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Posidonia oceanica L. (Delile) meadows regression: Long-term affection may be induced by multiple impacts

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ABSTRACT

Coastal development has an undeniable impact on marine ecosystems resulting in the detriment of the more sensible communities. *Posidonia oceanica* meadows are climax communities which offer a wide variety of ecosystem services both ecological and socio-economic. Human-derived impact on these habitats has been widely assessed although conclusions may vary depending on the area. *P. oceanica* meadow regression next to the city of Alicante (SE Spain) was analyzed on the long term (1984–2014) using bionomic cartographies and side-scan sonar images and, during the last two decades (2003–2021), using cover percentage and shoot density descriptors in the remaining meadow. Results showed a 25% colonized area reduction since 1984, this process being more rapid during the 1984–1994 period and decreasing with time. Cover and density have suffered a significant decrease in the last 20 years, mainly in the upper limit of the meadow. Dead matte cover was also assessed and have shown a significant increase in the same period following an inverse trend with the other metrics. There are several coastal impacts which have co-occurred in the area in the last few decades (port enlargement, brine and sewage discharges, industrial activity) thus resulting in the regression of the meadow. The existing negative trend of the measured descriptors indicate the necessity of implementing management actions which focus on the present sources of impact and actively reduce their effect on *P. oceanica* beds.

1. Introduction

Human development imply the occupation of natural areas and use of its ecosystem services, changing environmental dynamics at local and sometimes global scales (Goudie, 2000). This is particularly relevant along coastal regions where economic growth have resulted in a health decline of their associated marine ecosystems (Boesch, 2001; Lotze et al., 2006; Montefalcone et al., 2012); indeed, the Mediterranean Sea is an example of this issue (Benoit and Comeau, 2012; Bianchi et al., 2012). Coastal and marine ecosystems suffer from these perturbations, and especially when they are affected by several stressors simultaneously (Halpern et al., 2008; Turner et al., 1996) (He and Silliman, 2019; Short and Wyllie-Echeverria, 1996). The Mediterranean Sea region is an example, with decades of different sources of impacts associated with industrial, social development and tourism, such as port development, marine traffic, chemical discharges, etc. (Burak et al., 2004; Gonen, 1981; Telesca et al., 2015).

Seagrasses have suffered a relevant decline along most of the world's coasts in the last few decades (Dunic et al., 2021; Green et al., 2021; Hemminga and Duarte, 2000; Orth et al., 2006; Short et al., 2011a; Waycott et al., 2009a) and among them, *Posidonia oceanica* at the Mediterranean Sea is one of the main exponents of the phenomenon (Boudouresque et al., 2009; Marbà et al., 1996). The relevance of *P. oceanica* meadows have been widely proven as an ecosystem bioengineer, sustaining a variety of fundamental habitats with ecological and economic importance (Boudouresque et al., 2012; Campagne et al., 2014). Among these ecosystems services, some of the most relevant are their support for coastal fisheries (Unsworth et al., 2019), coastline protection from erosion, sustainability of habitats for ecotourism (Barbier et al., 2011; Hemminga and Duarte, 2000) and climate change mitigation through carbon sequestration and storage (Duarte et al., 2013; Fourqurean et al., 2012; Pergent-Martini et al., 2021; Piñeiro-Juncal et al., 2021). Assessing the economic value of ecosystems is a way of simplifying and putting in value the role of their services

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(Costanza et al., 1997, 2011; Pagiola et al., 2004); in this regard, seagrasses-based ecosystems, and especially *P. oceanica*'s, are among the most valuable (Dewsbury et al., 2016; Tuya et al., 2014) (Campagne et al., 2014; Vassallo et al., 2013). However, this species has suffered significant degradation because of its vulnerability to anthropogenic disturbances (Short et al., 2011a; Waycott et al., 2009b). There are several ways in which human development can interact with seagrass beds and promote their degradation, although pollution and water quality loss have been observed as main causes (Ardizzone et al., 2006; Peres and Picard, 1975; Ruiz and Romero, 2003; Short and Wyllie-Echeverria, 1996; Thomsen et al., 2020). Coastal cities act as a sources of several impacts of different nature: sewage discharge, marine litter, industrial activity, dredging, etc. (Burak et al., 2004; Wang et al., 2019; Zahedi, 2008); thus, becoming "hot spots" for potential environmental degradation of *P. oceanica* (Coll et al., 2010; Gonen, 1981; Holon et al., 2015a,b). In this regard, it has been observed that *P. oceanica* is generally sensitive to these different source impacts, especially if more then one is present (Boudouresque et al., 2009; Leiva-Dueñas et al., 2021; Telesca et al., 2015), considering its slow recovery capacity (Kilminster et al., 2015).

