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National blue carbon assessment in Spain using InVEST: Current state and future perspectives

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ABSTRACT

Coastal and marine ecosystems supply multiple services in which human well-being is highly dependent. However, high-resolution spatial distribution studies of marine ecosystem services are scarce, even if it is known that this information is needed to better manage and conserve these ecosystems. With the aim of filling this gap, in this study we have: (1) mapped and assessed the current capacity of marine phanerogams (*Posidonia oceanica, Cymodocea nodosa, Zostera noltii, Zostera marina, and Halophila decipiens)* to store and sequester blue carbon in Spain; (2) mapped and assessed the future capacity of marine phanerogams to store and sequester blue carbon under three plausible futures; and (3) assess the economic implications of these scenarios. Our results are based on the InVEST Blue Carbon model and exhibit high spatial resolution (100 m/pixel) of carbon stored in marine phanerogams. We found that 82% of carbon storage and sequestration by marine phanerogams is currently managed within Natura 2000 areas. However, results from the modeled future scenarios indicate a constant decrease in the amount of carbon stored in these ecosystems by 2050 (24% lost in the business-as-usual scenario). The economic impact of these losses is equivalent to 17,974 million € (around 1.6% of the Spanish GDP). Finally, we consider that a transformative management change is needed to conserve marine phanerogams in Spain, and we discuss the importance of the Natura 2000 Network in managing marine ecosystems and their services in the near future.

1. Introduction

Marine biodiversity loss is increasingly impairing the ocean's capacity to provide fundamental ecosystem services (ES) for human well-being (Worm et al., 2006). The loss of coastal and marine ecosystems will be further increased by climate change (Short and Neckles, 1999; Harley et al., 2006; Koch et al., 2013) and, ironically, marine ecosystems play a fundamental role in the carbon storage and sequestration processes that contribute to climate change mitigation (Duarte et al., 2013a; Marbà et al., 2014). Several studies have indicated that seagrass habitats, the main contributor to this carbon storage, are declining worldwide due to human impacts, which implies an alarming increase in their extinction risk (Short et al., 2011). Nevertheless, studies on marine ecosystems, especially studies that quantify and spatially assess marine ES, remain scarce (Townsend et al., 2014).

Coastal and marine ecosystems are, and have always been, a source of multiple ES, not only for providing food (fisheries and aquaculture) and the extraction of raw materials (biotic and non-biotic) but also regulating (climate regulation, coastal protection) and cultural services such as tourism and cultural heritage, among others (Peterson and Lubchenko, 1997; Böhnke-Henrichs et al., 2013; Hattam et al., 2015). One of the most important marine ecosystems in terms of ES is seagrass meadows formed by marine phanerogams, such as *Posidonia oceanica*, *Cymodocea nodosa,* or *Zostera noltii.* Marine phanerogams are flowering plants that live totally submerged in shallow marine waters on all continents except Antarctica (Short et al., 2007). They form extensive underwater meadows that provide a wide range of ES, such as providing food and shelter for a wide variety of organisms, acting as fish nursery, protecting the coastline against disturbances, enhancing water purification, and even providing trophic resources and shelter to terrestrial

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organisms when dead plants are washed upon the shore (Lau, 2013; Nordlund et al., 2018). They also support local and small-scale fisheries in many countries (Nordlund and Gullström, 2013). Furthermore, seagrasses play a specific role in carbon storage and sequestration dynamics (Macreadie et al., 2014; Duarte and Krause-Jensen, 2017). However, their locations in coastal and shallow waters make them accessible and sensitive to human activities, such as habitat destruction, and water pollution. As a result, seagrass meadows have experienced a significant decrease in the last decades, jeopardizing the supply of ES for human society and causing them to be a priority for conservation policies and ecosystem management (Orth et al., 2006).

In this context, ES mapping and modeling has been demonstrated to be a powerful tool to improve the capacity of management authorities to achieve sustainable solutions for ecosystems (Maes et al., 2012). These modeling tools have been widely applied in terrestrial ecosystems (Lavorel et al., 2017). However, mapping ES in marine and coastal areas presents more difficulties due to the high dependency on available data, which is currently scarce (Townsend et al., 2018). For example, InVEST model has been used in multiple published studies with several scenarios on terrestrial ecosystems, but there is a clear gap on scientific publication that map and assess marine blue carbon at national or finer scale. Thus, increasing marine ES knowledge through contrasted modeling tools has become an expanding topic in the scientific literature (Liquete et al., 2016; Maes et al., 2016; Teixeira et al., 2016), and the growing production of data in research projects (i.e., INTEMARES and Blue Natura summarized in Mateo et al., 2018) has allowed the quantification and development of better marine ES models. Indeed, an increasing interest is emerging in the assessment of 'Blue Carbon' or carbon sequestered by seagrasses from coastal ecosystems worldwide (Lavery et al., 2013).

Given this situation, Spain offers one of the best opportunities to map and quantify carbon storage and sequestration by seagrass meadows. This is especially relevant in relation to the Natura 2000 Network because Spain is the country that contributes the most to the network of protected areas in the European Union, considering both, marine and terrestrial areas (https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer). Furthermore, climate change will affect the mitigation capacity of these ecosystems, exponentially increasing the emissions of CO_2, so that specific management strategies would be needed to alleviate the impact. Thus, this study aims to provide specific information on how Spanish seagrass meadows can be managed to achieve sustainable development following the next objectives: (1) to map and quantify the present blue carbon storage and sequestration in marine phanerogams, (2) to assess blue carbon storage and sequestration under three plausible future scenarios, and (3) to analyze the economic impact of coastal blue carbon contributions under the Natura 2000 areas.

2. Methods

2.1. Study area

We studied four of the five marine demarcations in Spain, which comprise 758,109 km^2: (1) South Atlantic Spanish Coast (2%), (2) Canary Islands (64%), (3) Alboran Sea (3%), and (4) Western Mediterranean Sea (31%) (Fig. 1). We did not consider the North Atlantic Spanish Coast marine demarcation because most of the marine phanerogams are at the mouths of rivers rather than in marine or coastal areas. Spain is the country with the second larger protected marine area in the EU with 84,405 km^2, which is 19% of the total protected marine areas in the EU. The total protected surface in each marine demarcation includes the South Atlantic Spanish Coast (9%), Canary Islands (41%), Alboran Sea (7%), and Western Mediterranean Sea (43%). In each of the marine demarcations, we studied five different types of seagrass: *P. oceanica, C. nodosa, Z. noltii, Z. marina,* and *H. decipiens* (see Table 1).

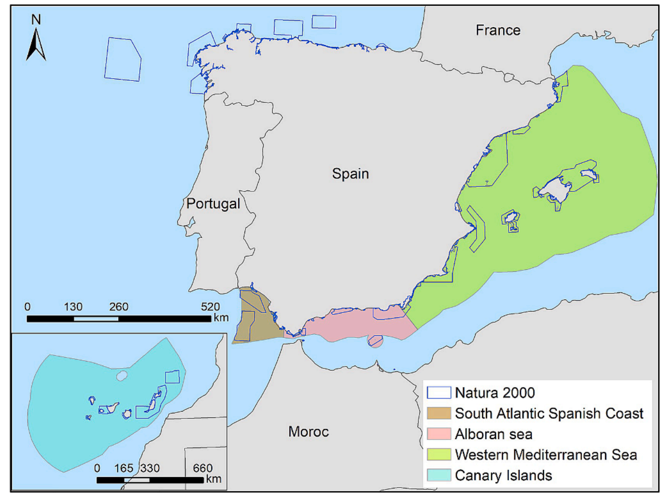

Fig. 1. Study area: Spanish marine demarcations and Natura 2000 site distribution.

