



Research Article

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# Mapping and Ecological Assessment of the *Posidonia Oceanica* Status in the Maloula region, Tabarka



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## Abstract

*Posidonia oceanica* meadows along the Tunisian coast represent a significant ecosystem, providing both ecological and economic benefits. *P. oceanica* landscapes are heterogeneous, impacted by natural and anthropogenic sources. Our study focuses on sediment analysis and morphological, phenological, and ecological parameters of *P. oceanica* at nine sites in the Maloula Bay. These sites are categorized into three depths: lower (-3 m), intermediate (-8 m), and upper (-13 m) boundaries. The *Posidonia oceanica* meadows along the Tunisian coast form a vital ecosystem that provides both ecological and economic benefits. These meadows constitute a heterogeneous landscape influenced by both natural and human activities. Our study examines the morphological and ecological parameters of *P. oceanica* in nine sites in Maloula Bay. These sites are divided into three depth zones: lower (-3 m), middle (-8 m) and upper (-13 m) limits. Foliar density and morphological parameters (foliar biomass, length, number, leaf category, etc.) show significant values at the lower boundary sites, gradually decreasing with depth. However, epiphyte biomass increases progressively with depth. Furthermore, the examined meadows at the upper and intermediate boundaries (20 years) are older than those at the lower boundary (15 years). In-situ observations and cartographic analysis indicate regressions in the meadows primarily due to natural sources, as evidenced by the Irregularity Source Index (PaSI). These natural regressions manifest as the formation of 'intermatte' sand zones. Other sources such as anchoring and fishing activity may also influence meadow regression. Utilizing surface characteristics and intermediate nature, ecological indices (Conservation Index CI, Overall Quality EQR, and PREI) of the meadows were determined. Despite observed regressions, these indices confirm that the meadows of Maloula Bay are preserved and in "good" condition.

**Keywords:** Underwater ecosystem; *Posidonia oceanica*; Intermatte; Cartography

## Introduction

**Magnoliophytes**, flowering and rhizomatous plants living exclusively in marine habitats, constitute a group of flowering plants abundantly distributed at the universal level, forming large seagrass beds in surface waters up to 40 m deep [1]. These marine species play a vital role for coastlines by providing beneficial services to marine ecosystems [2].

In the Mediterranean Sea, several Magnoliophytes constitute a significant hotspot characterized by unique, valuable, and

productive habitats. They support high biodiversity and provide essential ecological goods and services, including

- oxygen production
- carbon dioxide emissions absorption
- sediment stabilization
- coastal protection against erosion [3-5]

Additionally, these marine plants may play a potentially important role in climate change mitigation [6]. Five seagrass species are found in the Mediterranean Sea, specifically *Posidonia oceanica*, *Cymodocea nodosa*, *Zostera marina*, *Zostera noltii* Hornemann, and *Halophila tipulacea*. The most abundant among them is *Posidonia oceanica*, forming climax species that spread slowly and constitute considerable carbon stocks [7].

In the Mediterranean, *Posidonia oceanica* is an endemic species highly dominant on the Tunisian coast [8]. It forms bundles of five to eight ribboned leaves, 40 to 80 cm high and one centimeter wide, arranged at the end of an erect rhizome. It builds remarkable structures called “mattes,” composed of intertwined rhizomes and roots, which are not easily destructible and can reach several meters in thickness, persisting for millennia [9].

*P. oceanica*, a slow-growing plant with low genetic diversity, forms grasslands and ecosystems with greater primary productivity, contributing to neighboring systems [10]. This flowering plant serves multiple ecological functions, such as limiting erosion, supporting biodiversity, and storing carbon [11]. *P. oceanica* conducts photosynthesis to obtain essential nutrients and energy for its development [12,13]. Its ability to grow in diverse environmental conditions is attributed to physiological and morphological adaptations, sometimes unique to endemic species [14]. Apart from its ecological roles, *P. oceanica* contributes 11 to 42% of carbon dioxide emissions produced by Mediterranean countries since the industrial revolution, averaging 29 g of carbon per m<sup>2</sup> per year at an average depth of 15m [15].

Many primary habitats of *P. oceanica* in the Mediterranean are currently at risk due to the degradation of seagrass beds caused by reduced water circulation, increased sedimentation, and decreased resuspension of particulate organic matter [16]. These degradations lead to elevated burial rates and hinder the remineralization process due to poor aeration.

