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Note

Economic impact of human-induced shrinkage of *Posidonia oceanica* meadows on coastal fisheries in the Gabes Gulf (Tunisia, Southern Mediterranean Sea)

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ABSTRACT

In early XXth century, the Gulf of Gabes (SE Tunisia) used to host the most extended *Posidonia oceanica* seagrass beds in the Mediterranean Sea, and a highly productive hotspot of benthic/demersal biodiversity. Sponge harvesting and seabed trawling provoked a first step of seagrass degradation. Subsequently, phosphogypsum releases from Gabes Industrial Complex, since mid-1970s, accelerated the decline of the remaining patches. A sharp reduction of coastal fisheries landings took place with the establishment of the last industrial plant units in 1985. The decrease in coastal commercial species landings was found to be directly correlated with *P. oceanica* decline. The trophic web system switched from a 'benthic-dominated' to a 'pelagic-dominated' system. The economic loss related to coastal fisheries was estimated at ~60 million € in 2014 and the 1990–2014 cumulated loss exceeded 750 million €. This first economic valuation of the only direct-use consumptive value of the coastal fishing service provided by *P. oceanica* in Gabes Gulf is a first step towards the assessment of the environmental cost of the negative externalities caused by the local phosphate industry. It may be used as a preliminary decision-making aid to consider alternative industrial solutions.

1. Introduction

Over 40% of the oceans are impacted by pollution (Halpern et al., 2015). In the last fifty years, the number of marine dead zones has doubled with each passing decade (Diaz and Rosenberg, 2008; Limburg et al., 2020). Marine ecosystems contaminated by pollutants such as toxic runoff, dredged materials, oil spills, trash and debris, industrial wastes and sewage sludge, are persistently disrupted (Rabaoui et al., 2020). The Mediterranean basin is among the most impacted regions in the world together with the North Sea, South and East China Seas, east coast of North America, Red Sea and Arabian Gulf (Halpern et al., 2008, 2015, 2019). Consequently, the socio-economic status of some coastal fisheries has become threatened by habitat degradation (Pedro et al., 2020). Such an environmental and socio-economic status regarding coastal fisheries is the rule for all countries bordering the Mediterranean basin, where nearly 500 million people live on the coasts (UNEP/MAP, 2017)(UNEP/MAP, 2017) along with more than 350 million tourists per year (Pons et al., 2009). The United Nations Environment Program (UNEP) has estimated that 650 million tons of sewages, 129 thousand tons of mineral oil, 60 thousand tons of mercury, 36 thousand tons of phosphates and 3800 tons of lead are dumped into the Mediterranean Sea each year (UNEP, 2012).

The good health status of essential fish habitats like seagrass ecosystems is an essential factor for the maintenance of Mediterranean coastal fishing economic activity because of its ecosystemic functions for benthic and demersal commercial species (Unsworth et al., 2018). Seagrass meadows are among the most valuable coastal ecosystems worldwide in terms of goods and services they provide (Costanza et al., 1997; Hemminga and Duarte, 2000). According to Waycott et al. (2009), almost one third of the areal extent of seagrass has disappeared globally since the end of the XIXth century. In the Mediterranean basin, *Posidonia oceanica* is the most important endemic seagrass species and it

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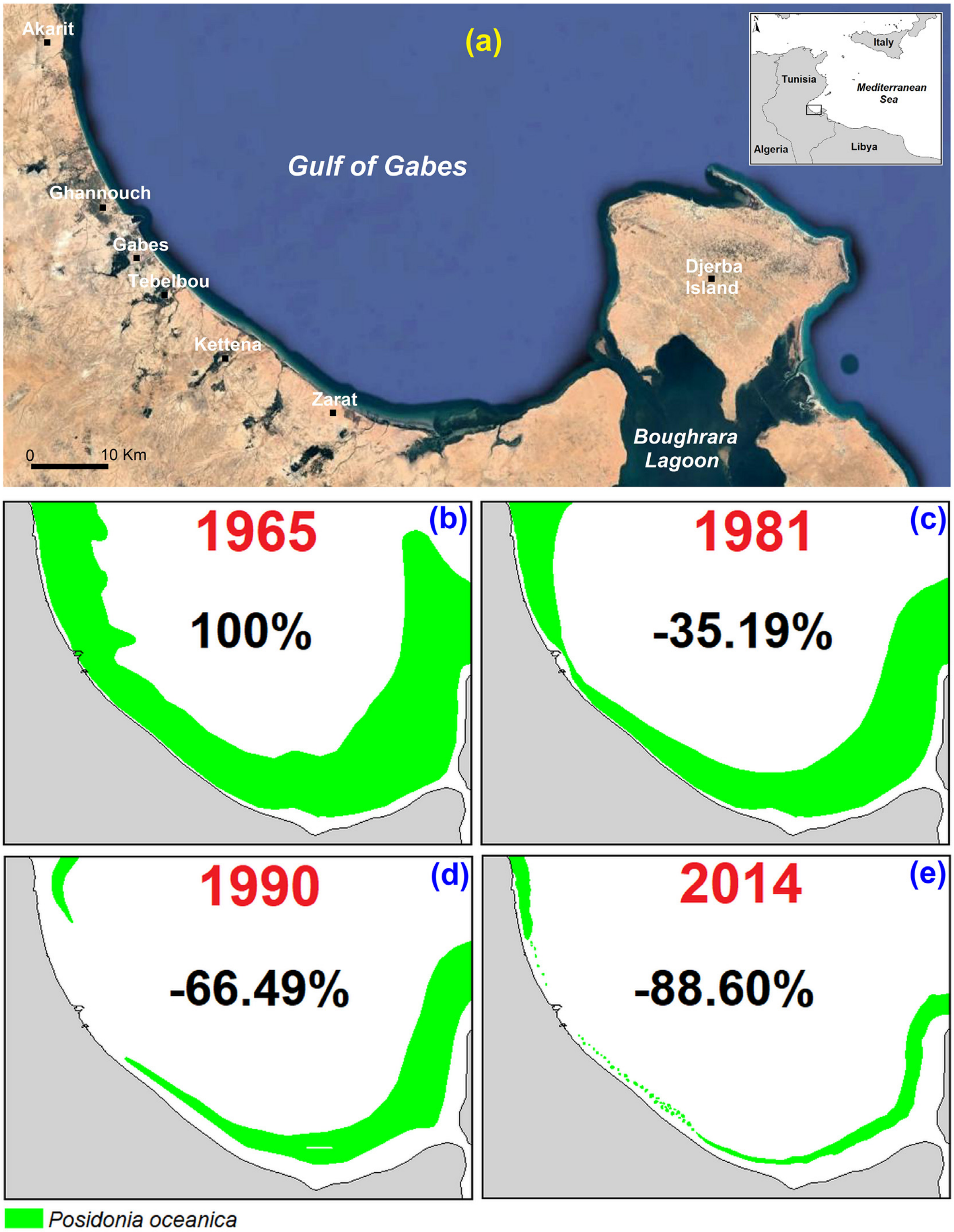