The coast of Alicante, Spain, is a model highly populated area where several human impacts have historically co-occurred, affecting mostly ecosystems sustained by *P. oceanica* meadows (Clemente et al., 2021; Fernández-Torquemada et al., 2005; Pastor et al., 1994; Ramos-Hidalgo et al., 1995). The most relevant impacts are associated with sewage outfalls, industrial activities, construction activities related with port enlargement, marine vessel traffic, bottom trawling fishing and brine discharges from desalination plants (de-la-Ossa-Carretero et al., 2016; Fernández-Torquemada and Sánchez-Lizaso, 2005; González-Correa et al., 2005; Ramos-Esplá et al., 1994). The aim of this study is to address historical regression patterns of *P. oceanica* meadows since 1984 until nowadays in the Alicante coasts, and discuss the potential relation with the co-occurring impacts present in the area and the implementation of potential management strategies for the protection of the seagrass-based ecosystems overall.

2. Materials and methods

2.1. Study area

This long-term study took place along to the city of Alicante (Spain) in the Mediterranean Sea. The studied area extended from the Alicante port to approximately 5 km to the south, covering extended *P. oceanica* meadows (Fig. 1).

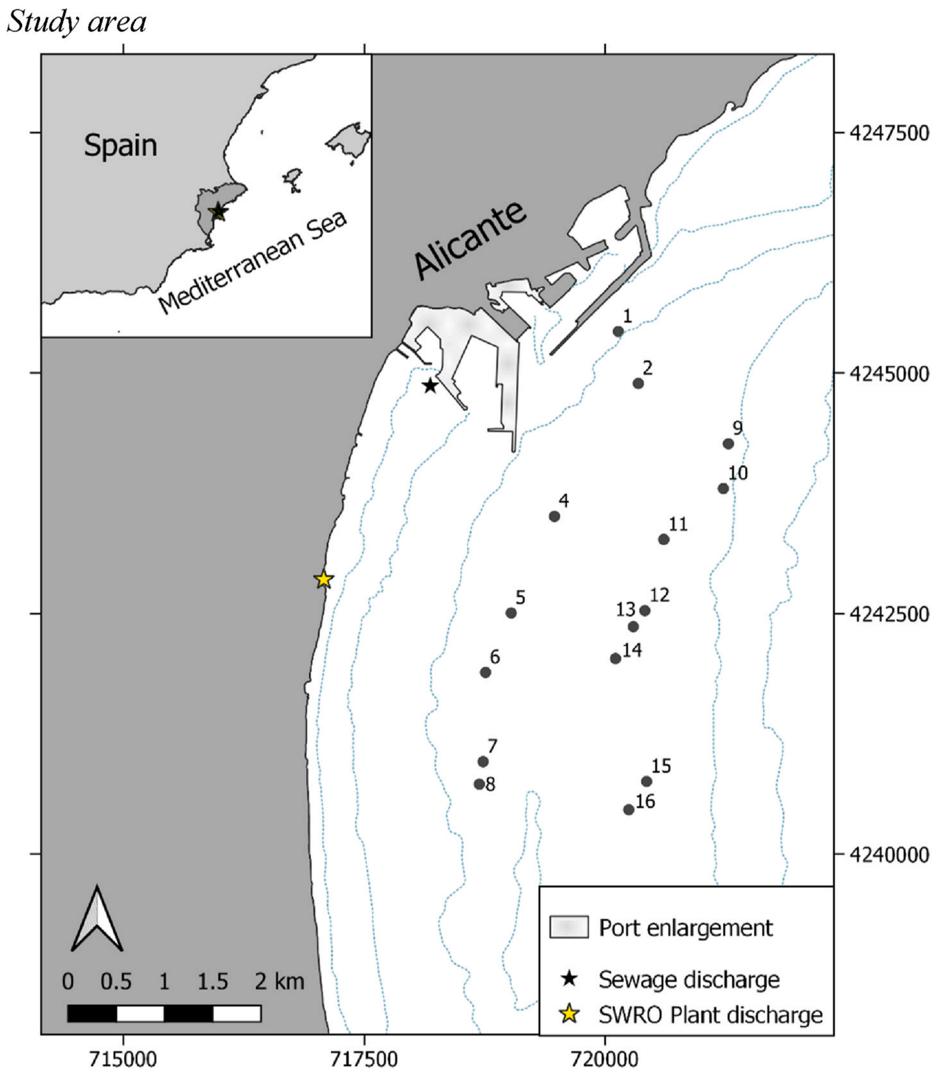

Fig. 1. Map of the study area representing 16 sampling locations: 1–8 meadow upper limit and 9–16 continuous meadow. Some potential pollution sources are shown: Alicante port, sewage discharge and seawater reverse osmosis (SWRO) desalination plant discharge.

2.2. *Meadow extent*

P. oceanica meadows total extent was estimated from side-scan sonar imaging (GeoAcoustics 100/500 kHz) (Sánchez-Carnero et al., 2012). Sonar data was corroborated with scuba diving observations to verify meadow presence. Sonar cartography data were taken in the years 2003, 2007, and 2014, with a total of 2500 ha of mapped area each year. Also, shallow dead matte and upper meadow limits at 1984 and 1994 were taken from previous studies (Ramos-Esplá, 1984; Ramos-Esplá et al., 1994); in these, *P. oceanica* extent was assessed by diving transects every 500 m, and used to assess the total meadow loss through the whole period of time (1984–2014) and its regression rate (RR = Extent loss/year).

2.3. *Cover and density measurements*