The decline of *P. oceanica* meadows, classified as “priority habitats,” reflects the challenge of distinguishing between climatic and anthropogenic effects [17]. This degradation can be attributed to both pollution and a natural decline of the species. In the Mediterranean, the state of *P. oceanica* has declined by approximately 34% over the last 50 years [1]. However, this figure is based on a small portion of the total herbarium coverage and different calculation methods, mainly relying on maps. The evolution of mapping techniques over recent decades, affecting precision, is a significant factor contributing to observed differences [18].

Following protection, it is the responsibility of managers to implement conservation measures, assess the state of seagrass beds, and establish protection rules. *P. oceanica* is utilized as a bioindicator of good water quality by studying its physiology and the structure of seagrass beds, linking them to anthropogenic pressures in the study area [19]. Several synthetic indices have been developed for monitoring coastal waters’ quality and

providing quantified and coded results accessible to coastal environment managers [20,21].

However, reasoned management is essential to reconcile the preservation of fragile environments, erosion mitigation, and tourism issues. Data on the distribution and status of *Posidonia* meadows in the Tabarka region are still fragmentary, with Abidi (2012) being the only researcher to map the *Posidonia* herbarium in the Tabarka area. Therefore, the present work aims to evaluate *P. oceanica* meadows as dynamic structuring elements of underwater landscapes. However, before incorporating them into management programs or developing specific applied tools, it is imperative to precisely study their dynamics and ecological state through various analyses such as sedimentology, morphology, and herbarium structure.

## Materials and Methods

### Sampling Site Presentation

The northern part of Tunisia is divided into two regions, forming a northern Tell in the north (composed of the Kroumirie mountain ranges peaking at around 1,000 meters, the Nefzas at 600 meters, and the Mogods at 500 meters located in Ain Draham, Nefza, and Bizerte, respectively); and a steppe zone to the south. The coastal area of Tabarka is located in the northwest of Tunisia and covers an area of approximately 330 hectares to a depth of 40 meters. Extending from Tabarka to Cape Blanc, the region features a windy, humid to sub-humid climate, rugged and inaccessible terrain, rocky shores providing varied marine landscapes, extensive dunes, and vast sandy dunes. The natural bathymetric topography exhibits a steep slope, facilitating seawater movement. Consequently, the coastline consists of a series of cliffs, rocky shores, beaches, and dunes, sometimes over short distances.

### Diving Exploration Strategy and sites

During the summer in Tabarka, inclement weather had a negative impact on the number of days suitable for exploration. Indeed, exploration is only feasible when the water is very clear to carefully assess the boundaries, the state of the seagrass, associated fauna and flora, sediment composition (rock, sand, etc.). Before starting the survey and sampling, it was necessary to delineate the marine portion of the study area, where the isobaths varied between -3, -8, and -13 meters. A handheld GPS was used during the exploration phase to specify the bathymetry and relative coordinates of each site. Once in the laboratory, these data were analyzed, sorted, and transferred to an Excel spreadsheet for cartographic analysis.

### Assessment of Seagrass Density

Seagrass density was measured at each site through underwater diving using a quadrat of 25 cm x 40 cm. Between six and ten replicates, randomly distributed within the seagrass bed, were conducted at each station [22]. The quadrats were randomly dropped from a height of one meter, and counting was done at the

point of impact. The evaluation of foliar biomass benefits from a standardized protocol that allows for differentiating seagrass beds based on their density [23]. In our study, seagrass classification is based on Giraud's method [23], which relies on the density of shoots/m<sup>2</sup> [22] (Giraud, 1977). Simultaneously, bundles of each seagrass meadow were sampled (n = 10) for laboratory analysis.

### Biometric Analysis

In the laboratory, the leaves of each bundle are separated to measure various morphological parameters. These measurements allow for defining different parameters related to the biometrics of *Posidonia oceanica*, including the average number of leaves per bundle, the average length, and the average width of the leaves (adult and intermediate). The measurements obtained enable us to categorize the leaves into three classes (adult, intermediate, and juvenile) following Giraud [23].

### Foliar Biomass

Initially, the bundles are rinsed with freshwater to remove some sediment particles from the leaves. The leaves are carefully scraped using a blade along both sides to separate all epiphytes, including encrusting algae [23,24]. Subsequently, the leaves are dried in an oven for 48 hours at 70°C until a constant weight is achieved. Each batch of leaves is weighed using a precision balance to ± 0.001 g.