2.2. Mapping and assessing coastal blue carbon

We mapped and assessed the coastal blue carbon using InVEST model V3.6.0 (https://naturalcapitalproject.stanford.edu/invest/). This model quantifies the total amount of carbon stored and sequestered in coastal and marine ecosystems currently and in the future, providing spatial quantitative results in a raster format (100 × 100 m pixel in our study). To our knowledge, InVEST coastal blue carbon model has been applied in few studies (Reddy et al., 2016; Adi et al., 2020; Wedding et al., 2021), most of them focusing on North America. In this study, we present the first application of this model in a European country at national level. We considered carbon stored as the total amount of CO_2 eq. that contains the ecosystem and carbon sequestration as the CO_2 eq. between two time periods, that is, the amount of carbon sequestered throughout the period (Lal, 2008; González-García et al., 2020). The model analyzes the potential pressures that lead to carbon emissions (such as removal of non-buried biomass or soil carbon) as well as the potential accumulation of carbon during the time period (carbon sequestration). The model is fed by four data sources: (1) spatial distribution of ecosystems that store and sequester carbon, (2) net carbon contained in the soil, biomass, and dead matter in t CO_2/ha for each species; (3) current pressures that will alter the carbon stored in the future scenarios by reducing the marine phanerogam surface, and (4) carbon accumulation during the time period. We used the Marine Phanerogams Atlas from Spain (Ruiz et al., 2015) for the spatial distribution of the seagrasses and the data of carbon stocks and fluxes obtained from Andalusian seagrass meadows (Mateo et al., 2018; Table 2). To obtain the amount of carbon from each species, we calculated the average value of all the plots provided from Andalusian seagrass meadows (Mateo et al., 2018) for the same species (Eq. (1)). To obtain the amount of carbon stored in each species type, the average value was estimated based on the proportional distribution of the species (Eq. (2)). The total carbon storage was estimated by summing the carbon in the aboveground living/dead biomass and carbon in the belowground living/dead biomass.

$$(CO_2\ eq/ha\ ssp1_a + CO_2\ eq/ha\ spp1_b + \dots CO_2\ eq/ha\ ssp1_n)/n \quad (1)$$

$$(CO_2\ eq/ha\ ssp1 + CO_2\ eq/ha\ ssp2)/2 \quad (2)$$

To estimate the loss of carbon storage in future scenarios (corresponding with point 3 in the paragraph above), the model uses a table to explain the potential alteration between two different habitats (i.e., change from *P. oceanica* meadow to bare soil). This table shows if the change supposes an accumulation, low-impact-disturb, or high-impact-

Table 1
Number of hectares of each spp. in each marine demarcation. SCI: Site of Community importance, SPA: Special Protection Areas, SAC: Special Areas of Conservation.

Marine demarcation	Total surface (km^2)	Total Natura 2000 surface (km^2)	Number of Natura 2000 sites	*Spp.*	Surface (ha)
South Atlantic Spanish Coast	14,070	5,579	SCI: 7 SPA: 7 SAC: 4	*C. nodosa* *Z. noltii* *Z. marina*	1,151 912 0.09
Canary Islands	486,185	25,553	SCI: 2 SPA: 13 SAC: 28	*C. nodosa* *Z. noltii* *H. decipiens*	6,709 0.48 399
Alboran Sea	24,989	4,324	SCI: 4 SPA: 6 SAC: 16	*P. oceanica* *Degraded P. oceanica* *P. oceanica and C. nodosa* *C. nodosa* *Z. noltii*	3,031 165.2 741.6 2,208 1.1
Western Mediterranean Sea	232,863	26,231	SCI: 52 SPA: 52 SAC: 24	*P. oceanica* *Degraded P. oceanica* *Dead P. oceanica* *P. oceanica and C. nodosa* *P. oceanica and C. racemose* *C. nodosa* *C. nodosa and Z. noltii* *C nodosa and C. racemosa* *Z. noltii*	112,897 195.3 3,869 1,873.7 89.4 14,192 138.6 91.1 7.1

Table 2
Carbon stocks data based in Mateo et al. (2018) and their association with marine phanerogams atlas of Spain (Ruiz et al., 2015).

Atlas classes	tCO_2/ha aboveground living/dead biomass	tCO_2/ha belowground living/dead biomass	Total t CO_2/ha	Yearly accumulation tCO_2/ha
Non seagrass	*NA*	*NA*	*NA*	*NA*
C. nodosa	*1.63*	*469.3*	*470.93*	*0.48*
C. nodosa and Z. noltii	*1.175*	*243.95*	*245.125*	*0.39*
Dead P. oceanica	*8.06*	*900*	*908.06*	*0.6*
P. oceanica	*8.06*	*1,813.91*	*1,821.97*	*1.81*
Z. noltii	*0.72*	*18.6*	*19.32*	*0.11*
Degraded P. oceanica	*8.06*	*1,560.69*	*1,568.75*	*NA*
P. oceanica in regression	*8.06*	*1,560.69*	*1,568.75*	*1.14*
P. oceanica and C. nodosa	*4.84*	*1,137*	*1,141.84*	*1.81*
P. oceanica and C. racemosa	*NA*	*NA*	*NA*	*NA*
C. racemosa	*NA*	*NA*	*NA*	*NA*
H. decipiens	*NA*	*NA*	*NA*	*NA*
C. nodosa and C. racemosa	*NA*	*NA*	*NA*	*0.24*
Z. marina	*0.72*	*18.6*	*19.32*	*0.11*

disturb into the carbon contained in the ecosystem (Appendix A1). Next, another table that includes the quantification of the effect on the different carbon pools is needed (Appendix A2). Then, spatial representation of the future state of each habitat is needed to apply the effects of the tables. To create the layers that represent the future state of habitats, we used the data of accumulated pressures in the marine demarcations of Spain provided by the Spanish Ministry (MITECO, 2019a, b). Finally, we estimated the total amount of carbon contained in the coastal/marine Natura 2000 protected areas of Spain in two steps: (1) We dissolved all the SCI, SPA, and SAC polygons to avoid overlapping and double counting, and (2) we used the zonal statistics tool from ArcGis to measure the amount of CO_2 eq. inside the Natura 2000 Network and in the rest of the marine demarcation based on the results of the InVEST model. We then analyzed the relative importance of the Natura 2000 sites by marine demarcation in terms of contribution to the carbon storage of marine phanerogams.

2.3. Future scenarios for coastal blue carbon

We considered three plausible future scenarios based on the following seven environmental characteristics: (1) extent and state of the Natura 2000 area, (2) number of strategies in species and protected area management, (3) quality and quantity of public investigations and accessible scientific databases; (4) governance and participation among stakeholders; (5) environmental vigilance and monitoring programs; (6) financing dedicated to the environment; and (7) environmental education and awareness. These characteristics were selected based on previous works developed in the marine Natura 2000 areas (Gantioler et al., 2014; Böhnke-Henrichs et al., 2013; Russi et al., 2016).

Depending on the level of implementation of these characteristics, we defined three plausible scenarios. (A) Business-as-usual future: we maintained the level of past implementation assuming no net positive change in any of the proposed characteristics (in the past, these management strategies had the negative effect of losing 50% of *P. oceanica* meadows, see Marbà et al. (2014) and Pergent et al., (2016). (B) Sustainable future: a significant increase compared with the business-as-usual scenario in the level of implementation and conservation was considered in all the environmental and management characteristics, which will have a positive effect on the conservation of marine phanerogams by 2050. (C) Non-sustainable future: we assumed a loss in all the proposed characteristics, which will create a significant loss of marine phanerogams compared with the business-as-usual scenario by 2050. Appendix B provides a detailed explanation on how the characteristics presented above change in the three scenarios.

To spatially represent the effect of each scenario, we considered the different pressures that alter marine phanerogams, based on those provided by Spanish marine authorities (MITECO, 2019a,b), which consist of a set of 11 different pressures that are quantified in a grid for the entire Spanish marine area (Table 3). To identify where changes will occur in future scenarios, we set different thresholds in the pressures that could lead to the destruction of the entire cell (Fig. 2). To set the threshold values, we reviewed the scientific literature to set references (Table 3) searching for information regarding the sensitivity of marine phanerogams to the different pressures, and we conducted an expert consultation on how an increase in the pressures would affect

Table 3
Pressures thresholds. Thresholds represent the point at which the value of the pressure could affect the seagrass in future scenarios. These values are indices used in the study based on the cumulative source pressures. The numbers in brackets indicate the range of values in the index of each pressure. The Reference column is the source used to set the tipping point.