Sixteen study locations were selected between 14 and 16 m (meadow upper limit) and 20–23 m (continuous meadow) depth. Data collection was conducted by scuba divers in each location. Cover and shoot density data begun to be collected in 2003, and repeated in 2007, 2014 and 2021; thus, having long-term perspective of the behaviour of the meadows. *P. oceanica* and dead matte cover was measured in percentage of surface along a 20-m linear transect, while shoot density was assessed by counting the number of living shoots in a 40 × 40 cm^2 quadrat randomly thrown (Pergent-Martini et al., 2005). At each station, 3 replicates of each variable were measured each year.

Cover, density, global density (shoot density × cover) and dead matte (dead *P. oceanica*) metrics were analyzed by using a linear regression model to determine their evolution through time. Data normality requisite was assessed by using a Kolmogorov-Smirnov test and, when necessary, data was log-transformed to ensure their homogeneity of variance. Analyses were carried out using the R package 'lmtest' (R CoreTeam, 2017).

3. Results

3.1. *Evolution of the surface of the P. oceanica meadow in the Alicante Bay*

The first estimate of *P. oceanica* meadows extent in Alicante Bay was conducted by Ramos-Esplá (1984), using aerial photographs and scuba diving transects. In this study, an extensive area of dead matte and regression of *P. oceanica* meadow was observed. On the basis of this cartography, we estimated that dead matte covered 348 ha in the area (Fig. 2). Since then, the surface area covered by *P. oceanica* dead matte has increased to approximately 1001 ha in 2014, although today most of this dead matte is covered by a thin layer of silty sediment; therefore, difficult to differentiate from historical inputs.

P. oceanica meadow in 1984 covered approximately 2500 ha of the bay, but it steadily declined to 2289 ha as assessed in 1994 (Ramos-Esplá et al., 1994). Subsequently, our data evidenced an estimated a surface of 2083 ha in 2003, 2002 ha in 2007, and 1881 ha in 2014; i.e. approximately *75%* of the initial surface area in 1984 (Fig. 2A). With all these data, it is estimated that the *P. oceanica* beds have lost an average of approximately 21 ha per year from 1984 until 2014; which implies a 1.01% meadow reduction per year (Fig. 3).

Moreover, in terms of vertical distribution of the meadow, in 1984 the upper limit was observed at 13 m depth (Ramos, 1984). In 2000, this limit decayed to 15 m Ramos-Esplá et al., 2000; however, our current observations show that the upper limit had even dropped to 16–17 m depth (Fig. 3).

The regression pattern shows a greater area loss in the meadow located 1–1.5 km south from Alicante's harbor (Fig. 3). The regression rate (area loss/year) reached its maximum value in the period between 1984 and 1994 (Fig. 2B), and then followed a decreasing trend until 2014.