### Epiphyte Biomass on Leaves

The biomass of epiphytes on the leaves is determined using the method of Dauby & Poulicek [24]. The material collected during the scraping of the leaves is rinsed with freshwater, filtered, dried in an oven at 70°C, then weighed before and after drying to 0.001 g. Our results are expressed in mg of dry weight per bundle per site and then multiplied by the density of bundles per square meter [24].

### Ecological Indices of Seagrass Beds

To assess the ecological status of the seagrass beds, quality indices are calculated. Several synthetic indices have been developed to conduct the necessary monitoring for maintaining or improving the quality of coastal waters [21]. In our study, the following indices were determined:

a) Conservation Index (CI) according to Moreno et al. (2001), which compares the coverage of live *P. oceanica* to dead matter using the following equation:

$$CI = (Live\ Posidonia) / ((Live\ Posidonia + dead\ matter))$$

b) Ecological Quality Ratio (EQR) [25] measures the level of ecosystem change due to regression (natural and/or anthropogenic):

$$EQR = ((Density + Foliar\ Surface + N(Epiphytic\ Biomass) / Foliar\ Biomass + Lower\ Limit) / 3.5)$$

c) Overall Seagrass Quality Index (PREI) [25] calculates the ecological quality ratio including EQR:

$$PREI = ((EQR + 0.11) / ((1 + 0.10)))$$

These indices, estimating the health status of *P. oceanica* seagrass beds, are reported in Table 1 with reference values, providing information on the health status of the ecosystem according to five quality classes [17]. To assess the primary origin of irregularities observed in the *P. oceanica* seagrass beds, we used the PaSI index developed by Moreno et al. [26], by calculating the areas of the different identified structures. PaSI ranges from 0 to 1 and has no unit.

$PaSI = ((Snp)) / ((Snp + Sap))$  where Snp: percentage of the area covered by different types of natural patches; Sap: percentage of the area covered by different types of anthropogenic patches.

**Table 1:** Values of ecological indices and state of seagrass beds.

| Limit              | Sites | IC   | EQR   |        | PREI  |        | PaSI  |                          |       |
|--------------------|-------|------|-------|--------|-------|--------|-------|--------------------------|-------|
|                    |       |      | Value | Status | Value | Status | Value | Description              | Codus |
| Lower limit        | S1    | 1    | 0,94  | High   | 0,95  | High   | 1     | Strong natural influence | High  |
|                    | S2    | 1    | 0,94  | High   | 0,95  | High   | 1     | Strong natural influence | High  |
|                    | S3    | 0.79 | 0,93  | High   | 0,94  | High   | 1     | Strong natural influence | High  |
| Intermediate limit | S4    | 1    | 0,95  | High   | 0,96  | High   | 1     | Strong natural influence | High  |
|                    | S5    | 1    | 0,96  | High   | 0,97  | High   | 1     | Strong natural influence | High  |
|                    | S6    | 0.8  | 1     | High   | 1     | High   | 0,9   | Strong natural influence | High  |
| Upper limit        | S7    | 1    | 1     | High   | 1     | High   | 1     | Strong natural influence | High  |
|                    | S8    | 1    | 1     | High   | 1     | High   | 1     | Strong natural influence | High  |
|                    | S9    | 0.82 | 0,75  | Good   | 0,89  | High   | 0,9   | Strong natural influence | High  |

## GIS Process

Once clearly identified, the boundaries of sandy and bare patches in the *P. oceanica* meadows were traced in GIS software. Their origin was estimated by searching for the presence of human activities near the patches. Additionally, the *P. oceanica* seagrass beds are represented in maps according to their density and area. The GIS files were then converted into rasters (GeoTIFF grid) and analyzed using the QGIS software program to obtain the

desired maps.

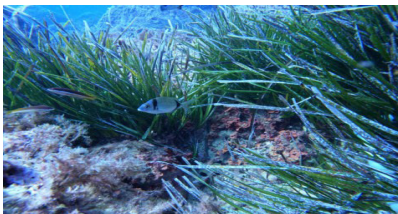
## Statistical Analysis

The mean values of the parameters studied are expressed with their standard deviations and represented on figures by a vertical line (error bar) and on tables by  $\pm$ . The comparison of means is estimated using the t-student test between the studied sites. The difference is considered significant for  $p < 0.05$ ,  $p < 0.01$ , and highly significant when  $p < 0.001$ .