Pressures	Threshold (tipping point)	Cumulative source pressures	Reference
Hydrographic alterations	3 (0–20)	Port and defense infrastructures, sediment retention by dams, exploitation of submarine deposits, artificial reefs and wreck sinking, mussel rafts	Díaz-Almela and Duarte 2008
Terrestrial litter	8 (0–10)	Coastal population density, port areas, presence/absence of dumpsites, presence/ absence of a river mouth	IUCN
Maritime litter	60,000 (0–60,000)	Density of fishing boats and merchant ships	IUCN
Pollutants	3.25 (0–3.6)	Ship accidental spills, river contributions, atmospheric diffuse pollution, diffuse pollution by runoff water, liquid and solid waste-controlled disposal	IUCN Díaz-Almela and Duarte 2008
Non-native species	8 (0–10)	Biological intrusions, ballast water, commercial and recreational fishing, trawls, aquaculture, living bait, dredging material spill, biological control, habitat alterations	Díaz-Almela and Duarte 2008
Physical extraction	50 (0–50)	Exploitation of submarine deposits and port dredging, exploration and exploitation of hydrocarbons	IUCN
Nutrients	2 (0–3)	Fertilizer discharge, aquaculture, solid waste, atmospheric diffuse pollution, diffuse pollution by runoff water	Díaz-Almela and Duarte 2008
Pathogens	6 (0–6)	Wastewater spills, aquaculture, ballast water, bathing water, mollusk farming	MITECO, 2019b
Bottom profile modifications	8 (0–20)	Exploitation of submarine deposits, dredging material spill, beach regeneration, submarine cable and pipes, artificial reefs and wreck sinking	IUCN
Salinity	8 (0–4,5)	Desalination plant, urban waste, industrial waste, and highly altered rivers.	Díaz-Almela and Duarte 2008
Sealing	7.5 (0–7.5)	Port and defense infrastructures, monobuoys, artificial reefs, and wreck sinking	MITECO, 2019b

seagrasses. We altered the pressures by increasing them in 25% in business-as-usual scenario, 5% in the sustainable scenario and 50% in the non-sustainable scenario. The relations between the pressures and the scenarios are provided in the Appendix C. Then, we erased the seagrass in those cells where one or more pressures would overcome the tipping point and used that layer in the second time period. This is, T1 consists of the non-altered seagrass distribution (2020), and T2 consists of the altered layer of seagrasses based on the cells that would disappear in each scenario (2050). In the cases where the seagrass does not disappear in the future scenarios, the carbon stored will increase based on the yearly accumulation provided in Table 2. The carbon accumulation between the present and future was estimated by summing the total accumulation per hectare and year.

2.4. Sensitivity analysis

With the aim to test the results provided by Blue Carbon model using InVEST V3.6.0, we conducted a sensitivity analysis. We applied different modifications on the input data needed to run the model using as an example the Alboran Sea marine demarcation. Analyzing the results of the application of these changes, we were able to observe the variations of the model outputs. We applied these modifications in four variables related to different parts of the model, i.e., changing the type of ecosystem or the amount of CO_2 in the most biophysical part and changing the degree of impact of future scenario changes, as well as the percentage of alteration based on this degree.

The modifications applied in the model were set intentionally to better perceive the magnitude of the change as follows: (1) to change 58% area of *P. oceanica* to *C. nodosa* in order to represent it in the initial time raster, we chose this value as it represents the larger patch of *P. oceanica* in our dataset; (2) to multiply by 100 the CO_2 sequestration values of each seagrass class, where we set this value randomly to better perceive the magnitude of the change; (3) to change all degrees of impact to "high-impact-disturbance" when one type of seagrass change to another type of habitat regardless of the type (see Appendix A1), which was done to understand the effect of the level of change in the final results; (4) to reduce the biomass loss percentage in "low-impact-disturbance" from 30% to 10%, in "medium-impact-disturbance" from 50% to 30% and in "high-impact-disturbance" from 100% to 50% (see Appendix A2), which was done in order to understand the intensity of change based in the percentage of alteration in this variable in the future scenarios. Finally, we presented the results in a table comparing the variations between the modifications.

2.5. Economic valuation of coastal blue carbon

Calculations for the economic value of coastal blue carbon in Spain were done based on the current total carbon stock as well as for the predicted value in 2050 under three scenarios that consider different ecosystems area loss rates. A price approach is used in this study, following previous studies published on the topic of economic valuation of carbon sequestration and storage of coastal blue carbon (Beaumont et al., 2014; Jerath et al., 2016; Luisettiet al., 2013). For the purpose of this study it is selected the social price of the European Investment Bank (World Bank, 2018). The central European Investment Bank price for carbon emissions in 2018 is 38€/t CO_2 eq., increasing annually in real terms to 121€/t CO_2 eq. by 2050.

3. Results

3.1. Current assessment and spatial distribution of coastal blue carbon

The Mediterranean and Atlantic areas of Spain clearly contrast the average value of coastal blue carbon per hectare. The Western Mediterranean demarcation stores 216,116,542 tonnes of CO_2 eq. (95% of total coastal blue carbon in Spain) (Table 4). The Alboran Sea is the second marine demarcation with a total of 7,353,838 tonnes of CO_2 eq. (3% of the total in Spain). Canary Islands demarcation is the next highest with a total of 3,173,478 tonnes of CO_2 eq. (1.3% of the total in Spain). Finally, the South Atlantic Spanish Coast demarcation only supplies 556,261 tonnes of CO_2 eq. (0.7 %) because it is the smallest marine demarcation, and the most frequent marine seagrass is the small-sized *C. nodosa*. The western Mediterranean Sea marine demarcation presents the highest average value of 1,659 CO_2 eq. ha^{-1} (std 408) because it is the one exhibiting the largest coverage of *P. oceanica.* Alboran Sea demarcation presents an average CO_2 eq. ha^{-1} of 1,232 (std 616) tonnes, which is slightly less than Mediterranean since almost half of the seagrasses area present in this demarcation is *C. nodosa*, which contains half of the CO_2 eq. ha^{-1} than is shown in *P. oceanica*. Canary Islands and South Atlantic Spanish coast demarcations present 473 (std 0) and 445

