table 1). Depth was negatively

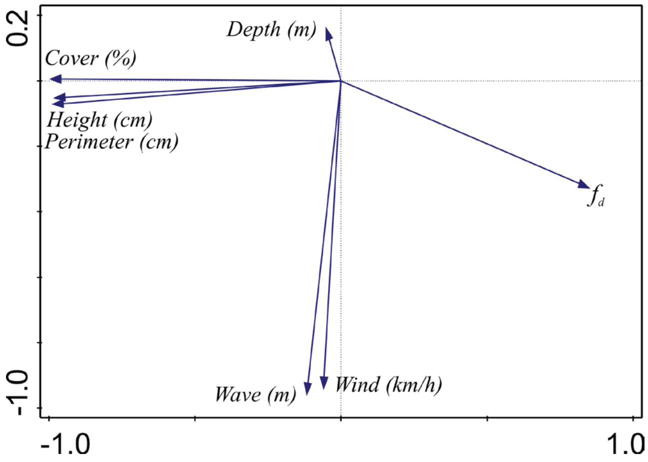

Fig. 3: Principal component analysis (PCA) for abiotic and biotic variables and dissolution rate of gypsum (f_d). The length of the arrows indicates the strength of representation and contribution of each parameter to PC axes. For further information see Table 1.

Table 1. Loading scores of abiotic and abiotic variables and dissolution rate of the gypsum cones (f_d). The correlation coefficients (ρ) are shown in the matrix. Axis =PCA axis.

	Axis 1	Axis 2	Axis 3	Axis 4
***f*$_d$**	**0.8474**	-0.3267	-0.0027	0.3942
Cover (%)	**-0.9939**	0.0057	0.0337	0.0551
Periphery (cm)	**-0.9852**	-0.0718	0.0339	0.1309
Height (cm)	**-0.9796**	-0.0519	-0.0056	0.155
Waves (m)	-0.1173	**-0.9576**	-0.0658	0.1149
Wind (km/h)	-0.0603	**-0.9398**	-0.1011	-0.2683
Depth (cm)	-0.0505	0.1592	**-0.9856**	0.0243

Table 2. Spearman's correlation between the dissolution rate of the gypsum cones (fd) and biotic and abiotic variables. Significance level (* significant $p < 0.05$, ** highly significant $p < 0.01$, *** very highly significant $p < 0.001$).

	f_d (n = 100)
Thalli cover (%)	-0.905***
Thalli perimeter (cm)	-0.698***
Thalli height (cm)	-0.651***
Wave height (m)	0.246**
Wind speed (km/h)	0.112
Depth (m)	0.059

correlated to both wind speed and wave length.

According to the Spearman's test, the strongest biotic significant negative correlation was between *E. barbatula*'s thallus cover (%) and f_d (Table 2). However, similarly strong relationships were detected between f_d and thalli perimeter and height. Only a weak but significant negative correlation was witnessed between f_d and wave height.

The results of the Greek experiments showed a negative and significant linear relationship between *E. barbatula* variables and f_d (Fig. 4). The most accurate relationship was found between f_d and cover (%) ($R^2 = 0.81$). A strong correlation between f_d and cover (%) was also observed in the Tunisia experiments ($R^2 = 0.71$). In fact, and despite the different *Cystoseira s.l.* species of this study and the different geographical locations, the regression models that estimated the relationship between independent and dependent variables were very similar (Fig. 5).

Discussion

Several studies have documented that vegetated habitats have the potential to reduce wave action (Kindeberg *et al*., 2023; Morris *et al*., 2020). The data collected bothin the Greek and Tunisian coastal areas showed that stipitate *Cystoseira s.l.* forests attenuate wave action, i.e. hydrodynamic energy, for up to 38%, when compared to controls, in conditions of moderate wind speeds (mean values ranged from *ca.* 20 to 24 km/h). The experiments of the present study demonstrated that as cover (%) of *Cystoseira s.l.* and thalli size increase, f_d decreases (Table 2). Therefore, the greater their cover (%), the greater the hydrodynamic dissipation and the coastal protection. The strong correlation between f_d and cover suggests that the latter could be a suitable indicator for the attenuation of the wave action in different *Cystoseira s.l.* forests and conditions.

While there is no available evidence on wave dissipation by *Cystoseira s.I.* forests, similar effects have been