3.2. *Changes in P. oceanica meadow structure*

Additionally, in the persisting meadows, we have found an important reduction in its shoot density and cover (Fig. 4). In the case of the meadow limit stations, significant values were obtained in the linear regression analysis for all tested metrics (Fig. 5). Density, cover and global density declined significantly, and limit locations presented higher reductions in comparison with the continuous meadow (Fig. 4). On the other hand, dead matte cover increased more in deeper locations.

Similar trends were observed for the continuous meadow, although the regression was not significant at the 95% confidence interval in the case of *P. oceanica* cover. Density, cover and global density showed lower values, and a significant negative trend in the case of the meadow limit locations. In the case of the dead matte cover, the values were higher in the limit locations, although in both cases a significant increment was found (Fig. 4).

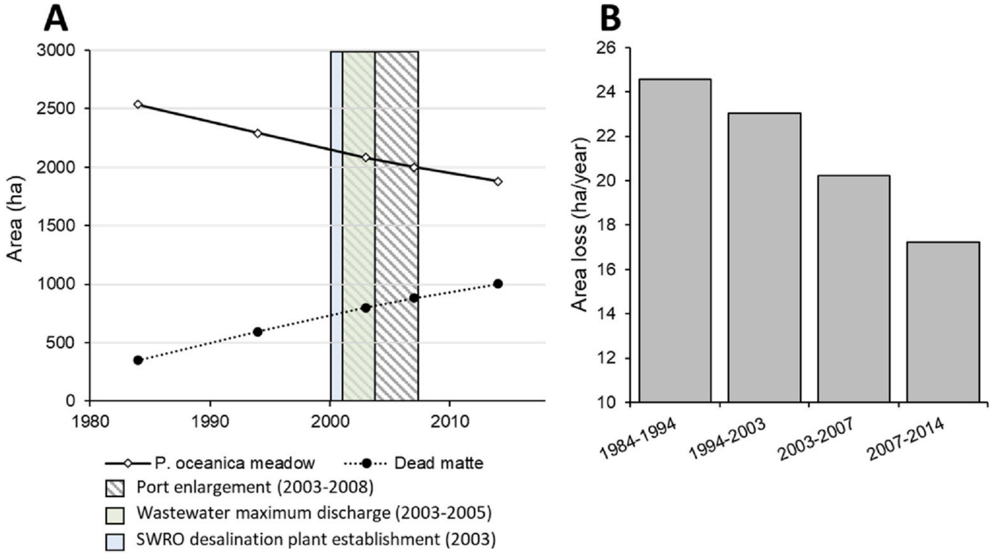

Fig. 2. Historical evolution of P. oceanica and dead matte extent (ha) in the Bay of Alicante, representing some of the known human activities developed during this period (A). Regression rate of P. oceanica meadow in the area (B).