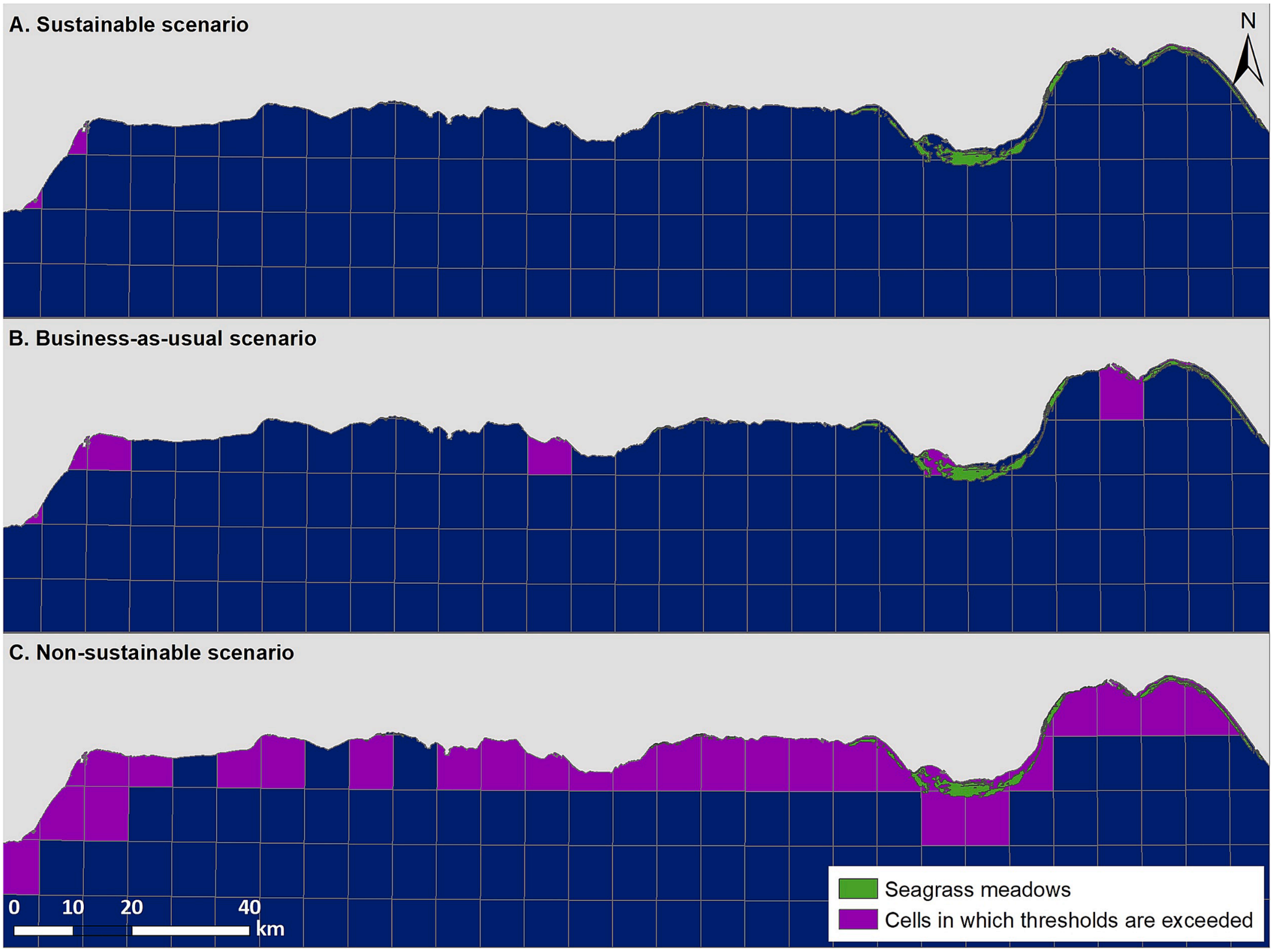

Fig. 2. Spatial representation of potential pressures (MITECO, 2019b) under each plausible future and its impact on marine phanerogams. For example, under the sustainable or business-as-usual (A and B), few cells exceed the thresholds (purple cells), while under the non-sustainable scenario (C), most of the cells exceed the limit, leading to a major destruction of existing seagrass (green cells).

Table 4
Total and average carbon stored per marine demarcation and species in Spain. ± represents the standard deviation.

	C. nodosa	H. decipiens	P. oceanica	Z. marina	Z. nolti	Average CO_2 eq. per ha	Total CO_2 eq.
Western Mediterranean Sea	23,373,663	-	192,742,744	-	135	1,659 (±408)	216,116,542
Alboran Sea	2,641,919	-	4,711,900	-	19	1,232 (±616)	7,353,838
Canary Islands	3,173,469	-	-	-	9	473 (±0)	3,173,478
South Atlantic Spanish Coast	310,352	-	-	-	245,909	445 (±109)	556,261

(std 109) tonnes CO_2 eq. ha^{-1} since most of their seagrasses are *C. nodosa* and *Z. nolti*.

The most significant areas for coastal blue carbon are in the Western Mediterranean demarcation (East of Spain; Fig. 3). We found multiple sites (117,889 hectares) with more than 1,000 CO_2 eq. ha^{-1}, similar to the Balearic Islands (Fig. 3A) or Cape of la Nao (Fig. 3B), further, 16,660 hectares in this demarcation presented between 400 and 1,000 tonnes of CO_2 eq. ha^{-1}. In the Alboran Sea demarcation, we also found different areas (3,787 hectares) with more than 1,000 tonnes of CO_2 eq. ha^{-1}, similar to Cape Gata (Fig. 3C) and Cape Sacratif (Fig. 3D), on the other hand, 2,183 hectares presented between 400 and 1,000 tonnes of CO_2 eq. ha^{-1}. The South Atlantic and Canary Island demarcations do not present any hectares with more than 1,000 CO_2 eq. However, multiple sites in the South Atlantic (1,153 ha) and Canary Islands (6,716 hectares) were found within a range of 400 and 1,000 tonnes of CO_2 eq. (Fig. 3E, F, G, and H).

3.2. Future scenarios for coastal blue carbon

Except for the Canary Islands, all the marine demarcations of Spain experienced a substantial reduction in the coastal blue carbon under the three proposed future scenarios (Fig. 4). The business-as-usual scenario shows lower values than the sustainable scenario, while the non-sustainable scenario clearly exhibits the highest carbon loss.

The South Atlantic Spanish Coast demarcation presents an important decrease in coastal blue carbon under the three scenarios (Fig. 4A). This area decreased from 556,284 tonnes of CO_2 eq. in 2020 to 155,637 under the business-as-usual scenario, 174,053 in the sustainable scenario, and 155,135 in the non-sustainable scenario.

The Canary Islands demarcation is the only one exhibiting an increase under the three plausible scenarios (Fig. 4B). We observed an increase from 3,173,713 tonnes of CO_2 eq. in the present to 3,266,530 in the business-as-usual scenario, 3,270,426 in the sustainable scenario,

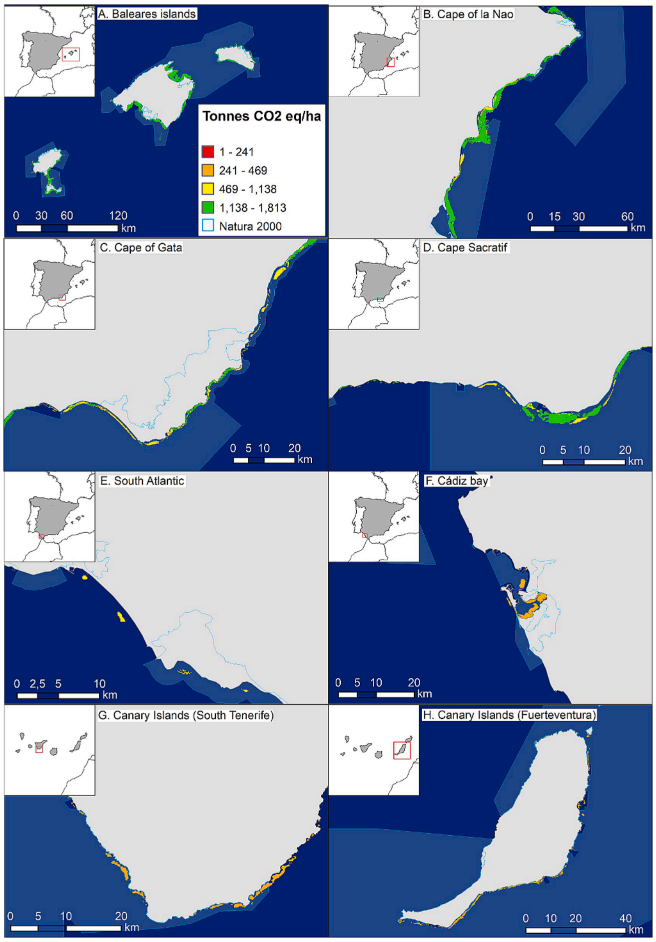

Fig. 3. Spatial representation of coastal blue carbon model in Spain. Examples A and B correspond with South Atlantic Spanish Coast marine demarcation, C and D are in the Alboran Sea marine demarcation, E and F in South Atlantic Spanish Coast marine demarcation, and G and H in Canary Islands marine demarcation.

and 3,260,686 in the non-sustainable scenario. This increase is because most of the pressures are in areas that do not affect the seagrass.

The Alboran Sea demarcation shows some small differences between the business-as-usual and sustainable scenarios but exhibits an abrupt difference for the non-sustainable scenario (Fig. 4C). We observed a decrease from 7,355,015 tonnes of CO_2 eq. in the present to 5,205,540 in the business-as-usual scenario, 6,945,980 in the sustainable scenario, and 175,422 in the non-sustainable scenario (representing 97.6% of the present situation).

The Western Mediterranean Sea demarcation exhibits a similar pattern to that of the Alboran Sea demarcation because both are in the Mediterranean Sea (Fig. 4D). Our results indicate a decrease from 216,127,783 tonnes of CO_2 eq. in the present to 163,498,407 in the business-as-usual scenario, 211,872,605 in the sustainable scenario, and 40,447,700 in the non-sustainable scenario.

