Blue carbon accounting of *Posidonia oceanica* seagrass in the Balearic Islands using Earth Observation and *in situ* data

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1. Introduction

Coastal vegetation (seagrasses, tidal marshes, and mangroves) occupy <1% of Earth's surface, yet play an outsized role in the carbon cycle by burying around 10% of residual land sink (Duarte *et al.*, 2013). This "**blue carbon**" is stored as organic carbon (C_{org}) mainly within their soils, and their monitoring and accounting as Blue Carbon Credits (BCC) can finance their protection and conservation, key to contribute to **climate change mitigation** (Howard *et al.*, 2017).

Posidonia oceanica is an endemic seagrass from the Mediterranean Sea connected by thick and robust horizontal and vertical rhizomes forming reefs (Fig. 1), having the **highest carbon sequestration rate among all seagrasses** worldwide, observing **higher stocks** and burial rates in **shallower meadows** (Serrano *et al.*, 2014). However, these meadows are experiencing a widespread decline (1/3 in the past 50 years) which may imply a loss of its C_{org} sink capacity (Marbà *et al.*, 2014). They accumulating a massive C_{stock} through promoting particle trapping and high sedimentation rates, but their major advantage lies in its capacity to store carbon from annual carbon sequestration for centuries to millennia (Pergent-Martini *et al.*, 2021).

The **Balearic Islands** rank among the top touristic destinations in Europe and hosts a high density of *P. oceanica* meadows, being their main threat **recreational boat anchoring**, which generates remineralization of the sequestered C_{org} (Fig. 2). Multiple efforts are spent every year on monitoring seagrass extent and C_{stock} (Mazarrasa *et al.*, 2017), but satellites can be used to complement this task. We present an Earth Observation method to **cost-effective monitor** *P. oceanica* meadows from space down to **30 m depth**.

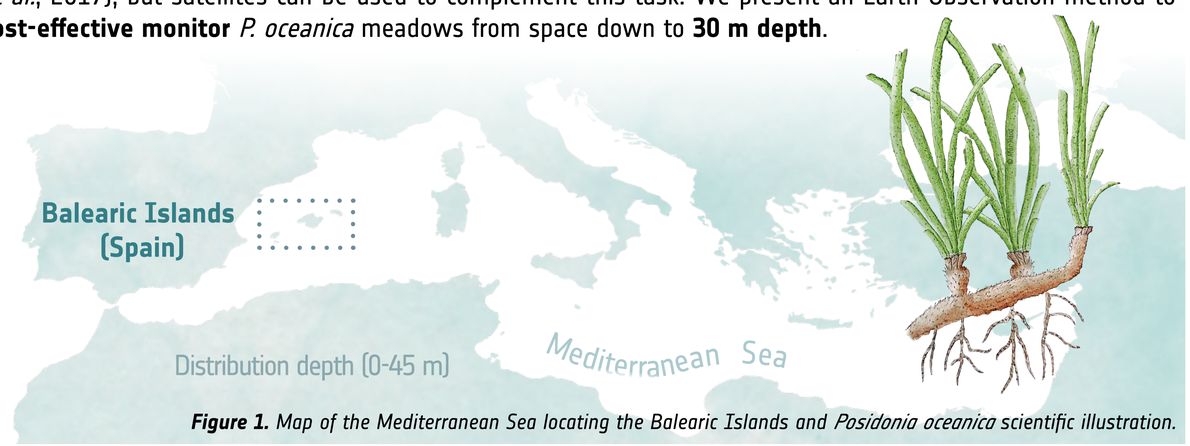


Figure 1. *Map of the Mediterranean Sea locating the Balearic Islands and Posidonia oceanica scientific illustration.*

2. Material & methods

- Processing of **Sentinel-2 L1C 3500 images** to obtain a **7-year multi-temporal composite** (2016-2022) applying the 20th percentile (removing sunglint), the atmospheric correction (Dark Pixel Substraction), land and Optical Deep Water (ODW) masking (30 m depth using a developed bathymetry).
- **Training** and **validation data design** in three classes (seagrass, ODW and sand), 80% (n=3900) and 20% of points (n=750), respectively, homogeneously sampled in depth and applying a 30 m buffers to sample pixels.
- Classification of the composite runing **Random Forest** machine learning algorithm (threshold=45) using B1-B5. Seagrass extent obtained at 10 m spatial resolution (Traganos *et al.*, 2022) and accuracy assessment.
- Systematic literature review of *in situ* **C_{org} data** of *P. oceanica* meadows in the Balearic Islands (48 sediment samples of 1st m sediment thickness along a gradient of water depth). "Mean" value used to extrapolate the C_{stock} according to the seagrass extent mapped in **Megagrams** (Mg) **C_{org} km^{-2}** and transfered to Carbon Market values.