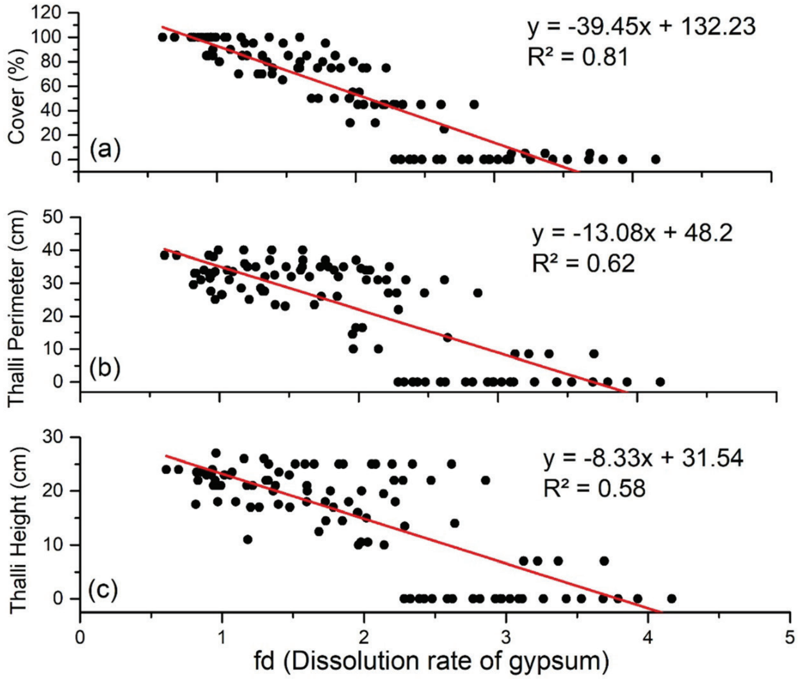

Fig. 4: Linear regression of the fd (Dissolution rate of gypsum) with *Ericaria barbatula's* (a) cover (%), (b) thalli perimeter (cm), and (c) thalli height (cm).

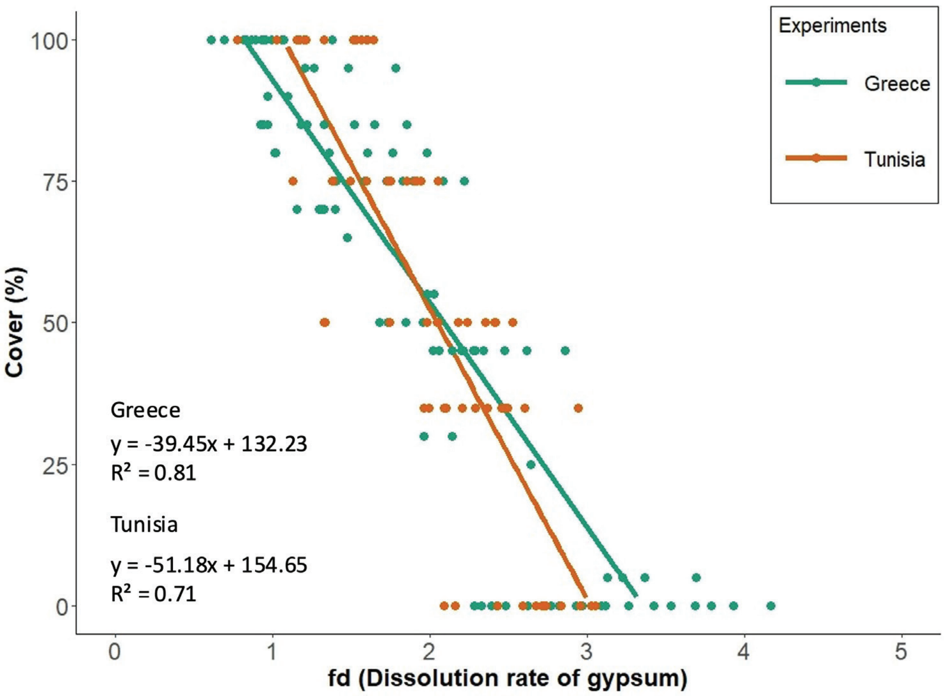

Fig. 5: Linear regression of the fd (Dissolution rate of gypsum) with *Cystoseira s.l.* cover (%) in two experimental areas (Greece, Tunisia) in comparison.

reported for other marine vegetated habitats, such as kelp and mangrove forests, seagrass meadows and salt-marshes (Duarte *et al*., 2013). For example, in conditions of moderate wave exposure, canopies of the stipitate kelp *Ecklonia radiata* attenuated the waves by 10% more than in control conditions (Morris *et al*., 2020). Coastal protection from erosion mediated by seagrasses is widely recognized (Bouma *et al*., 2005; Ferretto *et al*., 2023), and makes the conservation and restoration of these vegetated habitats one of the priorities in many restoration projects (Paulo *et al*., 2019). Other studies have reported that the degree of protection is related to species-specific characteristics, such as shoot density, leaf length, plant stiffness, or standing biomass (Ondiviela *et al*., 2014). Indeed, Paul *et al*. (2012) also showed that the attenuation of wave energy in shallow waters was affected by a combination of submerged vegetation shoot density and leaf length (i.e., the Leaf Area Index, which is an adimensional indicator).

The ratio of vegetation height to water depth has been identified as a factor influencing wave attenuation potential. As indicated in studies on the kelps *Laminaria hyperborea* (Dubi & Tørum, 1995) and *Ecklonia radiata* (Morris *et al*., 2020), the value of 20% was shown to be the lower limit, i.e., vegetation attenuates waves if it occupies at least 20% of water column. The effect of *Cystoseira s.l.* on wave attenuation has been estimated here with the forests occupying *ca.* 30% of the water column on average. However, Christianen *et al*. (2013), by investigating the small-sized seagrass *Halodule uninervis*, emphasized the importance of even low-level vegetation on wave energy attenuation and attributed the significant effects to the relatively high density and cover (%) of the investigated meadow.