Changes in the spatial distribution of coastal blue carbon in the different scenarios are shown in Fig. 5. This area presents the most pressured zones covered by *P. oceanica* meadows. Two sites are shown in the Western Mediterranean Sea demarcation (Fig. 5A, B, C, and D) and the Alboran Sea demarcation (Fig. 5E, F, G, H). The persistence of pressures in the business-as-usual scenario highly affects the carbon stored in several hectares of this demarcation, while the non-sustainable scenario predicts that almost all the seagrass in this area would disappear. The sustainable scenario does not present substantial changes from the present situation because under this scenario, most of the pressures in the area would be reduced.

3.3. Contribution of Natura 2000 Network to carbon storage and sequestration

The contributions of the Natura 2000 sites to conserve coastal blue carbon under the three future scenarios are shown in Fig. 4. Currently, marine Natura 2000 sites represent 7.9% of the coastal and marine areas in Spain but contain 82% of the carbon stored in marine phanerogams. For example, in the Western Mediterranean Sea demarcation, 82% of the coastal blue carbon (176,246,376 tonnes of CO_2 eq.) is included in the Natura 2000 sites. The Alboran Sea demarcation exhibits 90% of the total CO_2 eq. stored in marine phanerogams inside the Natura 2000 sites, which supposes 6,613,452 tonnes of CO_2 eq. Marine demarcations in the Atlantic Ocean (Fig. 5A, B) exhibit similar values regarding the proportion inside the Natura 2000 area.

Most of the changes occur outside the Natura 2000 Network in the future scenarios. The South Atlantic Spanish Coast demarcation does not present high variability in the carbon stored within the Natura 2000 Network in the three scenarios because the main changes occur outside the Natura 2000 sites (Fig. 5A). The Canary Islands demarcation did not show significant changes inside and outside the Natura 2000 sites (Fig. 5B). The Alboran Sea demarcation exhibits greater variability in coastal blue carbon inside the Natura 2000 sites; in this case, the non-sustainable scenario implies a loss of almost all the coastal blue carbon inside and outside the Natura 2000 sites (Fig. 5C). Finally, the Western Mediterranean Sea demarcation presents a similar pattern to that of the Alboran Sea demarcation, with a substantial decrease in the coastal blue carbon in the non-sustainable scenario.

3.4. Sensitivity analysis

Results of sensitivity analysis are provided in Table 5. This table represents the comparison of the four modifications introduced in the models with the original results in the Alboran Sea demarcation (Fig. 1). In general terms, the most significant modification is Mod 2, in which we altered carbon pools values. The second most significant modification is the habitat type, in which we sifted several hectares of *P. oceanica* to *C. nodosa*. Modifications in tables associated to changes and their intensity in future scenarios present low impact in the results. The Mod 1 shows high decrease in comparison with the original model in present (−31.74%) and future business-as-usual scenario (−27.19%), similarly, average CO_2 eq. ha^{-1} is −27.24% in 2050. Mod 2 increases 9,899% in 2020 and 9,620% in 2050 since most of carbon pools were augmented, similarly, the average CO_2 eq. ha^{-1} increases 9611% in 2050. Mod 3 presents a slight decrease in CO_2 eq. (−1.08%) in comparison with the original model, the average value of CO_2 eq. ha^{-1} decreases also −1.15%. Finally, Mod 4 increases CO_2 eq. in 0.09% and has no effect in the average value of CO_2 eq. ha^{-1}. The outcome of the sensitivity analysis reveals that the most important variable is the amount of carbon in each pool so that the model is highly sensitive to the input data. Similarly, the type of ecosystem, which is highly related with carbon pools, affects the robustness of the model.

3.5. Economic value of the coastal blue carbon

The monetary value of the total coastal blue carbon currently stored in Spain is 8,634 million € (227,000,000 tonnes of CO_2 eq.), approximately 0.7% of the Spanish GDP. The Natura 2000 sites contain 82% of the total coastal blue carbon in Spain, which is more than 7,000 million €. This estimation would be highly altered in future scenarios, considering that the World Bank estimates an increase in the price of the social value of carbon to 121 €/tonne of CO_2 eq. in 2050. Thus, coastal blue carbon in the non-sustainable scenario would expect a potential loss of 20,000 million €, with a loss of 6,000 million € in the business-as-usual scenario and 500 million € in the sustainable scenario.

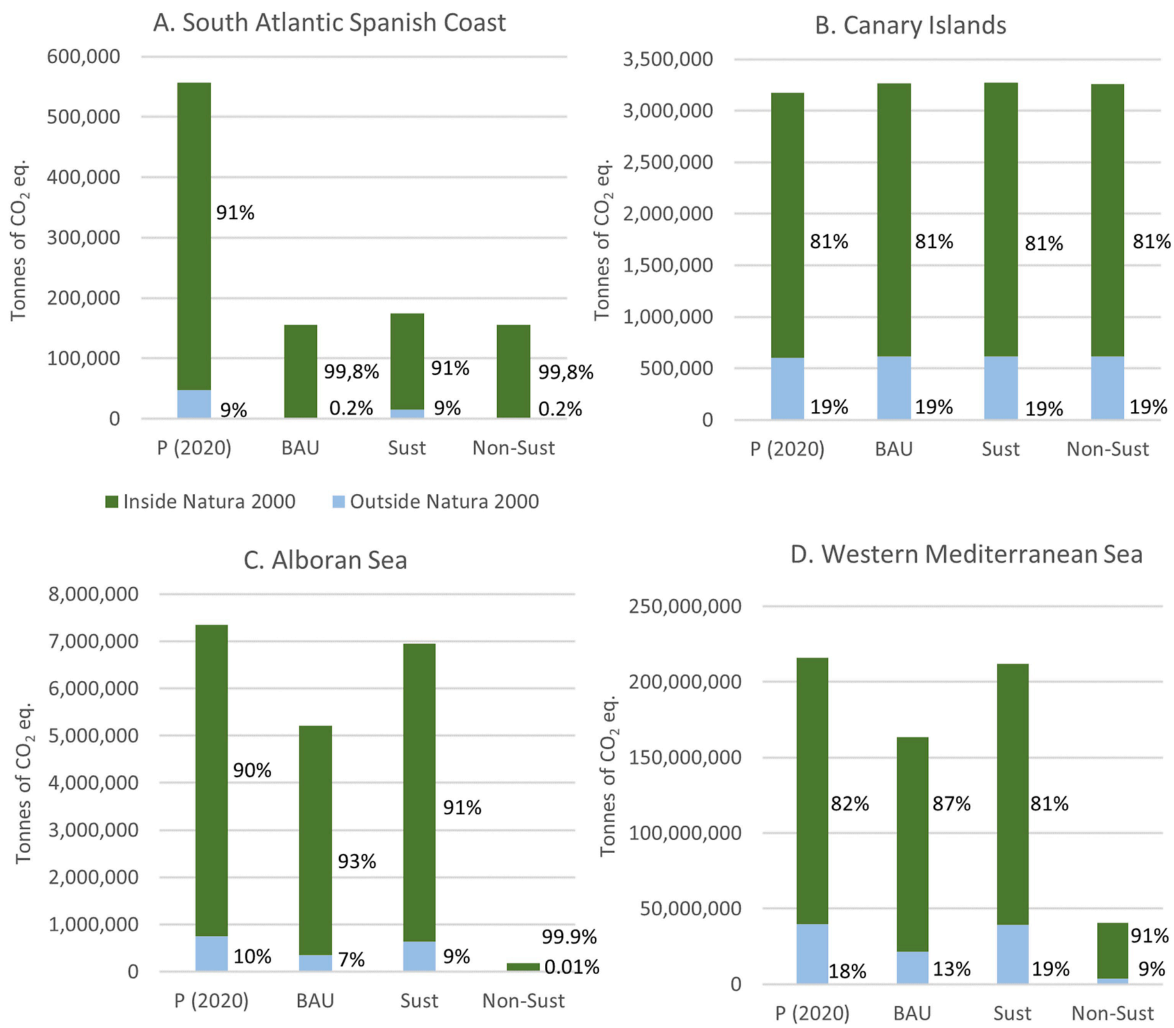

Fig. 4. Modeled changes in coastal blue carbon under the three future scenarios (2050) in reference to the present situation in each marine demarcation included in the study. P (2020): Present (2020), BAU: Business-As-Usual, Sust: Sustainable and Non-Sust: Non-Sustainable.