## Results

### Description of sampling sites

**Table 2:** Characteristics of the sampling sites at the level of Maloula Bay in Tabarka.

|                    | Site | Depth | GPS       |          | Herbarium | Real photo                                                                            |
|--------------------|------|-------|-----------|----------|-----------|---------------------------------------------------------------------------------------|
|                    |      |       | N         | E        | type      |                                                                                       |
| Lower limit        | S1   | -3m   | 36°96'34" | 8°71'82" | Hill      |    |
|                    | S2   | -3m   | 36°96'28" | 8°71'43" | Hill      |                                                                                       |
|                    | S3   | -3m   | 36°96'39" | 8°71'25" | Hill      |                                                                                       |
| Intermediate limit | S4   | -8m   | 36°96'51" | 8°72'04" | Hill      |  |
|                    | S5   | -8m   | 36°96'39" | 8°71'51" | Hill      |                                                                                       |
|                    | S6   | -8m   | 36°96'55" | 8°71'28" | Hill      |                                                                                       |
| Upper limit        | S7   | -13m  | 36°96'64" | 8°72'21" | Striped   |  |
|                    | S8   | -13m  | 36°96'54" | 8°71'60" | Striped   |                                                                                       |
|                    | S9   | -13m  | 36°96'74" | 8°71'34" | Striped   |                                                                                       |

Our study is conducted on the prospection of the *P. oceanica* meadow of Maloula Bay (Table 2). To do this, we chose to work by limit (upper, intermediate and lower) and according to depth (-3 m, -8 m and -13 m). For each depth, we prospected 3 sites colonized by the *P. oceanica* meadow. Generally, the meadows prospected at the lower and intermediate limit are hills, while the upper limit is characterized by striped meadows located on the rocks.

### Leaf density of *P. oceanica* by site

The in-situ examination of the *P. oceanica* meadows allowed us to determine the leaf density of each site (Table 3 & Figure 1). The

results obtained show that the density of the meadows located at -3 m varies between 367m<sup>2</sup> and 341 m<sup>2</sup>. These densities show that *P. oceanica* of the lower limit is type III (S1, S2 and S3) describing sparse meadows. The classification of the density of these meadows according to depth shows a Subnormal state ( $\approx 879\text{m}^2$ ) The meadows of the intermediate part located at -8 m are very sparse and type IV. A subnormal density according to the classification characterizes the latter by depth. The upper limit is characterized by type IV meadows qualified as very sparse since the number of bundles between 150 and 300 m<sup>2</sup>. These seagrass beds are classified by a subnormal state according to depth.

**Table 3:** Leaf density (bundles per m<sup>2</sup>) of sites at the lower, intermediate and upper limits of the Maloula region in Tabarka.

| Limit        | Sites | Depth | Density | Type | Description     | Status    |
|--------------|-------|-------|---------|------|-----------------|-----------|
| Lower        | S1    | -3 m  | 341     | III  | Clairsemés      | Subnormal |
|              | S2    | -3 m  | 367     | III  | Clairsemés      | Subnormal |
|              | S3    | -3 m  | 360     | III  | Clairsemés      | Subnormal |
| Intermediate | S4    | -8 m  | 236     | IV   | Très clairsemés | Subnormal |
|              | S5    | -8 m  | 208     | IV   | Très clairsemés | Subnormal |
|              | S6    | -8 m  | 223     | IV   | Très clairsemés | Subnormal |
| Upper        | S7    | -13 m | 168     | IV   | Très clairsemés | Subnormal |
|              | S8    | -13 m | 195     | IV   | Très clairsemés | Subnormal |
|              | S9    | -13 m | 208     | IV   | Très clairsemés | Subnormal |

The overall comparison of the leaf density of the *P. oceanica* meadows surveyed during the period of our study shows a remarkable variation (Figure 1). It is observed that the leaf density of the lower limit is very high compared to that of the intermediate part and the upper limit of the *P. oceanica* meadows

of Maloula Bay. This density decreases progressively with depth since it presents average values in the intermediate part of the meadows and low densities at the sites of the upper limit (Figure 1).