Fig. 1. Location of the Gabes Gulf (a) and the historical decline of *P. oceanica* (b. 1965 (De Gaillande, 1970b), c. 1981 (Darmoul, 1988), d. 1990 (Zaouali, 1993), e. 2014 (El Zrelli et al., 2017)).

forms meadows or beds covering an area between 21 and 55 thousand km^2 (Pasqualini et al., 1998). Among the ecosystemic services provided by *P. oceanica* is the fishing income (Costanza et al., 1997; Campagne et al., 2015; Vassallo et al., 2013; Boudouresque et al., 2016; Rabaoui et al., 2017). Direct monetary assessment of coastal fisheries through transformation of benthic and demersal species volumes into financial value testify of the concrete human benefits derived from ecological functions supplied by the seagrass meadows. Consequently, they can be considered as an ecosystem service sensu (Liquete et al., 2016) and as "supporting services" sensu (MEA 2005). A first global valuation of ecosystemic services of all types of seagrass at the worldwide scale has been estimated at about 19,000 US$ ha^{-1} y^{-1} (Costanza et al., 1997). After this founding work, economic valuations of these systems have been sparse (Dewsbury et al., 2016). This is all the truer in the case of the Mediterranean Sea, where few papers have addressed the value of ecosystem services provided by *P. oceanica* seagrass (Vassallo et al., 2013; Campagne et al., 2015).

The seagrass meadows of the Gulf of Gabes (SE Tunisia; Fig. 1) used to be considered as the most extensive beds in the Mediterranean Sea (De Gaillande, 1970a). But since the beginning of XXth century, they declined drastically because of multiple anthropogenic pressures (Ben Brahim et al., 2010; El Zrelli et al., 2017). According to Zaouali (1993), the decline of *P. oceanica* meadows from the Gulf of Gabes has occurred in three main phases: the first phase started with the development of the destructive dredge (or *gangava*), used to collect sponges, which had induced a first local degradation of the meadows leading to the initiation of a slow silting process in the central area of the Gulf (Poizat, 1970). The second phase happened between the mid and late sixties when a major shrinkage of *Posidonia* beds took place following the development of bottom trawling techniques for shrimping. This led to limit the *Posidonia*-covered areas to coastal strips only and to a depth rarely exceeding 20–25 m, and consequently has triggered the silting process from the centre of the Gulf to the coast (Poizat, 1970; Ktari-Chakroun and Azzouz, 1971). As for the third phase, it began in the mid-seventies when the remaining coastal strip of *P. oceanica* beds gradually disappeared around the first unit of Gabes phosphate fertilizer plant, put into operation in 1972 (Darmoul et al., 1980; Darmoul, 1988). By the second half of the seventies, the large quantities of dumped phosphogypsum wastes (≈14,400 $T{\cdot}d^{-1}$ of dry PG; El Zrelli et al., 2018a) in the surrounding marine environment were responsible for degradation of *Posidonia* beds in front of the industrial complex due to the increase of turbidity coupled with the radioactive and chemical contamination of seawater (Darmoul et al., 1980; Darmoul, 1988; El Zrelli et al., 2018b, 2019a). Several studies carried out across the central area of Gabes have confirmed a continuous degradation of the coastal belt of *P. oceanica* triggered by phosphogypsum releases (Pergent and Kempf, 1993; Zaouali, 1993; El Zrelli et al., 2017).

