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# National blue carbon ecosystem services assessment: current state and future perspectives

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# 1 National blue carbon ecosystem services assessment: current state and future perspectives

## 2 Abstract:

3 Coastal and marine ecosystems supply multiple services in which human well-being is  
4 highly dependent. However, high-resolution spatial distribution studies of marine  
5 ecosystem services are scarce, even if it is known that this information is needed to better  
6 manage and conserve these ecosystems. With the aim of filling this gap, in this study we  
7 have: (1) mapped and assessed the current capacity of marine phanerogams (*Posidonia*  
8 *oceanica*, *Cymodocea nodosa*, *Zostera noltii*, *Zostera marina*, and *Halophila decipiens*)  
9 to store and sequester blue carbon in Spain; (2) mapped and assessed the future capacity  
10 of marine phanerogams to store and sequester blue carbon under three plausible futures;  
11 and (3) assess the economic implications of these scenarios. Our results are based on the  
12 information provided by the InVEST Blue Carbon model and exhibit high spatial  
13 resolution (100 m/pixel) of carbon stored in marine phanerogams. We found that 82% of  
14 carbon storage and sequestration by marine phanerogams is currently managed within  
15 Natura 2000 areas. However, results from the modeled future scenarios indicate a  
16 constant decrease in the amount of carbon stored in these ecosystems by 2050 (24% lost  
17 in the business-as-usual scenario). The economic impact of these losses is equivalent to  
18 1.6% of the Spanish GDP. Finally, we consider that a transitional management change is  
19 needed to conserve marine phanerogams in Spain, and we discuss the importance of the  
20 Natura 2000 Network in managing marine ecosystems and their services in the near  
21 future.

22 Keywords: mapping ecosystem services, marine ecosystem services, InVEST, protected  
23 areas, future scenarios

## 24 1. Introduction

25 Marine biodiversity loss is increasingly impairing the ocean's capacity to provide  
26 fundamental ecosystem services (ES) for human well-being (Worm et al., 2006). The loss  
27 of coastal and marine ecosystems will be further increased by climate change (Short and  
28 Neckles, 1999; Harley et al., 2006; Koch et al., 2013) and, ironically, marine ecosystems  
29 play a fundamental role in the carbon storage and sequestration processes that contribute  
30 to climate change mitigation (Duarte et al., 2013; Marbá et al., 2014). Several studies  
31 have indicated that seagrass habitats, the main contributor to this carbon storage, are  
32 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 services such as climate regulation, air purification, disturbance prevention or attenuation, and cultural services, such as leisure, recreation, tourism, cultural heritage, and diversity, 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 submersed 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 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 tropical and subtropical 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 fisheries, 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., 2016).

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). 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 first country that contributes the most to the network of protected areas in the European Union, considering marine and terrestrial areas (<https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer>).

Additionally, the highly accurate available spatial data of marine phanerogams and the quantitative results from the project LIFE BLUE NATURA (Mateo et al., 2018) enable the fulfillment of the three objectives of this research: (1) mapping and quantifying the present carbon storage and sequestration in marine phanerogams in Spain, (2) mapping and quantifying carbon storage and sequestration in three future scenarios, and (3) analyzing the contributions of the Natura 2000 protected areas in comparison with the rest of marine demarcations to protect carbon storage and sequestration currently and in the future scenarios.

## 2. Methods

### 2.1 Study area

We studied four of the five marine demarcations in Spain, which comprise 758,109 km<sup>2</sup>: (1) South Atlantic Spanish Coast (2%), (2) Canary Islands (64%), (3) Alboran Sea (3%), and (4) Western Mediterranean Sea (31%) (Fig. 1). Spain is the country with the second most protected marine area in the EU with 84,405 km<sup>2</sup>, which is 19% of the total protected marine areas in the EU (<https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer>). 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%). 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. 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).

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

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.

## 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). InVEST has provided successful results when used for the assessment of blue carbon storage in different coastal wetlands (Li et al., 2018) and mangroves (Sudirman et al., 2018). We considered carbon stored as the total amount of CO<sub>2</sub> eq. that contains the ecosystem and carbon sequestration as the CO<sub>2</sub> 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 data of ecosystems that store and sequester carbon, (2) net carbon contained in the soil, biomass, and dead matter in t CO<sub>2</sub>/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 value of carbon from each species, we calculated the average value of all the plots provided in Mateo et al. (2018) for the same species (Eq<sub>1</sub>). 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<sub>2</sub>). The total carbon storage was estimated by summing the carbon in the aboveground living/dead biomass and carbon in the belowground living/dead biomass.

$$\text{Eq}_1. (\text{CO}_2 \text{ eq/ha ssp1}_a + \text{CO}_2 \text{ eq/ha ssp1}_b + \dots \text{CO}_2 \text{ eq/ha ssp1}_n) / n$$

$$\text{Eq}_2. \text{CO}_2 \text{ eq/ha ssp1} + \text{CO}_2 \text{ eq/ha ssp2})/2$$

To estimate the loss of carbon storage in future scenarios, we used the data of accumulated pressures in the marine demarcations of Spain provided by the Spanish Ministry (MITECO, 2019a; MITECO, 2019b). 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<sub>2</sub> 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.