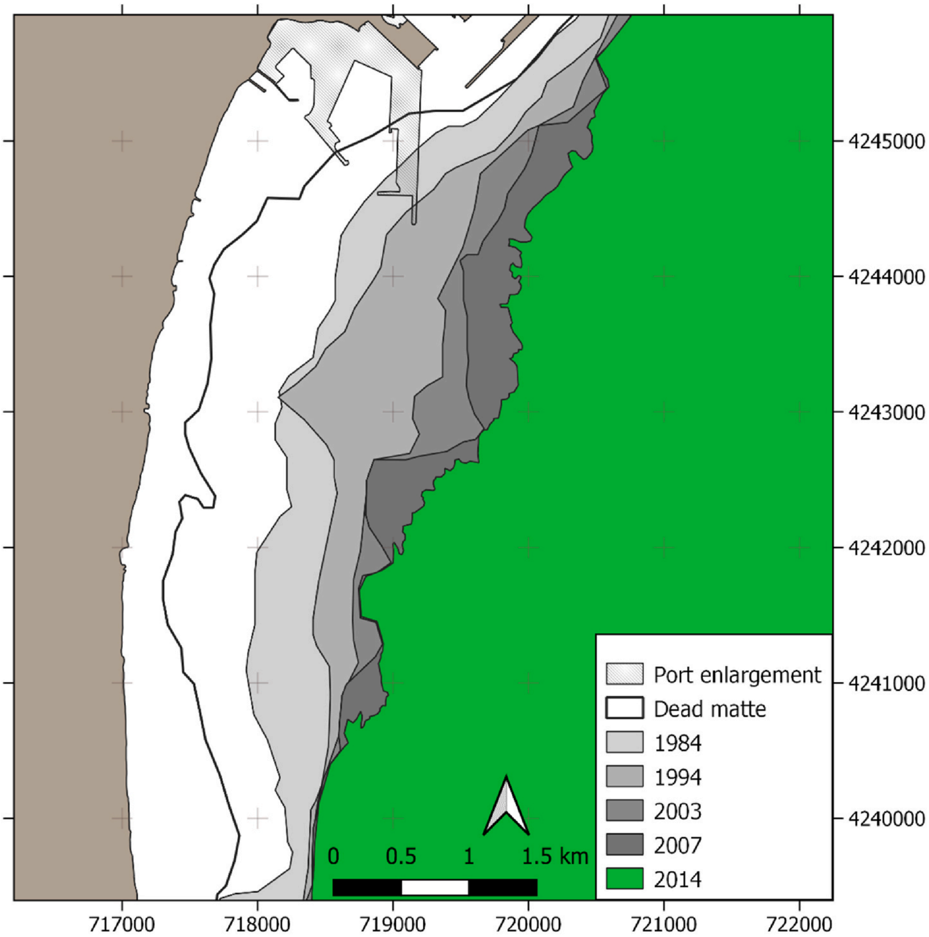

Fig. 3. Evolution of the upper limit of P. oceanica meadow in the Bay of Alicante between the years 1984 and 2014.

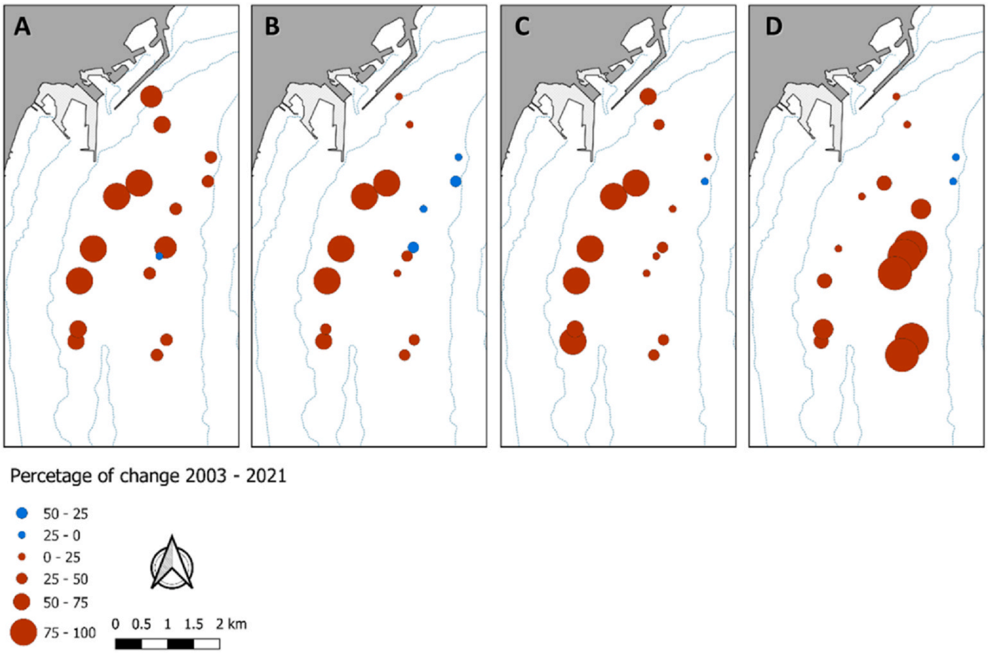

Fig. 4. Percentage change in shoot density (A), P. oceanica cover (B) and global density (C) between 2003 and 2021. Blue color represents an increment in the metric values while red represents a measured decrease. Percentage of change in dead matte cover (D), shows in red an increase of this metric and in blue its reduction. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