This continuous anthropogenic-induced regression of *P. oceanica* meadows has led to significant changes in the biodiversity of the impacted coastal area over the last few decades, causing thus significant changes in the catch composition and incomes of the coastal fisheries sector. In this context, several studies reported that the fisheries resources of the Gulf of Gabes are highly exploited, thus threatening the socioeconomic situation of Gabes coastal fisheries (FAO ArtFiMed, 2011a). In 1993, ~39 thousand people were directly employed in the coastal fisheries segment and only ~20 thousand in 2009 (FAO ArtFiMed, 2011a). Production varied from ~36 thousand tons in 1986–1990 (Pergent and Kempf, 1993) to < 14 thousand tons in 2009 (FAO ArtFiMed, 2011a). No studies have been conducted so far on the changes on coastal fisheries neither on the valuation of economic changes related to the losses in *P. oceanica* seagrass habitats. This work was conducted with the aims *i*) to describe the decadal changes in the catch and composition of coastal fisheries in relation to the decline of *P. oceanica* beds and increase of phosphogypsum wastes discharges, and *ii*) to assess the losses of economic value proceedings from goods and benefits provided by coastal fisheries in connection with the decline of *P. oceanica* meadows in the Gulf of Gabes.

2. Materials and methods

2.1. Study area

The Gulf of Gabes extends between Ras Kaboudia in the north and the Libyan/Tunisian boundary in the south (Fig. 1a). It is the widest area of continental shelf in the Mediterranean Sea together with the North-Central Adriatic shelf. It covers about 36 thousand km^2. The study area concerns the central part of Gulf of Gabes which extends between the north-western coast of Djerba Island and El Akarit covering more than 100 km of coastline (Fig. 1). This area hosts three main landing sites: Ghannouch, Gabes and Zaratt (Fig. 1a). Among these, Gabes landing site is the most important since its commercial landings represent more than 80% of the total commercial landings from the 3 sites. They are subdivided into "*small pelagics*" and "*coastal fisheries*". Since 1984, the small pelagics group represents an average of ≈80% of the commercial landings of Gabes governorate.

2.2. Fisheries data collection

Annual volumes of landed catches of coastal and small pelagic fisheries were collected, over 36 years extending from 1980 to 2016. The 1980–1993 data were collected from the General Fisheries Commission in Tunisia (*Commission Générale des Pêches de Tunisie*; CGP, 1996); while the 1994–2016 data were provided by the Tunisian Directorate-General for Fisheries and Aquaculture (*Direction Générale de la Pêche et de l'Aquaculture*: DGPA; http://www.onagri.nat.tn). Data collected were checked from various reports and since the catch volumes of coastal fisheries were not solid enough for the two years 1984 and 1986, these two records were excluded from the economic analyses (Table S1, Supplemetary Information).

Unfortunately, no official records of coastal and small pelagic fisheries catches were available before the eighties. According to FAO ArtFiMed (2011b), the coastal benthic/demersal landed volumes, before the eighties, were low and mostly composed of cephalopods (e.g. the common octopus, *Octopus vulgaris*) sold mainly in local markets. At that time, there were no estimations for volumes sold in local fish markets or indirectly by fishermen.

2.3. Economic data collection

Official economic data were obtained from the CGP, between 1990 and 2014. The starting year of 1990 was determined by (*i*) uncertain reliability of data before this date, (*ii*) its coincidence with the beginning of the second phase of landed volumes evolution (Table S1, Supplemetary Information), and (*iii*) with the end of the quick degradation phase of *Posidonia oceanica* meadows. The market prices of fish sold in Gabes market were in Tunisian Dinars (TND). These prices were updated (http://mon-convertisseur.fr) and converted to Euros (www.xe.com/fr/currencyconverter/).

2.4. Prediction of the area of Posidonia meadows over the period 1970 to 2014

The quantification of marine area covered by *Posidonia* meadows since the 60s has been established for four years using cartographic data of previous works (Table S2, Supplemetary Information). *Posidonia* maps have been digitized and their areas have been estimated using ArcMap software (version 10.2.2, Fig. 1b–e). Although this is a small sample, it is informative because it covers a long period of time and it has a clear trend of linear shrinking (Fig. 2a). Taking advantage of this informative sample, we fitted a linear regression model of *Posidonia* meadows area versus the year to predict the extension of these meadows in the years without measurements. These predictions and their prediction standard errors were then used for determining the effect of the *Posidonia* meadows shrinkage on fisheries output.

2.5. Relationship between P. oceanica meadow extension and discharges of phosphogypsum

We built a database with the annual meadow extension prediction and discharge of phosphogypsum in megatons into the Gulf of Gabes spanning the period of 1972 to 2016. Assuming that discharges of phosphogypsum have an additive effect, we examined the relation between cumulative annual discharges and the extension of *Posidonia* meadows with generalized linear models (*glm*). Taking into account that *Posidonia* meadow extension is a right-skewed positive random variable, we fit the *glm* assuming a gamma distribution with the log link function. The Gamma distribution model is appropriate for positive, continuous and right-skewed data with a variance that is nearly constant on the log scale.