4. Discussion

4.1. The importance of marine phanerogams for carbon sequestration

We proposed an empirical approach to estimate and assess the carbon sequestration of marine phanerogams at the national level. First, the method spatially represents the main hotspots for carbon sinks at a high-resolution level. Second, the approach allows the assessment to estimate how these areas will change under different management strategies in the future. Third, the approach is scale-independent and allows the comparison of systems or case studies with different conditions. For example, the approach allows the results to be linked at different scales by making carbon sequestration maps a key source of information for marine ecosystem planning and decision-making processes (Burkhard et al., 2012). As a result, we believe that the proposed approach can be used to inform more effective and efficient management decisions by reducing undesirable changes (i.e., destruction of marine phanerogams habitat) and enhancing desirable strategies (i.e., conserving hotspots of carbon sequestration areas under Natura 2000 sites to assure). However, we provide Appendix D to address caveats and limitations that need to be tackled in future works to refine the scenarios methodology and outcomes of the Blue Carbon InVEST models at national level.

Carbon stock differences among Spanish marine demarcations are a consequence of three combined factors: (i) total surface occupied by seagrass meadows, (ii) specific composition of those meadows, and (iii) variability in the amount of carbon sequestered and stored by the different seagrass species. This explains why the Western Mediterranean Sea demarcation stores a greater amount of carbon than the Canary Islands demarcation, even though the first one is roughly half the size of the second. Because of these capabilities, seagrass meadows have been included in several climate change mitigation strategies, the so-called blue carbon strategies, and even proposed for the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanism, although it was not originally designed for marine plants (Duarte et al., 2013b). They have also been considered as positive assets in different projects of ecological engineering because of their advantages over artificial structures for coastal protection (Duarte et al., 2013b; Ondiviela et al., 2013).

Some preliminary estimates suggest that the size of the carbon sink associated with European seagrass meadows could be approximately 7.5 Gt CO_2/EU BC (from Mateo, 2018 and references therein). According to our results, Spanish seagrass meadows store 227,212,795 tonnes of this carbon. However, European numbers are subject to some degree of uncertainty that largely arises from the different levels of accuracy in the maps outlining the spatial distribution of these ecosystems in different countries (Short et al., 2007; Pendleton et al., 2012; Duarte et al., 2013b).

According to Serrano et al. (2016a), *P. oceanica* meadows in the Western Mediterranean store an average of 750 ± 130 t CO_2 eq. ha^{-1}, and specific data for the Western Mediterranean demarcation range

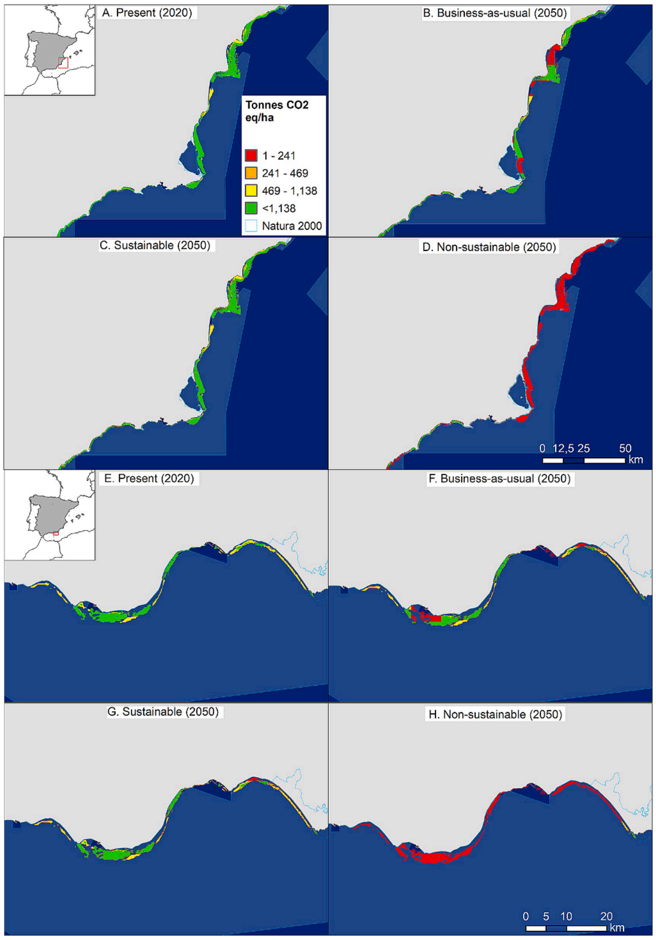

Fig. 5. Spatial representation of coastal blue carbon modeled under the three scenarios in two different marine demarcations. A–D correspond to Western Mediterranean Sea demarcation and E-–H correspond to the Alboran Sea demarcation.

from 300 to 1,760 t CO_2 eq. ha^{-1}, our estimation for that area falls in the higher part of that range (1,659 t CO_2 eq. ha^{-1}), and the results for the other Mediterranean area included in our work (Alboran Sea with 1,232 t CO_2 eq ha^{-1}) can also be considered in the higher part of the rank. These are extremely high values compared to the average global estimates that vary from 120 to 830 t CO_2 eq ha^{-1} and can be explained by the high biomass of *P. oceanica* compared to that of other seagrasses (Elkalay et al., 2003; Serrano et al., 2016b). The Alboran Sea and the Western Mediterranean demarcation show clear differences in biogeographical features. The Alboran Sea, at the entrance of the Mediterranean, has a strong influence from the Atlantic ocean, and water masses from the Mediterranean and the Atlantic cross the Strait of Gibraltar at different depths, together with the geomorphological characteristics, they create unique hydrodynamics and an ecological boundary at the Almeria-Oran front (Parrilla and Kinder, 1987), water temperature, salinity, primary productivity and other biogeochemical factors can affect species composition and accumulation rates of organic carbon by *P. oceanica* meadows (Serrano et al., 2016b), moreover, once the carbon has been sequestered there are biotic and abiotic factors (i.e. sediment accumulation rates, grain size, biochemical composition of organic matter) that can affect the preservation of stored carbon (Mateo et al., 2006; Serrano et al., 2016a; Röhr et al., 2018), these factors and inter-habitat variability play a key role in the ability to store and sequester carbon by seagrasses (Bedulli et al., 2020) and might explain the differences observed in *P. oceanica* meadows in both areas.

Values obtained in the South Atlantic Spanish Coast demarcation (445 t CO_2 eq. ha^{-1}) and the Canary Islands (473 t CO_2 eq. ha^{-1}) are in the middle range of the global values provided by Fourqurean et al. (2012) (120 to 830 t CO_2 eq. ha^{-1}) but are particularly high compared to those obtained for seagrasses meadows of low biomass and fast growing species, like *Cymodocea spp*, *Zostera spp*, or *Halophila spp*, in other parts of the world. Bedulli et al. (2020) estimated carbon storing rates and inventories in mixed meadows of *Halophila ovalis* and *Amphibolis spp* and obtained values much lower of those observed in our study areas (64 ± 13 t CO_2 eq. ha^{-1} for *Amphibolis spp*. and 12 ± 6 t CO_2 eq. ha^{-1} for *Halophila ovalis*). Campell et al. (2015) obtained values for *Halophila spp* and *Halodule uninervis* in Abu Dhabi averaging 49 t CO_2 eq. ha^{-1} in the soil of seagrass meadows. In Southeast Asia, Miyajima et al. (2015) estimated carbon stocks in the top meter of soil of different seagrass species (including *Zostera* and *Cymodocea* genus) and found values ranging from 38 to 120 t CO_2 eq. ha^{-1}, and values provided by Röhr et al. (2018) regarding *Z. marina* capacity to store carbon in different areas of temperate seas ranged from 23 in the Baltic Sea to 351 t CO_2 eq. ha^{-1} in the Mediterranean Sea. Considering these previously published results, the carbon values obtained with InVEST models in the Canary Islands and the South Atlantic marine demarcations, might be overestimated due to the use of reference values measured in the Mediterranean. Moreover, seasonal and habitat variability, exposure to currents, storms and other oceanographic phenomena, sedimentation rates and input of allochthones organic matter can affect the capability of carbon storing and sequestering of seagrasses (Serrano et al., 2016a; Bedulli et al., 2020; Dahl et al., 2020; Ricart et al., 2020), and sampling at local and regional spatial scales is essential to properly estimate the carbon stored in the Canary Islands and South Atlantic Spanish Coast.