The debate on the factors promoting coastal protection from wave action is still open: some studies indicate that the abundance of the species rather than the species richness, arises as being the most important factor for coastal protection (Gaston *et al*., 2018; Winfree *et al*., 2015). The reason is that not all species contribute to the same extent to coastal protection, while this ecosystem service is affected more by highly abundant species (Winfree *et al*., 2015). However, the relationship between species abundance and service provision is not always linear, due to intraspecific or interspecific competition of *Cystoseira s.l.* for light. It is known that larger individuals with a higher contribution to hydrodynamic protection also create a self-shading effect within the forest, forcing some thalli to receive a disproportionate share of light (a pre-emptiable resource) (Orfanidis *et al*., 2021). By doing so they further increase the size distribution asymmetry of the plant canopy, i.e., favour the growth of smaller thalli and do not lead to a linear increase of wave attenuation.

The effect of vegetation on coastal protection cannot be easily described and attributed to species traits, as it is also affected by a number of hydrodynamic phenomena, such as currents and their directions from and to the shore, depth of the region leading to different wave-damping patterns, coastal fetch, etc. (Maza *et al*., 2015). While other studies on other macrophytes suggest that wave-attenuation effect is stronger in shallower depths (Morris *et al*., 2020), no significant correlation was found between depth and f_d, at least at the depth range (average depth 46.5 - 60.1 cm) tested in this study.

We conducted two experiments in two different locations and at different dates. The Greek experiment took place at the beginning of summer, while the Tunisian experiment took place at the beginning of autumn. Season could be an important factor when studying wave attenuation by macroalgae, as it depends on the vegetation's biomass and, by extension, the area's morphology (Morris *et al*., 2020), which vary seasonally for *Cystoseira s.l.* species. *E. barbatula* present in the Greek area becomes fertile from April to July (Papadimitriou *et al*., 2022), while on Tunisian shores *E. brachycarpa* is fertile all year round (except in summer in some areas) and *C. crinitophylla* is seasonally fertile from October to March (Montesanto & Panayotidis, 2001). In this respect, samples from both areas were collected when the local populations could be considered at their developmental peak and were thus adequate to study their ecosystem services.

The relationship between *Cystoseira s.l.* cover (as % cover of the substrate) of similar morphology and wave attenuation was identical in both countries, even under different abiotic conditions (season, weather conditions, depth morphology, etc.). This result supports the Morris *et al*. (2020) conclusion that kelp-mediated wave attenuation depends on kelp morphology, which varies among different species. Indeed, field experiments in the two areas support the hypothesis that *Cystoseira s.l.* forests can significantly protect the coast from wave erosion.

An alternative approach to test the vegetation's effect on wave attenuation is based on laboratory experiments, which allow the set up of controlled conditions (Maza *et al*., 2015; Paul *et al*., 2012). Repeated experiments in different laboratory conditions (e.g., depth, wave direction and size, presence/absence of currents, etc.) can be implemented, focusing on different scenarios, although there are other contrasting factors limiting the reliability of such kind of experiments in controlled conditions. Nevertheless, an observation in a controlled environment can give us the information we could not get from the natural environment (Maza *et al*., 2015).

In conclusion, the results of the present study provided evidence that *Cystoseira s.l.* forests can have a significant effect of wave attenuation under moderate wind speeds. The results showed that their abundance, as estimated by cover (%), was an essential indicator of coastal protection against erosion through wave action. Although we have results from two different regions of the Mediterranean, different seasons, and different species under study, further research on macroalgal forest wave attenuation is imperative. Further study is needed to examine other geomorphic, ecological, and hydrodynamic factors that determine wave attenuation among different locations, seasons, and species. The results will be necessary for developing indicators of restoration success and providing data to managers and policymakers for sustainable and cost-effective coastal defense solutions.

Aknowledgements

This study was supported by the European Union's CINE (European Climate, Infrastructure and Environment Executive Agency) ex-EASME (Executive Agency for Small and Medium Enterprise) and EMFF (European Maritime and Fisheries fund) as part of the project AFRIMED, "Algal Forest Restoration in the Mediterranean Sea" (under grant agreement N° 789059; http://afrimed-project.eu/), and Biodiversa+, the European Biodiversity Partnership under the 2021-2022 BiodivProtect joint call for research proposals, co-funded by the European Commission as part of the project FORESCUE, "Innovative approaches FOr RESCUE and management of algal forests in the Mediterranean Sea" (under grant agreement N° 101052342).

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Supplementary Data

The following supplementary information is available online for the article:

Fig. S1: Map of the study area of the Greek coast.
Fig. S2: Map of the study areas of the Tunisian coast.
Fig. S3: Placement of gypsum cones in Greek coasts.
Fig. S4: Placement of gypsum cones in Tunisian coasts.
Table S1. Sea conditions for each treatment in the Greek experiment.