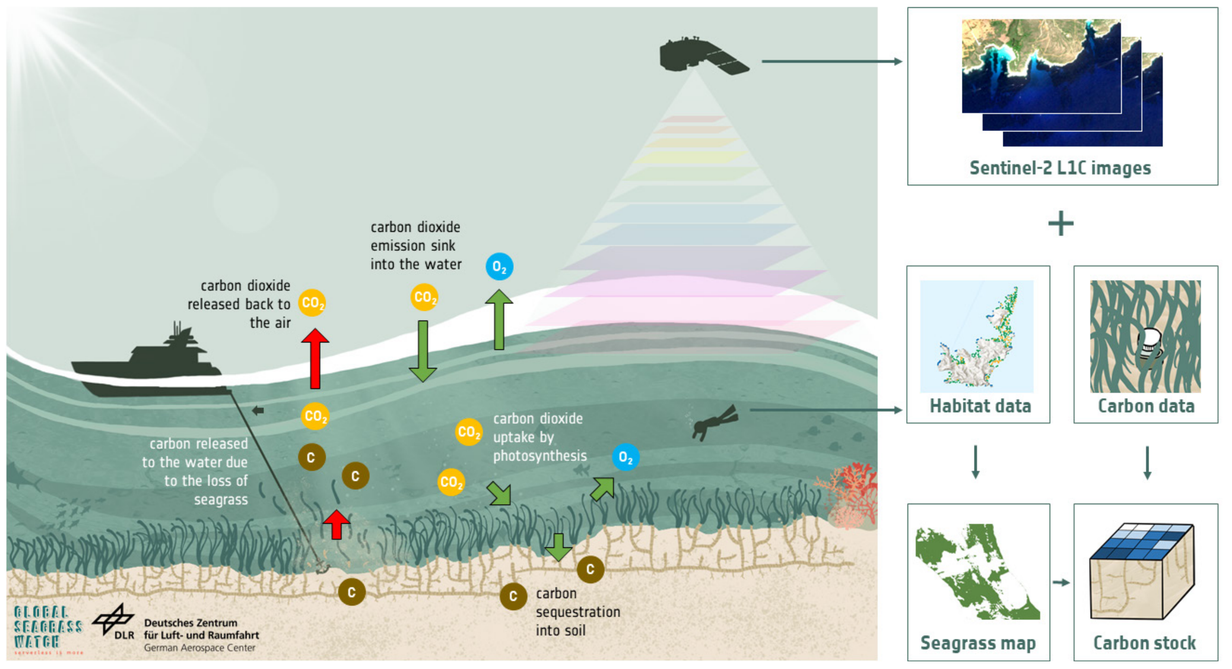


Figure 2. *Earth Observation methodology used for blue carbon accounting, and illustration about carbon pool in P. oceanica seagrass meadows (sequestration and remineralization), showcasing the impact of anchoring in the Balearic Islands (Avi Putri Pertiwi).*

3. Results & discussion

Training and validation data showed an optical consistency in the Sentinel-2 composite reflectances for the three classes (Fig. 3). Random Forest classification showed an overall accuracy of **92,5%** (Fig. 4), performing punctual misclassification between sand and seagrass at higher depths as a consequence of light attenuation, as shown in the confusion matrix (Producer's and User's accuracies can be checked in Table 1). We mapped a total **505 km²** of seagrass extent from 0 to 30 m (zoom of the Sentinel-2 composite and classification map of Ibiza-Formentera can be observed in Fig. 5).