4.2. Co-benefits and economic valuation

Blue carbon ecosystems are important natural carbon sinks which are recognized as the most efficient and cost-effective way to counteract GHG emissions, while providing other valuable ecosystem services, nevertheless, these ecosystems are declining globally. The data availability about these issues is still limited around the world and for this reason coastal ecosystems are not yet included in National GHG Inventories of most of the countries (Wedding et al., 2021). Marine phanerogams are considered engineer species, and the meadows they form are a critical source of a wide range of ES, including providing a fish nursery, food and shelter for fish and invertebrates, habitat for epiphytic species of invertebrates and algae, and sediment stabilization or water clarity, (Van der Heide et al., 2007; Petterson and Lubchenko, 1997; Nordlund and Gullström, 2013; Nordlund et al., 2018). However,

Table 5
Results of sensitivity analysis. The table represents the main changes detected in carbon pools in the modifications presented in the method section. Mod is the abbreviation of Modification. ± represents the standard deviation.

	2020 (t CO_2 eq.)	2050 (t CO_2 eq.)	Increase compared with 2020	Increase compared with 2050	Average per hectare 2020 (t CO_2 eq.)	Average per hectare 2050 (t CO_2 eq.)	Average increase in 2050
Original	7,355,015	5,205,539	-	-	2.943 (±67.25)	2.08 (±56.51)	-
Mod 1	5,020,225	3,789,918	−31.74%	−27.19%	2.009 (±49.09)	1.51 (±43.06)	−27.24%
Mod 2	735,501,142	505,988,742	9899%	9620%	294.33 (±6,725,2)	202.48 (±5,498.18)	9611.37%
Mod 3	7,355,015	5,149,185	0%	−1.08%	2.943 (±67.25)	2.06 (±56.27)	−1.15%
Mod 4	7,355,015	5,210,428	0%	0.09%	2.943 (±67.25)	2.08 (±56.49)	0.00%

considering the current scenario of climate change, two of these ES, related to the physical structure of the ecosystem, are considered of special importance: their ability to act as carbon sinks, storing 20% of global carbon despite occupying just 0.1% of the ocean surface (Duarte et al., 2005) and their capacity to reduce erosion, and their role as coastal protectors from disturbances associated with the rise in sea level (Ondiviela et al., 2013). They can also provide valuable information about the past oceanographic and atmospheric conditions that were present at the time of soil formation, in the case of *P. oceanica*, it can go back up to a few millennia (Mateo et al., 1997; Serrano et al., 2016a). In this study, we assessed the capacity to sequester blue carbon in marine phanerogams, but the protection of these ecosystems would widely improve the other ES.

The economic value of the current blue carbon stock in Spain was estimated in 8,634 million €. In terms of per hectare carbon value, the results of the Spanish seagrasses are 58,000 €/ha. Comparing with the Luisetti et al. (2013)'s study, the Spanish values are higher in seagrasses meadows than the European values (606 €/ha) for the same ecosystems. Similarly, comparing with Wedding's et al. (2021) market price, a minimum price of 993 $/ha and a maximum price of 3,221 $/ha is provided, nevertheless, the social price increases considerably ranging between 1,763 $/ha and 5,588 $/ha. This variability of results could be related with different aspects such as the reference price used in each study, the amount of carbon observed in Mediterranean seagrasses that is very high in comparison with other areas, or the accuracy of each study, in which seagrass density generalization can lead overestimation of carbon content.

Based on the scenario analysis our results reveal that by 2050 the coastal blue carbon in the non-sustainable scenario would expect a potential loss of 20,000 million €, with a loss of 6,000 million € in the business-as-usual scenario and 500 million € in the sustainable scenario. These estimations were done by using a social price approach, following previous studies published on the topic of economic valuation of carbon sequestration and storage of coastal blue carbon (Beaumont et al., 2014; Jerath et al., 2016; Luisettiet al., 2013). The social price considers the change in the discounted value of economic welfare from an additional unit of CO_2 emissions (Nordhaus, 2017). The application of the social price assumes that the loss of one hectare of ecosystem will no longer provide the carbon sequestration service leading to an economic damage. The social price calculation integrates with some uncertainties as the usual models used to get it fail to consider significant risks and costs related to climate change, biodiversity losses or labor productivity impacts, among others (Stiglitz et al., 2017). All these limitations anticipate the final estimates for social price results being underestimated. In the literature, different social values that range between $5 and $312 each t CO_2 eq. are found (Luisetti et al., 2013). In this study we selected the social price of the European Investment Bank (World Bank, 2018) with a value of 38€/t CO_2 eq. in 2018 and increasing annually in real terms to 121€/t CO_2 eq. by 2050. Moreover, we addressed a single ES provided by marine phanerogams but quantifying the rest of ES would widely increase the economic value of seagrass.

The economic value of carbon storage estimated in this study is just a component of the total economic value of coastal ecosystems. Besides their role as natural carbon sinks, the blue carbon ecosystems are suppliers of other vital services as shown for example in Reddy et al., (2016) for the coastal protection service. Therefore, the values estimated in this study must be used with caution and in reference to appropriate contexts. Thus, the economic and ecological value of these ecosystems should be considered into decision-making for conservation and can be strategically used to help Spain be compliant with climate agreements.

4.3. Protected areas and future scenarios for conservation

Spanish seagrass meadows presently cover an area of 148,674 ha. The non-sustainable scenario predicts the virtual disappearance of the ecosystems, and 132,663 hectares are lost when a heavy increase in anthropogenic pressures is applied to the model. In the business-as-usual scenario (which we consider to be the most realistic), the total seagrass surface is reduced by 23% (34,403 ha), which roughly equals the total surface loss that occurred in European waters in the last half of the 20th century (de los Santos et al., 2019). This surface reduction is attributed to impacts such as coastal destruction (Medina et al., 2001, González-Correa et al., 2007), water quality degradation (Díaz-Almela and Duarte 2008), waste discharge, and mechanical damage (González-Correa et al., 2005). Other stressors include salinity increases from water desalination facilities that induce diebacks of the plants (Fernández-Torquemada and Sánchez-Lizaso, 2005), while the proliferation of invasive algal species compete for space and light (Ballesteros, 2007). The regression of the seagrass meadows by the impact of these threats could be irreversible in some areas given the extremely slow growth rate of some of the species (i.e., *P. oceanica,* 1–6 cm yr^{-1}) (Díaz-Almela and Duarte, 2008). Thus, the ability of ecosystems to provide the desired ES can be in jeopardy. However, the best scenario shows that when the right management measurements are implemented, the reduction is much lower, and the surface loss in the sustainable scenario is 1,175 hectares. Recovery is also possible when these measures are implemented over time and space, as shown by the trend found in European waters after the enactment of the EU Habitats Directive that strictly protects *P. oceanica* meadows, and the EU WFD (Water Framework Directive) that clearly allows the natural recovery of the other species that are especially sensitive to water quality (de los Santos et al., 2019).

The results of the different future scenarios highlight the need for urgent and specific management measures to protect the seagrass meadows and their function as ES providers. The results of the business-as-usual scenario show a generalized reduction in the stored amount of carbon in all the demarcations except in the Canary Islands region. The loss of more than 50,000,000 t of CO_2 eq. in the Western Mediterranean Sea demarcation is especially dramatic, demonstrating a reduction of almost 25% of the currently stored carbon and five times the total carbon presently stored in all the other demarcations combined. If we look at the results of the worst scenario in that same demarcation, the loss of stored carbon reaches 81% of the present stored quantity. Equally worrying is the situation in the Alboran Sea demarcation, where every seagrass meadow virtually disappears in the non-sustainable scenario with losses reaching nearly 30% of the stored carbon in the business-as-usual scenario.