### Morphological parameters and composition of *P. oceanica* by site

**Table 4:** Morphological parameters of the *P. oceanica* herbarium from 9 sites in the Maloula region of Tabarka.

| Limit                                    | Lower       |             |             | Intermediate |             |               | Upper        |               |                | P   |
|------------------------------------------|-------------|-------------|-------------|--------------|-------------|---------------|--------------|---------------|----------------|-----|
| Sites                                    | S1          | S2          | S3          | S1           | S2          | S3            | S1           | S2            | S3             |     |
| Epiphyte biomass                         | 0.24±0.01   | 0.32±0.00   | 0.21±0.05   | 0.44±0.02    | 0.51±0.01   | 0.79±0.03*    | 1.21±0.29    | 1.15±0.62     | 1.05±0.41      | *   |
| Leaf biomass                             | 0.48±0.05   | 0.51±0.02   | 0.51±0.00   | 0.63±0.01    | 0.65±0.05   | 0.67±0.02     | 0.87±0.03    | 0.86±0.08     | 0.88±0.09      | **  |
| Average number of leaves per bundle      | 5,50±1,00   | 7,00±1,00*  | 10,33±1,52* | 3,33±0,57    | 5,00±1,00*  | 7,10±1,00*    | 4,00±1,00    | 4,66±0,57     | 6,66±1,15*     | ##  |
| Average number of adult leaves           | 3,33±0,57   | 6,00±0,11*  | 5,33±1,15*  | 2,56±0,57    | 3,33±1,15   | 3,66±0,57     | 4,00±1,73    | 3,00±0,10     | 3,66±0,57      | #   |
| Average number of intermediate leaves    | 2.66±1.15   | 1.50±0,71*  | 4,10±0,12** | 0,56±0,16    | 1,33±0,19** | 3,00±0,21***  | 0,66±0,16    | 1,33±0,19**   | 2,30±0,57***   | ##  |
| Average number of juvenile leaves        | ND          | ND          | 1,50±0,70   | 0,20±0,03    | 0,33±0,19   | 0,33±0,11     | 0,33±0,19    | 0,33±0,09     | 0,66±0,38*     | ND  |
| Total length of adult leaves (mm)        | 105,91±1,65 | 105,25±1,10 | 107,46±4,26 | 116,22±3,28  | 118,66±3,01 | 124,66±3,81** | 251,77±16,02 | 258,00±6,11   | 280,63±6,93*** | ### |
| Total width of adult leaves (mm)         | 10,57±0,41  | 9,81±0,54   | 9,00±0,20   | 9,91±0,10    | 10,23±0,46  | 9,22±0,24     | 9,32±0,89    | 9,36 ±0,56    | 9,29±1,01      | ND  |
| Total length of intermediate leaves (mm) | 100,18±0,57 | 103,31±2,28 | 98,75±1,54* | 107,00±1,41  | 102,00±3,46 | 106,61±0,97   | 159,50±4,94  | 163,16±12,33* | 165,66±8,38*   | ### |
| Total width of intermediate sheets (mm)  | 7,11± 1,91  | 6,25±0,35   | 6,67±1,43   | 8,56±0,70    | 8,50±0,50   | 8,36±0,12     | 6,90± 0,14   | 6,50 ±0,50    | 6,61±0,78      | #   |

ND: not determined

Results are presented as mean ± standard deviation

Significant differences between meadows of the same boundary are detected at \*p<0.05; \*\*p<0.01 and \*\*\*p<0.001. Significant differences between boundaries are presented by *P. oceanic*.

This study presents the morphological differences between the meadows of *P. oceanica* of the region of Maloula in Tabarka (Table 4). The Posidonia meadows located in the Lower limit have significant average values of leaves per bundle compared to those of the upper limit and the intermediate part. The examination of the main morphological parameters reveals that most of the bundles are adults characterized by lengths greater than 50 mm and benefiting from a petiole ( $\geq 2$  mm) (Table 4). These last 'adult leaves' are recorded at the level of the meadows of the Lower limit with large quantity in comparison with those located at -8m and -13m.

The analysis of the composition of the bundle samples in the laboratory allowed us to determine intermediate bundles with average lengths varying between  $98.75 \pm 1.54$  and  $165.66 \pm 8.38$ . These bundles are present in all the samples examined. The examination of juvenile leaves shows a significantly lower density compared to the other categories (adult and intermediate) (Table 4). In addition, these leaves are saved in the three sites of the upper limit and the intermediate part. However, note the absence of this category at the level of the seagrass bed of Maloula Tabarka Bay at shallow depth (-3 m) particularly at S1 and S2.

According to Table 4, it is noted that the morphological characteristics of the seagrass bed, particularly the length and width of adult and intermediate leaves, increase significantly with depth. This increase is indicated at the lower limit by lengths that vary between  $105.91 \pm 1.65$  mm and  $107.46 \pm 4.26$  mm, and between  $98.75 \pm 1.54$  mm and  $103.31 \pm 2.28$  mm respectively in adult and intermediate leaves. A progressive evolution of this parameter is marked at the level of the herbariums of the intermediate part with adults of lengths between  $116.22 \pm 22$  mm and  $124.66 \pm 3.81$  mm and intermediate leaves of lengths between  $102.00 \pm 3.46$  mm and  $107.00 \pm 1.41$  mm. Concerning the upper limit, the Posidonia meadows present are characterized by high morphological parameters with lengths that vary from  $159.50 \pm 4.34$  mm to  $280.63 \pm 6.93$  mm (Table 4).