Since meadow extension was not directly measured data but rather a prediction from the linear model described in Section 2.4, it was necessary to account for the prediction error when fitting the generalized linear model. To that effect we fitted the *glm* to each one of 1000 realizations of the predicted meadow extension, with each realization coming from a truncated normal distribution defined by a mean (μ) equal to the predicted extension, a standard deviation (σ) equal to the predicted standard error of prediction, and bounds of [$\mu - 0.25\sigma$, $\mu + 0.25\sigma$]. This marginalization of the distribution of the meadow

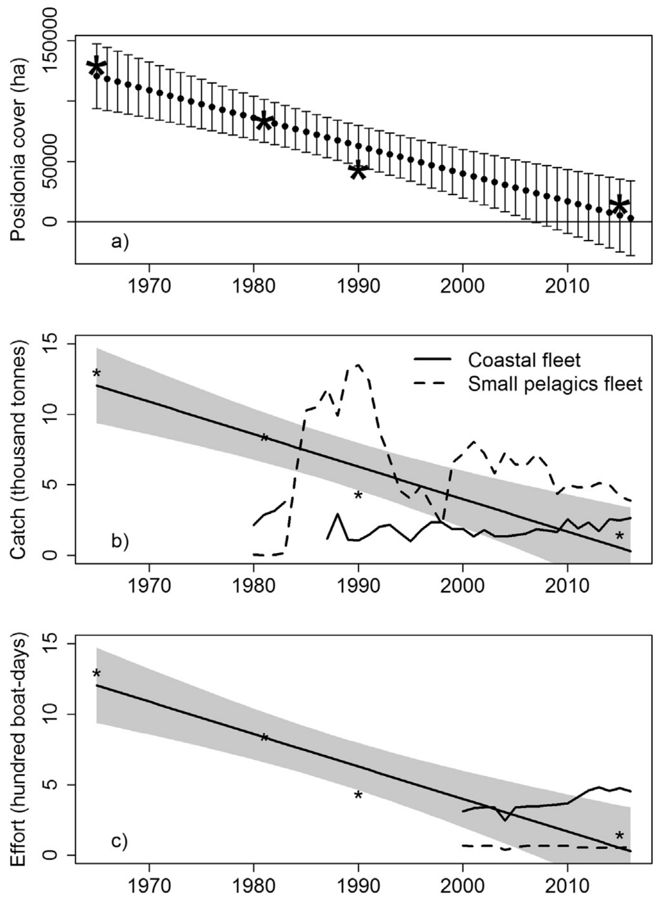

Fig. 2. Historical trends of observed (asterisks) and predicted *Posidonia* cover in the Gulf of Gabes, from a linear model of annual decay plus two standard errors (a), and historical variations of "coastal" (b) and "small pelagic" (c) landing volumes and fishing efforts as well as the *Posidonia* area, during 1970–2015.

extension data accounted for some, though not all, the uncertainty from replacing actual meadow extension data with the predictions from the linear regression between year and the four available direct measurements of meadow extension.

2.6. Economic analysis

Our goal is to assess the economic impact on commercial coastal fisheries in the central part of Gulf of Gabes over the last twenty-five years in relation to the gradual shrinkage of *P. oceanica* seagrass meadows. We value the provisioning services by *P. oceanica* meadows sold on official Tunisian market using the market price-based approach (Silvis and van der Heide, 2013), where the main output of the service offered by *P. oceanica* is the production of benthic and demersal commercial fishery stocks. This method consisted in valuation of the part of benthic/demersal species value dependent on *Posidonia*. We assume that the production in tons of benthic/demersal species at a time t (Q_t) is as follows:

$$Q_t = a_t p_t = b_t z_t \tag{1}$$

where p is the area of *P. oceanica* per hectare (ha) at time t, z is the set of ecological factors that contribute to the production of benthic/demersal species per ha, and a and b are the corresponding yield coefficients. The total value of *Posidonia* corresponds to Q_t multiplied by the market price of benthic/demersal at time t (m_t),

$$V_t = m_t Q_t \tag{2}$$

From the Eq. (2), we can determine the hectare value of *Posidonia* at time t:

$$v_t = m_t a_t \tag{3}$$

We also measured the economic losses due to the degradation of *Posidonia* (ELDP) meadows in the Gulf of Gabes. For that, we compared the maximum potential quantity of *Posidonia*, P, with the quantity p_t, which is the quantity of *Posidonia* at time t. Then the loss value (l_t) can be measured by the following formula:

$$l_t = v_t (P - p_t) \tag{4}$$

2.7. Fishing effort modelling (2000–2016)

Fishing effort data, including the number of boats and number of fishermen, were collected on yearly basis from the annual reports of fisheries statistics published by DGPA. To relate fisheries output to *P. oceanica* meadows extension, we built a database consisting of annual fisheries output in tons of landings, fishing effort in number of boats operating per year, the prediction of meadows extension and the prediction standard error. The fishery effort and output were split between two fleets operating in the Gulf of Gabes, the coastal fleet and the small pelagic fish fleet. This database covered the years between 2000 and 2016. The limiting factor was the unavailability of fishing effort of both fleet components before 2000. Generally, the raw fishing yield data show differences between the coastal and the small pelagic fish fleets (Fig. 2b). The former shows a fairly constant annual yield around 2–3 thousand tons and a rise in effort over the last few years, while the latter shows a decreasing yield and constant effort (Fig. 2c).

To test the effect of meadows extension, we fitted a *glm* with the fisheries output as response variable and the fishing effort and the meadows extension as potential predictor variables, each fleet component separately. The fishing output data was assumed to have a gamma probability distribution with a log link function. As in the previous analyses, we accounted for the uncertainty in the prediction of meadows cover by marginalizing over 1000 realizations of the annual series of meadow shrinkage with the same parameters used to generate the data for the modelling of meadows extension versus cumulative phosphogypsum discharge.