However, in both cases, the sustainable scenario indicates that a better situation can be achieved if managing actions greatly reduce the intensity of the present pressures, especially those specifically threatening *P. oceanica* because it is the most predominant species in both areas. *P. oceanica* meadows are particularly sensitive to water and sediment eutrophication, disruption of the sedimentation/erosion balance (caused by reduced sediment transported by rivers and coastline transformation), direct damage by trawling or anchoring, salinity increase, and proliferation of invasive algal species (Díaz-Almela and Duarte, 2008). Thus, any successful conservation plan should address these threats. In both demarcations, most of the stored carbon is included in the Natura 2000 sites, and the marine protected areas (MPAs) successfully protected the seagrass meadows in the sustainable scenario and were moderately effective in the business-as-usual scenario. These results demonstrate that MPAs are a good conservation measure for *P. oceanica* meadows but need to coincide with other strategies focusing on the threats originating outside the Natura 2000 sites.

Future scenarios in the South Atlantic Spanish Coast demarcation are pessimistic and demonstrate an abrupt reduction in stored carbon; the business-as-usual and non-sustainable scenarios are similar with both predicting a 72% loss from the present values, and the sustainable scenario is not sustainable, predicting a 68% loss. The seagrass species found in the South Atlantic Spanish coast are smaller and respond differently than *P. oceanica* to human impacts and stressors. In this demarcation, 91% of the stored carbon is included in the Natura 2000 sites, but the protection provided by MPAs seems to be unable to stop the loss of most of the storage capacity in any of the proposed scenarios. In this demarcation, seagrasses are especially sensitive to stressors originating from outside the boundaries of the MPAs such as pollution and water temperature and quality, and the presence and management of the Natura 2000 sites need to coordinate with other measurements that tackle these factors.

The present and future scenarios of the Canary Islands are the only ones that show no change in their carbon storage values both inside and outside the Natura 2000 sites. The steep slope of the continental shelf inhibits the growth of extensive meadows of *P. oceanica*, and only two seagrasses are currently inhabiting the islands: *C. nodosa* and *H. decipiens* (Pavón-Salas et al., 2000). *C. nodosa* is the most significant seagrass in the shallow coastal waters of the Canary Islands, and their meadows have been subjected to an overall deterioration in the last two decades (Fabbri et al., 2015). In our study, no changes were found, these results are explained by the interaction of ecological and methodological factors because the pressure map does not overlap with the geographical distribution of these species, so the mapped pressures are outside the meadow coverage. In addition, *H. decipiens* is a seagrass that occurs mostly in the tropics globally, including the Canary Islands. It is found in deeper waters that protect it from major threats (Short et al., 2010). Indeed, the different habitat preferences of the five studied seagrasses and their sensitivity to human impacts and stressors provide insight into the results of the scenarios.

Beyond research, it is crucial the implementation of a legal framework that includes restoration of coastal ecosystems and best-management practices to protect them, supporting its preservation and enhancing of blue carbon stocks as a tool to mitigate CO_2 emissions and, hence climate change. The total carbon stored in Spanish seagrass meadows is equal to 72% of the total GHG emitted by the country in 2019, but annual sequestered carbon by these ecosystems (229,521 t CO_2 eq. y^{-1}) only amounts for 0.61% of the net absorptions of the country during the same time period (MITECO, 2021), this highlights the relative importance of the stocks of carbon in seagrasses soils compared to the impact of annual accumulation rates, and how conservation efforts should focus on protecting the seagrass patches that are already storing a vast amount of carbon avoiding sifting to other habitats/uses as pointed other studies in mangroves such as Adi et al. (2020) in Indonesia. The state and trend of blue carbon ecosystems in Spain have experienced historical area losses and consequently in their carbon sequestration and storage capacity. If Spain fails to protect these ecosystems there will be future losses due to an increase in human pressures (such as contamination and habitat alteration) as also demonstrated in this study.

Our results enhance the importance of MPAs (Tonin, 2018), particularly in Natura 2000 sites, which contain SACs and SPAs, in the delivery of carbon storage by seagrass meadows (i.e., 82% of the total coastal blue carbon of Spain) in the present and future scenarios, especially for the Alboran Sea and Western Mediterranean Sea demarcations (Fig. 5). All the demarcations, except for the Canary Islands, exhibited the same decreasing trend of the stored carbon in the seagrass under the business-as-usual and non-sustainable scenarios, showing a dramatic decline in coverage near the extinction rate outside the MPAs. Among the protected seagrass meadows, this trend is especially relevant to the contribution of the Mediterranean patches of *P. oceanica*, a species identified as a 1120 priority habitat type for conservation in the Habitats Directive of the European Union (Dir92/43/CEE). Therefore, the effect of the protection of this management strategy is derived as an improvement in the conservation status of the *P. oceanica* meadows inside the Natura 2000 sites.

Thus, an urgent review of current management plans for fisheries and MPAs is needed to promote active conservation and protection actions outside the Natura 2000 Network limits (Rouillard et al., 2017). The current regulations consider the linkages from human activities to pressures and their impacts on the ecosystem components summarized in the second appendix of the Spanish Marine Strategy (MITECO, 2019b). However, there are still many pressures that are not yet well understood and inventoried, and they should be considered in other planning levels and processes of decision making in maritime policy.

The conservation of these habitats could be possible only if active and coordinated management actions are performed at all levels of maritime and continental water policies. The EU Marine Strategy (https://ec.europa.eu/environment/marine/index_en.htm) aims to achieve a good environmental status of the EU's marine waters by 2021. In addition, the EU Water Framework Directive (https://ec.europa.eu/environment/water/water-framework/index_en.html) is focused on a similar objective to achieve a good environmental status of the EÚs continental and transitional waters. To achieve this goal, coordination among the different environmental agencies is necessary at the national and regional levels to implement the EU regulations and support them with an economical budget that guarantees the design of protection management actions (Rouillard et al., 2018).

The management actions proposed for the protection and conservation of seagrass meadows in the different MPAs are oriented to mitigate the impact of the threats explained above and, on many occasions, deal with the necessary actions on the continents (i.e., diminish inputs of nitrates in the crops) or on the coast (i.e., control and environmental evaluation studies of works). In the maritime environment, the most common protective measures are the installation of artificial reefs in MPAs and seagrass-friendly moorings for boats in order to reduce the erosive pressure of otter-trawling and free anchoring in shallow meadows. A design of a monitoring network for measuring the status and trends of the meadows is needed (Bianchi et al., 2008; Díaz-Almela and Duarte, 2008).

Another relevant issue is whether the protected marine surface under the strong protection level (i.e., areas that are either no-go, no-take, or no-fishing areas) in the MPAs is enough to protect the marine biodiversity in the long term. We only have three examples of this kind of strong protection management in the Natura 2000 sites included in this study: Cap Creus (Purroy et al., 2014), Medes Islands (Martín et al., 2012), and Tabarca Island. In some regions, such as the Mediterranean Sea, only 0.15% of the total area is covered by this type of protection, which is far from the target of 2% agreed in the Tangier Declaration (MedPAN, 2019). In this sense, the realization of studies of mapping and assessing the regulation of ES as carbon storage and sequestration provides useful results to be considered in the development of management guidelines for MPAs. These results can be used to track the ES being launched from existing MPAs or derived from existing biodiversity protection or incorporate the ES into protected area planning.

5. Conclusions

The amount of carbon stored in the marine phanerogams of Spain needs to be managed to avoid future scenarios in which the loss of carbon could lead to an increase in climate change and a loss of human well-being. Moreover, separate strategies must be applied based on the different marine demarcations due to the distinct characteristics of the Atlantic and Mediterranean areas. Additionally, 82% of coastal blue carbon in marine phanerogams is in the Natura 2000 area, so that specific strategies in the Natura 2000 Network must be applied to improve and preserve this ES. Nevertheless, the future scenarios demonstrate that the Natura 2000 Network is not enough to conserve marine phanerogams, so specific management strategies will need to be applied. Further, mapping and assessing the ES and future scenarios provide highly relevant information for management purposes, and it is a powerful tool to communicate conflicts between pressures and human well-being. Policy makers and Natura 2000 managers can use this model to improve seagrass management and to generate more accurate schemes in which economic valuation can help to attract founding opportunities. However, we conclude that marine seagrass needs to be assessed from multiple perspectives, including social benefits and cultural ES to better quantify the whole contributions of these ecosystems.

This research provides the first application of the InVEST Coastal Blue Carbon model for management purposes, and this methodology could be extrapolated to other countries, especially in the Mediterranean Sea, where marine phanerogams are highly relevant ecosystems.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2021.101397.

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