### Leaf biomass of *P. oceanica* by site

The leaf biomass determined at 9 sites in the Maloula region of Tabarka is presented in Table 4. Generally, the leaf biomass varies similarly at the sites of each limit from where no significant difference was recorded in the sites at the same depth. Furthermore, a progressive and significant increase in leaf biomass is noted at the level of the Posidonia meadow sample of the intermediate part. This biomass also increases and marks high values at the level of the Posidonia sample of the upper limit. These results allowed us to conclude that the leaf biomass increases according to the depth.

### Epiphyte Biomass of *P. oceanica* by Site

Epiphyte biomass varies in a similar way to leaf biomass, i.e. it increases progressively with depth (Table 4). At the lower limit,

epiphyte biomass is slightly small at S3. In the intermediate part of the meadow, epiphyte biomass is higher at S6 compared to S4 and S5. Significant biomass is reported at the upper limit sites with significant increases observed at S7, S8 and S9.

### Ecological indices of the state of the seagrass beds

**Conservation index (CI):** The evaluation of the conservation index (CI) of the *P. oceanica*

seagrass beds in the Maloula region of Tabarka allowed us to elucidate values that exceed the reference interval of the ecological indices ( $\geq 0.9$ ) (Table 1). These results indicate that the *P. oceanica* seagrass bed is in high conservation (in blue). Other results are observed in the western part of the Maloula Bay at depths of -3 m, -8 m and -13 m. These results confirm that the posidonia of these three sites is in Good condition since the values of the CI conservation index are between 0.7 and 0.9 (in green).

**Ecological Quality Ratio (EQR) and Overall Seagrass Quality Index (PREI):** The ecological

indices EQR and PREI presenting the quality of *P. oceanica* seagrass beds in the Maloula region of Tabarka are illustrated in Table 1. These indices show that the seagrass beds surveyed at all depths have high ecological indices (0.89 – 1) according to the reference intervals adopted internationally. However, only the seagrass bed located at S9 (-13 m) in the western part of Maloula Bay is characterized by good quality with a value of 0.75 associated with the EQR.

**Irregularity Source Index (PaSI):** The survey of the studied sites allowed us to determine the

irregularity source index (PaSI) (Table 1). This index shows that the *P. oceanica* meadows of Maloula Bay are subject to a strong natural influence. This natural influence is based on the PaSI values that are recorded per site and range between 0.8 and 1.

### Cartographic distribution of the *P. oceanica* meadow in Maloula Bay in Tabarka

The bathymetric structure of Maloula Bay shows a sharp increase in depth from the shore to the open sea. This area is characterized by cliffs and coves where significant depths exceed 10 meters are noted. Also, there are shallow parts that are located far from the coast, this is related to the nature of the coast and the accumulation of rock blocks, particularly at Cap de Maloula.

The cartographic analysis is based on "real mapping" which is coupled with the certainty of what exists in the ecosystem. The map of Maloula Bay shows a varied structure composed of *P. oceanica* meadows on sandy and also rocky substrates. In addition, there is a deep zone where the *P. oceanica* meadow does not exist or is rarely reported.