To test the effect of the meadow extension on the fishing output, we fitted a *glm* where both the fishing effort and the meadow extension were included as predictors versus a model where the fishing effort was the single predictor. We then calculated the Akaike Information Criterion (AIC) difference between the model with both predictors versus the model with fishing effort as single predictor. Under the hypothesis that the extension of meadows did not contribute to the fishing output in addition to the effect of fishing effort, the distribution of the AIC difference across the 1000 realizations would be symmetrical and centred on 2 (Sakamoto et al., 1986). Conversely, under the hypothesis of the effect of the meadow extension on fishing output the distribution of the AIC difference would be skewed to the left, and the stronger the effect the stronger the skewness.

3. Results

3.1. Historical decline of P. oceanica

P. oceanica meadows have shrunk drastically along the last 5 decades. In spite of having only four data points the decline was well parameterized by the linear regression prediction, with rather narrow confidence bands (Fig. 2a). The reasons for this success with just four data points were that these points are well spaced in time and they are falling neatly on the linear trend (Fig. 2a). At the estimated rate of shrinkage, the meadows will disappear any year now, although the precision of this prediction allows for residual patches well into the future.

Table 1
Economic value of *Posidonia oceanica* meadows.

Year	1990	2014
Market price (€)	1965	2960
Quantity (tons)	1062	2560
Posidonia oceanica meadows (ha) and {in percent of total land area}	43,563 {33.51}	14,826 {11.41}
Total value of *Posidonia oceanica* (€)	2,086,640	7,576,473
Yield of ton of benthic species per hectare of *Posidonia oceanica*	0.024	0.173
Per hectare value of *Posidonia* (€)	48	511
Economic losses due to the degradation of *Posidonia oceanica* (€)	4,140,278	58,854,676

3.2. Economic valuation

Table 1 summarizes the main results of the economic valuation of *Posidonia* in the Gulf of Gabes in 1990 and 2014. First, we observed that the value has increased by 263% in the period, from €2 million to more than €7.5 million. This increase is due to the high increase in market price of benthic species combined with the rise of benthic species production. In the same periods, the yield of fish has varied from 0.024 to 0.17 tons per hectare of *Posidonia*. Thus, the value of *Posidonia* per hectare was €48 in 1990 and more than €500 in 2014. Between 1990 and 2014, the loss of cover of *Posidonia* meadows in the Gulf of Gabes has resulted in a loss of value from €4 million initially (1990) to almost €60 million currently (2014).

3.3. The phosphogypsum-Posidonia-fisheries connection

The hypothesis of the effect of cumulative phosphogypsum discharge on predicted *Posidonia* cover is overwhelmingly more supported than the alternative of no effect (Fig. 3a). This is noted in much lower AIC values for the hypothesis that included the cumulative phosphogypsum discharge effect versus the null model that did not include that effect (Fig. 3a). In addition, the largest *p*-value of the null hypothesis of no cumulative phosphogypsum discharge effect across 1000 realization of the predicted *Posidonia* cover was very close to zero. Examination of the coefficients showed that every new megaton of phosphogypsum discharged into the Gulf of Gabes reduces *Posidonia* meadow cover by 1 ha on average (Fig. 3b). Further, in the period from 2000 to 2016, the hypothesis of the effect of *Posidonia* meadows shrinkage is not supported for the coastal fishery but it is strongly supported for the small pelagics fishery (Fig. 3c & d). In the latter, the loss of 1 ha of *Posidonia* meadows is related on average the the loss of 1 tonne of fisheries yield.

4. Discussion

Since the early 70s, the central part of the Gulf of Gabes has been severely impacted by high anthropogenic pressures of industrial origin (Rabaoui et al., 2014; Mosbahi et al., 2019; El Zrelli, 2017; El Kateb et al., 2020), represented mainly by the huge untreated phosphogypsum quantities released directly in the coastal environment since 1972 (El Zrelli et al., 2015, 2018a). We have shown in this work that over the same period seagrass cover loss occurred linearly and connected to the cumulative effect of phosphogypsum discharges. The most likely mechanism of decline was a widespread process of siltation of the sea bottom. Further, Cyanophyceae proliferation increased markedly because of nutrients enrichment discharged by the phosphate processing industries directly into sea water (Zaouali, 1993). The benthic ecosystem became dominated by invertebrates of muddy substrata enriched with organic matter (Zaouali, 1993). This transformation of the benthic/demersal environment can be considered as a shift in the biocenosis of the central Gulf of Gabes which occurred between 1984/1985 and 1990 (Zaouali, 1993; Guillaumont et al., 1995).

The results showed that *Posidonia* meadows have an important contribution to the local economy with a per hectare value of €511 and a total loss of value of ~€60 million per year (Table 1). As previously mentioned, very few papers addressed this value in the scientific literature especially for the endemic Mediterranean *Posidonia*. For example, Campagne et al. (2015) valued the *Posidonia* seagrass at €513 per hectare and a total of €55 million. But these values have been evaluated for several services only one of which was the contribution to the coastal fisheries. In addition, it is valid only in the socioeconomic French context (Campagne et al., 2015). Nevertheless, an attempt to determine the economic value of *Cymodocea nodosa* seagrass meadows for local fisheries at the Island of Gran Canaria using standard market prices has been carried out giving a monetary value at €866 per ha (Tuya et al., 2014) which is comparable to our valuation.

The loss estimate is an indicator that demonstrates the potential of economic gains in developing the *Posidonia* meadows. Indeed, the degradation of *Posidonia* meadows seems constant at least since 1990. If we assume that this degradation is linear and so is the increase in loss, a cumulated loss from 1990 to 2014 would give a total loss of more than €750 million. Such a monetary loss should be considered by stakeholders that depend essentially on the fishing activity.