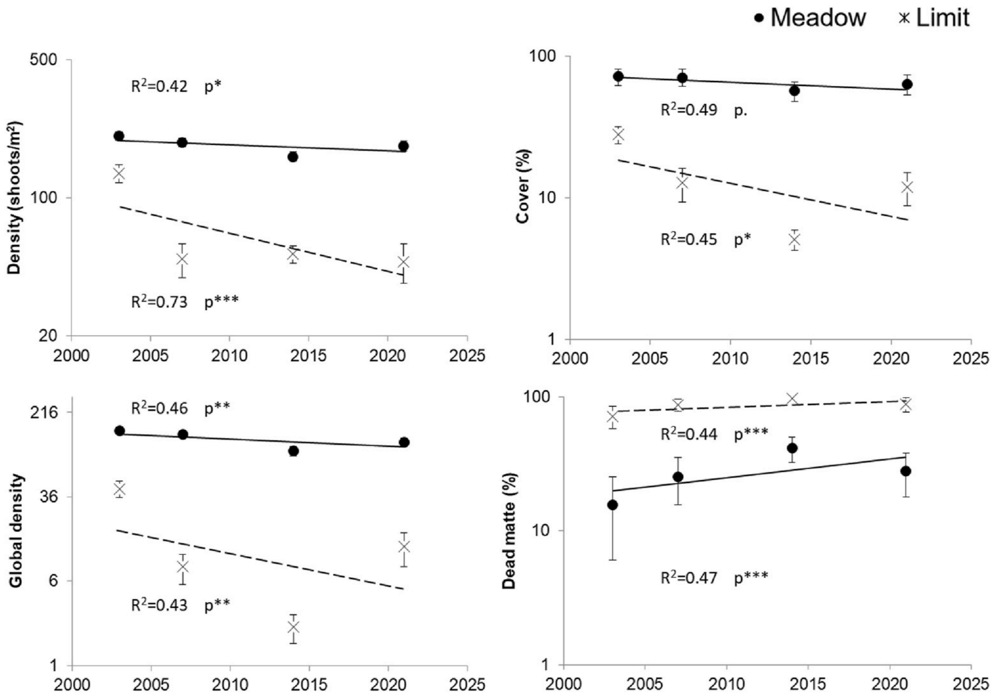

Fig. 5. Logarithm of P. oceanica measured descriptors as a function of time in the upper limit sites and inside the continuous meadow (≈20 m depth). The dots represent the average of each of 3 replicates per depth and time. Significance levels: p. (<0.1), p* (<0.05), p**(<0.01) and p*** (<0.005).

4. Discussion

Results showed a general trend of declining of *P. oceanica* meadow surface during the last 40 years. This regression is concordant with a general global trends observed in other coastal seagrass meadows across the world (Duarte, 2002; Orth et al., 2006; Short et al., 2011b), and particularly for the endemic *P. oceanica* (Holon et al., 2015a,b; Marbà et al., 2014; Sánchez-Lizaso et al., 1990). Our study indicates that the upper limit of the meadows has been generally displaced from 13 m depth in 1984 to 16–17 m in 2021, with a total loss of 619 ha of the total extent, representing a 25% of the initial colonized area.

The declining process has shown not to be constant throughout time. Its maximum regression values were reported between 1984 and 1994 and continue afterwards with less pronounced decline; the latter, despite to the concomitant enlargement of the port and the establishment of the reverse osmosis desalination plants, all between 2003 and 2008 (Fernández-Torquemada et al., 2005; Sánchez-Lizaso et al., 2020). This trend agrees with the general regression pattern of seagrass meadows in Europe, in which regressive meadows seem to be reaching a stable state (de los Santos et al., 2019) and other areas of the Mediterranean Sea (Badalamenti et al., 2011; Montefalcone et al., 2019).

Our density and cover data also reflect the current status of the meadows. Both variables show a general regression trend, especially measured at the upper limit of the meadow. This is consistent, considering that the upper limit of the *P. oceanica* meadow is usually closer landwards from human-derived physical or chemical pressures (Montefalcone et al., 2009). However, for instance, in France and Italy some authors have found a higher regression of the deeper limit of *P. oceanica* meadows (Ardizzone et al., 2006; Boudouresque et al., 2009). Recent and higher-scale studies, including Spanish coasts, concluded that upper limit decline could be the main process inducing *P. oceanica* retreat (Holon et al., 2015a,b; Montefalcone et al., 2019). On the other hand, dead matte presented a higher increment in the continuous meadow, but this might be due to the fact that dead matte values at limit locations were already close to the 100%, not varying importantly during the studied period. In spite of this information, our data for the deep meadows are not available for all the studied period, and thus comparisons with the upper limit cannot be fully conclusive.