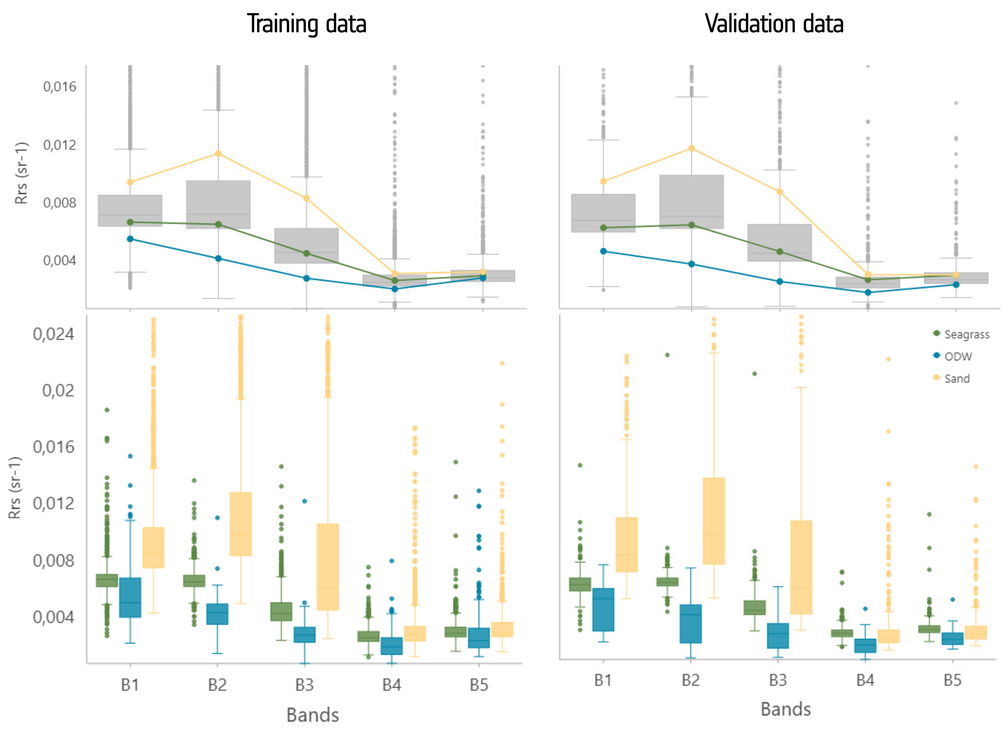


Figure 3. *Boxplots and spectral signatures of training and validation data for B1-B5 of the Sentinel-2 multi-temporal composite.*

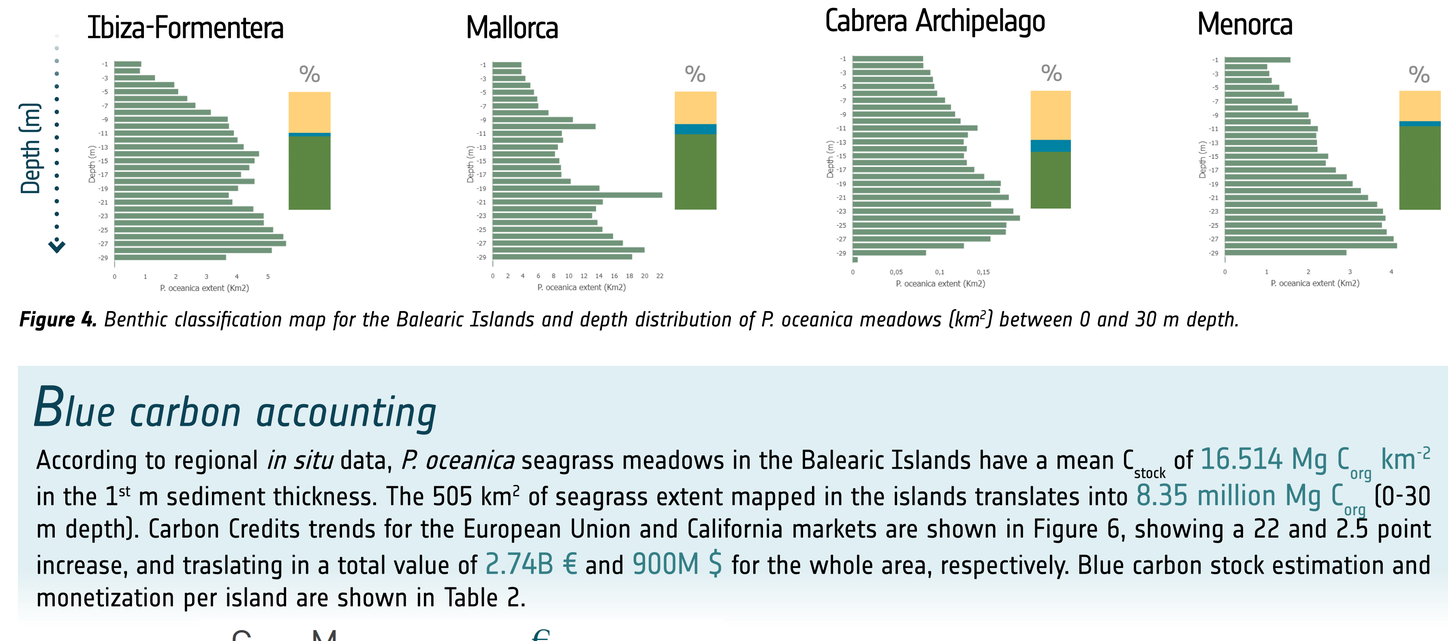
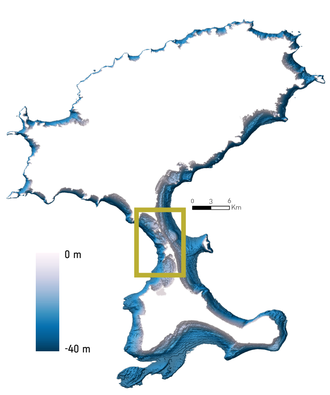