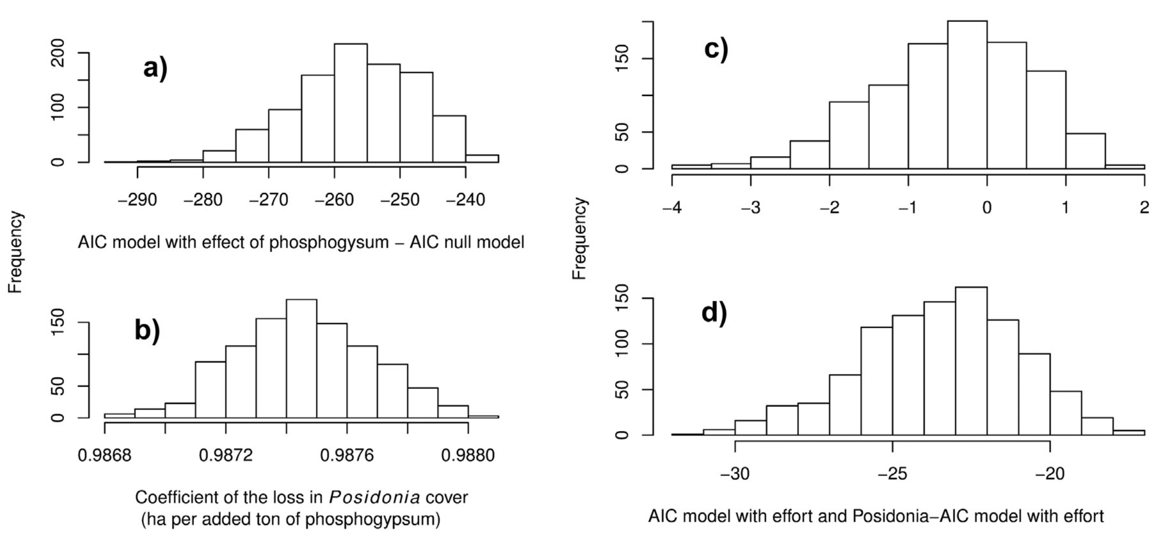

Fig. 3. Hypotheses testing using the Akaike Information Criterion (AIC) for the effect of fishing effort and predicted *Posidonia* cover on the fishing yield by two fleets in the Gulf of Gabes (a & b) and coastal (c) and pelagic (d) fishing fleets.

Table 2
Economic losses linked to the *Posidonia oceanica* degradation versus the added values of the GCT (*Groupe Chimique Tunisien*) factories at the national (Tunisia) and regional (Gabes) scales, during the 1990–2014 period.

Years/period		1990	2014	1990–2014
Economic losses due to the *Posidonia oceanica* degradation (ELDPO, M€)[a]		4	59	780
Added values of all GCT factories in Tunisia (AVTF)[b]	Added values (M€)	−24	152	3316
	Ratio ELDPO/AVTF (%)	117	39	24
Added values of Gabes GCT factories (AVGF)[b]	Added values (M€)	−12	92	1824
	Ratio ELDPO/AVGF (%)	132	64	43

[a] Estimates made based on the economic valuation carried out during the present study.
[b] Data collected from the European Community study conducted in 2017 (EC, 2017).

Comparing the economic losses due to the degradation of *P. oceanica* from the Gulf of Gabes to the added values of Gabes Industrial Complex (represented mainly by the GCT (*Groupe Chimique Tunisien*) factories), during the 1990–2014 period, we found that *Posidonia* meadows of Gabes Gulf are economically more important (Table 2). In fact, the economic losses related to the shrinkage of *P. oceanica* represented, in 2014, 39% and 64% of the added value of all Tunisian GCT factories and those of Gabes only, respectively. The cumulative economic losses, over the 1990–2014 period (15 years), reached ~€780 million, so that the quarter of added values of Tunisian GCT factories and ~43% of the added values of Gabes GCT factories (Table 2). According to the study conducted by the European Community in 2017 on the economic losses related to the industrial pollution in Gabes (EC, 2017), the estimated annual cost of environmental degradation in Gabes Gulf was found to reach a maximum of €34 million (≈76 million Tunisian Dinar), which represents nearly 27% of the added values of Tunisian GCT factories. However, it is worth noting that this latter economic valuation did not take into consideration the impact of phosphogypsum pollution on tourism and fisheries sector in the Gulf of Gabes in isolation, but also the impact of air pollution on other agricultural sectors, tourism, and human health. The fisheries sector *per se* represents ~47% (~€16 million) of this latter estimated amount (EC, 2017). Since the economic loss estimated during this study was found to be close to €59 million in 2014 (Table 2), it appeared that the EC (2017) study largely underestimated the economic losses in Gabes area (€16 million versus €59 million), although it took into account a wider range of economic sectors.