Causes of *P. oceanica* meadows regression are diverse and may have different consequences on the seagrass ecosystem (Boudouresque et al., 2012). Anchoring has proven to negatively affect these ecosystems causing physical damage on the meadow structure (Ceccherelli et al., 2007; Montefalcone et al., 2008), in this regard, coastal touristic cities in the Mediterranean Sea have an intense sailing activity, thus becoming a potential source of this impact. Also trawling fishery has been cause of meadow degradation in several areas of the Mediterranean Sea, including the Spanish coast; although its development is currently forbidden in areas with seagrass meadows, the associated historical impacts have not seem to improve (González-Correa et al., 2005). Furthermore, coastal development activities, implying sediment mobilizations and water quality alterations derived from beach replenishment and dredging, among others, have resulted in major regressions of *P. oceanica* both in the short and the long term (Badalamenti et al., 2011; González-Correa et al., 2008, 2009). Industrial and sewage discharges have also been reported to induce a detriment on *P. oceanica* meadows (Pergent-Martini and Pergent, 1996). Desalination plants have also become a potential threat to *P. oceanica* communities, mainly due to the high-salinity brine discharges associated with the reverse osmosis process. In fact, the low tolerance of this stenohaline marine angiosperm has mediated a special scientific attention the desalination impacts (Fernández-Torquemada et al., 2005; Fernández-Torquemada and Sánchez-Lizaso, 2005).

All the mentioned anthropogenic activities co-occur in the area of Alicante; indeed, these conditions are common globally and have been observed to significantly effect on seagrass meadows overall (Boudouresque et al., 2009; Grech et al., 2012; Turschwell et al., 2021; Yaakub et al., 2014). In this context, and in spite some authors as Leriche et al. (2006) have found certain resilience of a *P. oceanica* meadow under co-ocurring impacts, most surveyed meadows in urbanized areas have presented clear trends of decline (Ruiz and Romero, 2003; Telesca et al., 2015). Considering the continuous demographic expansion in coastal areas, this work allows a current and future perspectives of the general impacts of human activities on seagrass, and specifically *P. oceanica*, meadows.

Certainly, the gathered information would hardly attribute direct responsibility to specific stressors for the regression of *P. oceanica* meadows. This disparity may be mainly caused by local impacts which co-occur along the Mediterranean coast related to coastal development, instead of more broadly-ocurring processes (Boudouresque et al., 2009; de los Santos et al., 2019; González-Correa et al., 2007; Leriche et al., 2006; Telesca et al., 2015). Considering this information, the historical Alicante's meadow regression may work as a model of a high populated coastal area, where the multiple co-ocurring impacts suggests a responsibility on the *P. oceanica* regression. Therefore, *P. oceanica* meadows are highlighted as sentinel prospects for environmental biomonitoring. It should be the purpose of future investigations, however, to ascertain the specific effects and contribution of each of the co-ocurring impacts on *P. oceanica* and the retreat on their forming ecosystems.

Although management actions are the main cause of seagrass stability or recovery (de los Santos et al., 2019; Marbà et al., 2002), the effectiveness ofconservation measures remains not fully clear (Evans et al., 2018; Quiros et al., 2017). This fact might be caused by the still immature management actions regarding protection of *P. oceanica* meadows (Montefalcone et al., 2009). In this regard, land-use and coastal development seem to have a higher influence on seagrass conservation, rather than the creation of marine protected areas (Quiros et al., 2017); thus, the information suggests that management efforts should focus on mitigate impacts and not only on conservation initiatives.

5. Conclusions

P. oceanica meadows have lost 25% of its total surface in the study area, being the period between 1984 and 1994 the one with a highest regression rate, with a stabilizing trend afterwards. Also, meadow descriptors (shoot density and cover percentage) displayed a significant decline throughout time, mainly in the meadow's upper limit; this may indicate that the regression of *P. oceanica* meadows is still an ongoing process.

The eventual complex interactions between stressors highlight the importance of improving our current biomonitoring protocols in order to address the overall contribution of specific and/or combined impacts on the historical and current regression of *P. oceanica* meadows.

CRediT authorship contribution statement

Fabio Blanco-Murillo: Conceptualization, Methodology, Formal analysis, Resources, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Yolanda Fernández-Torquemada:** Methodology, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Aurora Garrote-Moreno:** Methodology, Formal analysis, Resources. **Claudio A. Sáez:** Writing – original draft, Writing – review & editing, Visualization, Supervision. **Jose Luis Sánchez-Lizaso:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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