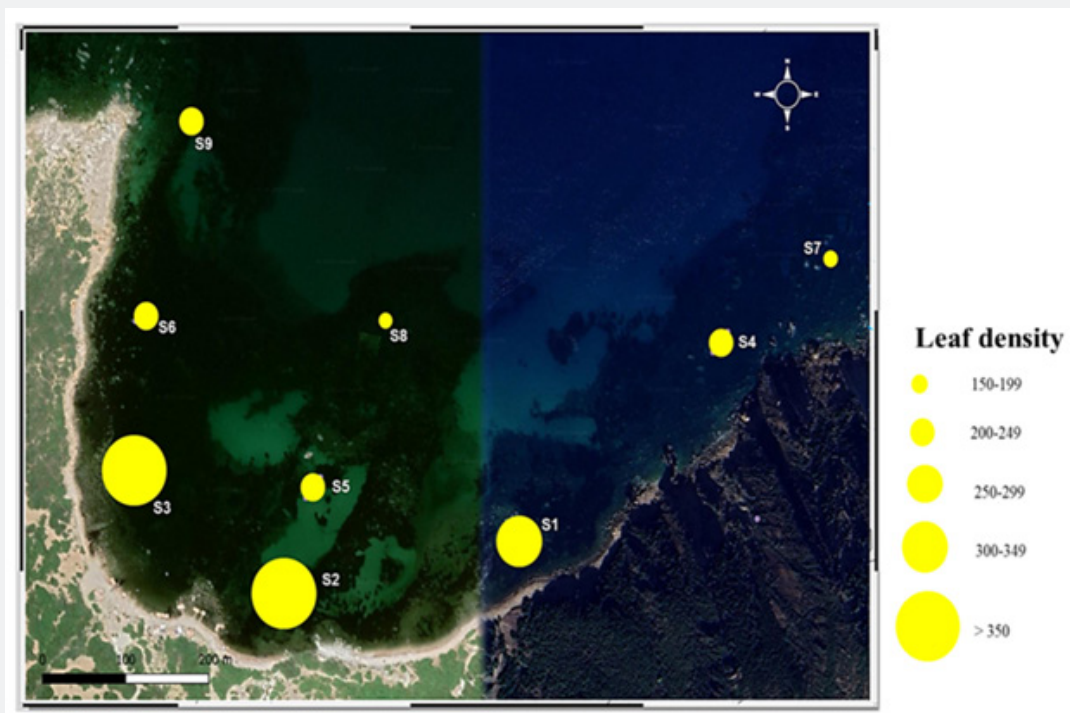


**Figure 1:** Leaf biomass (g) of *P. oceanica* from 9 sites of the lower, intermediate and upper limit of the Maloula region in Tabarka.