Ecological aspects of the *Posidonia* meadows shrinkage concern the life cycle of benthic/demersal coastal species, the role of *Posidonia* as primary producer and the morphological particularities of the central Gulf of Gabes. The strictly linear relationship applied between landing volumes of coastal fisheries and *Posidonia* meadows area is the most critical approximation used to carry out the evaluation. An estimation of the degree of residence of benthic commercial species has been proposed to improve the economic evaluation accuracy of *Posidonia* ecosystem services (Jackson et al., 2015). According to the available literature, the residence degree can be evaluated for the principal commercial landed species in the Gabes governorate (FAO, 2016). More than ~90% of the benthic and demersal commercial species landed in the Gabes governorate basically depend on the presence of *Posidonia* meadows (FAO ArtFiMed, 2011b; FAO, 2016). Consequently, the linear approximation retained to qualify the link between landed volumes and the seagrass beds is not far off with regards of the economic evaluation.

Phytoplankton constitutes the first step of the marine food chain sustaining all the aquatic life (e.g. Field et al., 1998) and especially oceanic life (Duarte and Cebrián, 1996). It feeds on mineral elements, mostly nitrogen and phosphorus. They are used to produce organic material via the photosynthesis process. The organic matter is reusable by zooplankton and then consumed by a wide variety of filter-feeding organisms. Nevertheless, Mediterranean waters are meso-oligotrophic to oligotrophic i.e. more or less depleted of mineral nutrients (Estrada et al., 1985; Herut et al., 2005). In this situation of overall nutrient deficiency, the eastern Mediterranean basin is the most oligotrophic region (Berman et al., 1984) and the Gulf of Gabes is known as the most oligotrophic region of the eastern basin (Drira et al., 2008) because of weakness of mineral stock inherited from arid hinterlands and limited intrusions of Atlantic waters into the Gulf (Bel Hassen et al., 2008). Therefore, coastal waters of the Gulf offer very low levels of nutrients and little to sustain organisms which should result in low levels of biological productivity. Nevertheless, the Gulf of Gabes has the peculiarity of being highly productive. This contrast is a matter of debate. Some authors emphasise the role played by certain types of phytoplankton and zooplankton to explain the productivity of the Gabes Gulf (Hamdi et al., 2015; Drira et al., 2009). An alternative view could be formulated in terms of the food web system. The combination of the well-established role of primary producer of *Posidonia* coupled with the great extent of the continental shelf covered by these seagrass meadows may be a pertinent approach to the paradoxical situation – ultra-oligotrophy vs. high productivity - of the Gulf of Gabes. The hypothesis herein proposed is to view the shallow-water (< 50 m) of the central part of Gabes Gulf food web as benthic-dominated rather than plankton-dominated.

Firstly, *Posidonia* seagrass are nursery habitats because the leafy underwater canopy they create provides shelter for small invertebrates, small fish and juveniles of larger fish species (Jehly et al., 2010). Other invertebrates grow nestled between the blades or in the sediments. The accumulation of smaller organisms among and on the *Posidonia* blades, as well as the *Posidonia* itself, attracts bigger animals. Thus, *Posidonia* can be home to many types of fish and invertebrates.

Secondly, *Posidonia* meadows contribute to global nitrogen cycling (Costanza et al., 1997; Duarte et al., 2010; Unsworth and Cullen, 2010). The role of *Posidonia* is essential because it retains mineral nutrients by reducing the water flow under the canopy of leaves, thus enabling nutrients to be trapped (Jehly et al., 2010). Consequently, the *Posidonia* biocenosis favoured expansion of phytoplankton populations as a permanent source of nutrients like nitrogen, phosphorous, and organic carbon used by them (Jehly et al., 2010). Nevertheless, the primary productivity of *Posidonia* is not the major direct source of carbon and nitrogen for higher trophic levels of the food web and most *Posidonia* meadow invertebrate herbivores utilize epiphytic species (Unsworth and Cullen, 2010). *Posidonia* is an adequate support for epiphytic species (Boudouresque et al., 2006; Duarte et al., 2004) and many species of algae and microalgae, bacteria and invertebrates that grow as "epiphytes" directly on living *Posidonia* leaves. Small invertebrates, such as crustaceans and snails, feed on epiphytes. They are in turn consumed by larger crustaceans and fish and are important links in the coastal food web (Duarte et al., 2004; Vizzini, 2009; Vizzini et al., 2002). Further, some epiphytic bacteria can extract nitrogen from the environment and make it available to larger animals (Jehly et al., 2010). Epiphytes are commonly associated to *Posidonia* leaves in the Gulf of Gabes (Ben Brahim et al., 2010).

Lastly, dead *Posidonia* leaves also play an important role in coastal ecosystems. When the leaves die, they decay on the sediment or are washed onto the beach, supporting a diverse community of decomposers that prosper on rotting material.

Taking into account the situation of small pelagic fisheries, it is worth noting that the efficiency of the purse seine technique coupled with the benthic to pelagic biocenosis shift hypothesis has strongly favoured the development of small pelagic fishing activity. Nevertheless, its decline at the end of the eighties (Fig. 2b & c) most probably corresponded to the effects of pollution load on the marine environment which reached a larger area in the central part of Gabes Gulf (Rabaoui et al., 2015; El Zrelli et al., 2017, 2019b, 2019c). The high proportion of toxic phytoplankton indicates that quality of marine waters is still poor (Feki et al., 2013; Abdennadher et al., 2014). Nowadays, part of small pelagic catch by coastal fisheries techniques (as beach seine for example) has increased, especially the sardinella volume (Fig. 3a & b). This could be the consequence of the high nutrients amounts in coastal sea water. It is probably the reason why the coastal fisheries volumes are irregular from one year to the next and can be, from times to times, relatively high (Fig. 2b & c).