Figure 4. *Benthic classification map for the Balearic Islands and depth distribution of P. oceanica meadows (km²) between 0 and 30 m depth.*



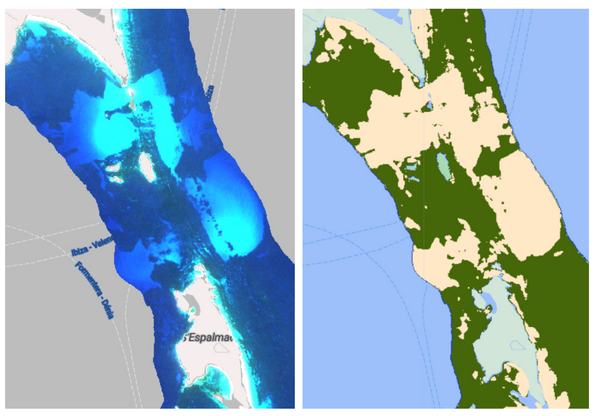


Table 1. *Producer's and User's accuracy from classification.*

	PA's	UA's
Seagrass	0.92	0.95
ODW	0.67	0.77
Sand	0.96	0.92

330	3	27
9	24	2
14	4	336

Figure 5. *Example of Sentinel-2 multi-temporal composite and classification map in Ibiza-Formentera with confusion matrix (Balearic Islands).*

Blue carbon accounting

According to regional *in situ* data, *P. oceanica* seagrass meadows in the Balearic Islands have a mean C_{stock} of 16.514 Mg C_{org} km^{-2} in the 1st m sediment thickness. The 505 km² of seagrass extent mapped in the islands translates into 8.35 million Mg C_{org} (0-30 m depth). Carbon Credits trends for the European Union and California markets are shown in Figure 6, showing a 22 and 2.5 point increase, and traslating in a total value of 2.74B € and 900M $ for the whole area, respectively. Blue carbon stock estimation and monetization per island are shown in Table 2.

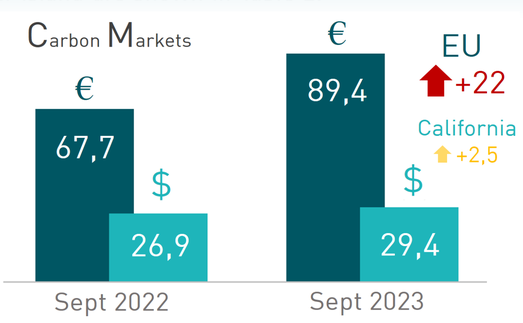


Figure 6. *Carbon Credit prices for 1 tone of CO_2 for the European Union and California markets (September 2022-2023).*

Table 2. *Blue carbon estimations and monetization of P. oceanica meadows in the Balearic Islands (0-30 m depth) according to September 2023 prices.*

	European Union (€)	California ($)	**European Union (€)**	California ($)
Island	Mg C_{org}		**Mg CO_2**	
Ibiza-Formentera	43.6M	14.3M	587.3M	193M
Mallorca	128.2M	42.1M	**1.73B**	567M
Cabrera	1.6M	516.4K	21.2M	7M
Menorca	30M	9.87M	404.5M	132.9M
SUMMARY	203.4M	66.8M	**2.74B**	900M

4. Conclusions and future steps

The on-the-cloud approach developed enables the monitoring of *P. oceanica* seagrass meadows through Sentinel-2 imagery at 10 m resolution with a high accuracy down to 30 m depth, as well as the quantification of the blue carbon stored at 1 m sediment. Further developments will include spatial-explicit blue carbon mapping considering sediment granulometry, wave exposure, leafs density and depth variation to optimize the accuracy of blue carbon stock estimation in *P. oceanica* seagrass meadows.

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