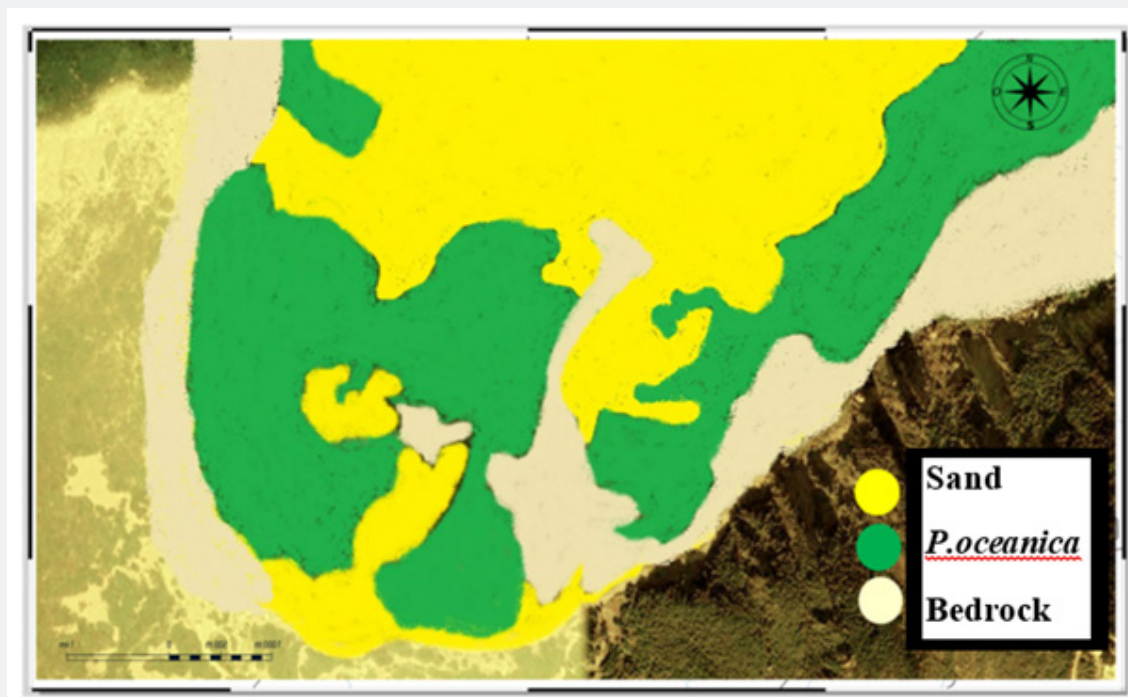


**Figure 2:** Actual mapping of the study area (Maloula Bay).

## Discussion

Currently, *Posidonia* meadows are adopted as key systems given the ecosystem benefits they provide [1]. Their ecological roles range from raw material production, coastal support for erosion, water purification, carbon sequestration and shelter for biodiversity. These are interesting sites for several tourism and leisure activities. Similarly, *Posidonia* is a biological material that is widely studied in scientific research [27]. The present study focused on the morphological, phenological and ecosystem characteristics of *Poceanica* meadows in Maloula Bay as a function of depth. This study shows that the density of recorded seagrass beds gradually decreases with depth since their number is significantly lower at sites at -13 m depth compared to those located at -5 m. The large number of adult leaves is observed at a shallow depth. Our results also show that the intermediate limit and the upper limit are characterized by low values relative to adult leaves. Nevertheless, we note the presence of juvenile sheets at these two limits compared to that of the lower limit. In this context, authors have reported the dominance of juvenile leaves in significant depths, which is explained by the slowdown in development of intermediate leaves [28,29].

In general, the morphological parameters analyzed during this work are important in the western region of Maloula Bay, regardless of depth. Comparing the depths, the morphological parameters of the leaves examined are more important at -5 m depth compared to -8 m and -13 m. These observations may be related to strong hydrodynamics and significant turbidity at great depths, inhibiting or dampening the growth of seagrass beds [30]. However, the abundance of nutrient elements at shallow depths is a key element in the growth of seagrass beds [31].

Leaf and epiphyte biomass increase progressively with depth, with very high values at -13 m and very low values at -5 m. Our results are relatively low compared to the leaf density in the Tabarka region in 2013 of around 556 m<sup>2</sup> [29]. Nevertheless, the leaf density of the seagrass beds of Maloula Bay is close and similar to those of the Tamentfoust region in Algeria [32] and the Ventimiglia region in Italy [33]. During this study, we found the dominance of the biomass of epiphytes, early warning indicators and descriptors of changes in the water column [34], compared to leaf biomass especially at the level deep sites. This observation is possibly due to the enrichment of nutrients and the reduction in water quality at these sites, which disrupts the *posidonia* and limits the absorption of available light [35]. This could be due to pollutants carried by shore currents and discharges from numerous boats (pleasure and fishing) which stop in the bays during the summer period. According to Ruiz et al. [36], the richness of epiphyte biomass can be a major cause in leaf degradation, this coincides with our in-situ prospecting. From an ecological point of view, the state of the *P. oceanica* meadows is consulted by diving where significant natural regressions have been detected followed by regressions caused by fishing

activity (mooring and nets). This observation is corroborated by significant regressions of their distribution on the scale of Tunisia and on a global scale [37,38] (Pergent et al., 2012). Also, the PaSI regression index showed values close to 1, which explains a strong natural influence exerted on the seagrass beds of Maloula Bay.

These regressions can constitute in the long term a net loss in terms of carbon sinks and an indirect risk of release of all or part of the carbon sequestered at the level of the mattes, but also of the contaminants, trapped within these structures [39]. To confirm these regressions, we used the cartographic analysis, already adopted, in previous works as a tool reliable reflecting reality [40]. The results found during this work show a remarkable regression at the level of *P. oceanica* seagrass beds compared to the results of Abidi et al [40].

From an ecological point of view, an classification of the property of seagrasses, from poor to good quality, has been established based on several vitality parameters (dead leaf, living, etc.). During our work, "good" values relating to the conservation index (CI) of seagrass beds are recorded at the level of *P. oceanica* in Maloula Bay, describing a "high" ecological state according to the reported classification in the literature [19]. The EQR landscape descriptor and the PREI index are consistent and indicate a better state of health for the seagrass beds of Maloula Bay, despite the regressions observed [41-71]. At the end of this work, we can deduce that the roles of *P. oceanica* are influenced by its ecological state, thus confirming the way in which human disturbances (fishing, boating, etc.) on ecosystems can hinder functioning by generating a reduction in ecosystem services [72-89].

## Conclusion

The information presented in this study represents a significant contribution to the description and study of *P. oceanica* meadows in the Maloula Bay. In addition, the results provided can serve as basic information to guide future studies concerning the abundance, growth, regression, and quality of these meadows. Generally, *P. oceanica* meadows in Maloula Bay are sparse to very sparse with a subnormal state. Most morphological parameters, except for epiphyte biomass, decrease with depth, marking minimal values at -13 m. The ecological status of *P. oceanica* in Maloula Bay is high, confirming the good quality of these meadows, despite the regressions observed during dives and through the Irregularities Index (PaSI). All these data strongly suggest that the current *P. oceanica* beds constitute a relic population that should be preserved.

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