A first step towards a better understanding of the vulnerability of the Gabes Gulf could consist in introducing an economic measure of this vulnerability in terms of producer surplus. The producer surplus loss measures the difference between the amounts a producer of a good receives, the market price, and the minimum amount the producer is willing to accept for the good. This minimum amount is called the marginal cost. The producer surplus is represented in Fig. 4, where we assume that the demand for fish of the Gulf of Gabes is perfectly elastic. The degradation of the *Posidonia* seagrass increases the marginal cost for the fishermen. This is translated into a move of the supply curve of fish from S_0 to S_1 or S_2 (Fig. 4). The producer surplus loss is estimated through the shaded area in Fig. 4: the more the marginal costs increase, the more the producer surplus losses increase.

Our indicator value and loss can be integrated in this figure. The value is represented by the rectangle pOQ_1S_1, when considering a loss of *Posidonia* from Q_0 to Q_1, and the rectangle pOQ_2S_2, when considering a loss of *Posidonia* from Q_0 to Q_2. The loss is represented by the rectangle $S_1Q_1Q_0S_0$, when considering a loss of *Posidonia* from Q_0 to Q_1, and the rectangle $S_2Q_2Q_0S_0$, when considering a loss of *Posidonia* from Q_0 to Q_2. The producer surplus can be considered as much accurate to value the *Posidonia* seagrass when the loss is important. Indeed, if we consider changing from S0 to S2 and use our value indicator, we can observe graphically in Fig. 4 that the value will be very low compared to the real producer surplus loss. However, the producer surplus method is not easy to apply in a large territory because of the need of data on marginal cost or production from fishermen which is difficult to obtain.

Furthermore, we focus our analysis on the marketed direct use value of the seagrass. Thus, we studied the supply side and the impact of *Posidonia* seagrass on the fishermen benefits. However, the economic value of *Posidonia* seagrass is not limited to this as seen in Campagne et al. (2015). Indeed, it provides benefits through the regulation and maintenance services, water purification value, water oxygenation and cultural services. In order to complete our economic valuation of *Posidonia* seagrass in the Gulf of Gabes and give more accurate information to decision makers, a future line of research would be to realize these valuations, including interviewing various stakeholders, other than fishermen, living around the Gulf of Gabes and valuate the benefits of the cultural service.

5. Conclusion

A gradual intensification of sponge, then shrimp fishing activities during the first half of the 20th century has triggered the process of *Posidonia* meadows area reduction in the central Gulf of Gabes. Subsequently, between 1972 and 1985, successive commissioning of phosphate fertilizer plant units in Gabes has induced a high environmental stress via phosphogypsum releases into coastal marine environments. Furthermore, the gradual disappearance of the seagrass beds caused the gradual silting up of the central part of the Gulf which progressed from centre to coast. This silting process contributed to the waters transparency decrease and thus to gradual disappearance of the seagrass beds. From an economic point of view, the loss of economic value provided by coastal fisheries income correlated to the decline of the *Posidonia* meadows has been valued at about €60 million in 2014 and a cumulated loss of more than €750 million from 1990 to 2014.

CRediT authorship contribution statement

Radhouan El Zrelli: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Lotfi Rabaoui:** Conceptualization, Formal analysis, Writing - review & editing. **Rubén H. Roa-Ureta:** Formal analysis, Writing - review & editing. **Nicola Gallai:** Formal analysis, Writing - review & editing. **Sylvie Castet:** Formal analysis, Writing - review & editing. **Michel Grégoire:** Formal analysis, Writing - review & editing. **Nejla Bejaoui:** Formal analysis, Writing - review & editing. **Pierre Courjault-Radé:** Conceptualization, Investigation, Formal analysis, Writing - review & editing.

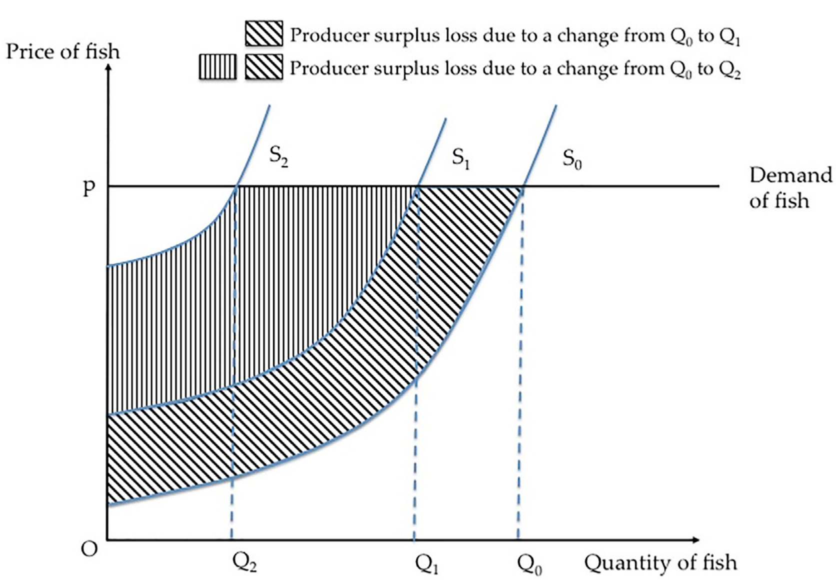

Fig. 4. Estimate of the producer surplus loss after the *Posidonia oceanica* seagrass service degradation.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111124.

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