*Table 2. Carbon stocks data based in Mateo et al., (2018) and their association with marine phanerogams atlas of Spain (Ruiz et al., 2015). NS: Non seagrasses, CN: Cymodocea nodosa, CNZN: Association of Cymodocea nodosa and Zostera noltii, DdPO: Dead Posidonia oceanica, PO: Posidonia oceanica, ZN: Zostera noltii, DPO: Degraded Posidonia oceanica, POR: Posidonia oceanica in Regression, POCN: association of Posidonia oceanica and Cymodocea nodosa, POOCR: association of Posidonia oceanica and Caulerpa racemosa, CR: Caulerpa racemosa, HD: Halophila decipiens, CNCR: association of Cymodocea nodosa and Caulerpa racemosa, ZM: Zostera marina*

### 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 (Gantolier et al., 2010; 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 5% of *Posidonia oceanica* meadows, see Marbá 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.

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, MITECO, 2019b), 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 (Figure 2). 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.

*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.*

*Figure 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 (Fig. 2 A and B), few cells exceed the thresholds (purple cells), while under the non-sustainable scenario (Fig. 2C), most of the cells exceed the limit, leading to a major destruction of existing seagrass (green cells).*

The carbon accumulation between the present and future was estimated by summing the total accumulation per hectare per year. To estimate the economic value of the carbon stored in the marine phanerogams of Spain, we used the social price of the European Investment Bank (EIB; World Bank, 2018). The central EIB price for carbon emissions in 2018 is 38€/t CO<sub>2</sub> eq., increasing annually in real 2016 terms to 121€/t CO<sub>2</sub> eq. by 2050. This is the most recent value available when writing this paper, and we are aware of the great variability of this price over time.

### 3 Results

#### 3.1 Spatial distribution of coastal blue carbon

The Mediterranean and Atlantic areas clearly contrast the average value of coastal blue carbon per hectare. The Western Mediterranean demarcation stores 216,127,783 tonnes of CO<sub>2</sub> eq. (95% of total coastal blue carbon in Spain) (Fig. 2). The Alboran Sea is the



second marine demarcation with a total of 7,355,015 tonnes of CO<sub>2</sub> eq. (3% of the total in Spain). Canary Islands demarcation is the next highest with a total of 3,173,713 tonnes of CO<sub>2</sub> eq. (1.3% of the total in Spain). Finally, the South Atlantic Spanish Coast demarcation only supplies 556,284 tonnes of CO<sub>2</sub> eq. (0.7 %) because it is the smallest marine demarcation, and the most frequent marine seagrass is the small-sized *C. nodosa*. The average value per hectare containing marine phanerogams in each marine demarcation is presented in Figure 3E. The western Mediterranean Sea marine demarcation clearly presents the highest average value of 1,659 CO<sub>2</sub> eq. ha<sup>-1</sup> (std 408.07) because it is the one exhibiting the largest coverage of *P. oceanica*.

Figure 3. Total and average carbon stored per marine demarcation in Spain.

The most significant areas for coastal blue carbon are in the Western Mediterranean demarcation (East of Spain; Fig. 4). We found multiple sites (117,889 hectares) with more than 1,000 CO<sub>2</sub> eq. ha<sup>-1</sup>, similar to the Balearic Islands (Fig. 4A) or Cape of la Nao (Fig. 4B). In the Alboran Sea demarcation, we also found different areas (3,787 hectares) with more than 1,000 tonnes of CO<sub>2</sub> eq. ha<sup>-1</sup>, similar to Cape Gata (Fig. 4C) and Cape Sacratif (Fig. 4D). The South Atlantic and Canary Island demarcations do not present any hectares with more than 1,000 CO<sub>2</sub> 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<sub>2</sub> eq. (Fig 4E, F, G, and H).

Figure 4. 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.

### 3.2 Future scenarios for coastal blue carbon

Except for the Canary Islands, all the marine demarcations of Spain experienced an substantial reduction in the coastal blue carbon under the three proposed future scenarios (Fig. 5). The business-as-usual scenario shows lower values than the sustainable scenario, while the non-sustainable scenario exhibits higher carbon loss.

Figure 5. 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.

The South Atlantic Spanish Coast demarcation presents an important decrease in coastal blue carbon under the three scenarios (Fig. 5A). This area decreased from 556,284 tonnes

of CO<sub>2</sub> 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. 5B). We observed an increase from 3,173,713 tonnes of CO<sub>2</sub> eq. in the present to 3,266,530 in the business-as-usual scenario, 3,270,426 in the sustainable scenario, 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. 5C). We observed a decrease from 7,355,015 tonnes of CO<sub>2</sub> 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. 5D). Our results indicate a decrease from 216,127,783 tonnes of CO<sub>2</sub> 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 Figure 6. This area presents the most pressured zones covered by *P. oceanica* meadows. Two sites are shown in the Western Mediterranean Sea demarcation (Fig. 6A, B, C, and D) and the Alboran Sea demarcation (Fig. 6E, 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.

*Figure 6. 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.*

### 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 Figure 7. 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<sub>2</sub> eq.) is included in the Natura 2000 sites. The Alboran Sea demarcation exhibits 90% of the total CO<sub>2</sub> eq. stored in marine phanerogams inside the Natura 2000 sites, which supposes 6,613,452 tonnes of CO<sub>2</sub> eq. Marine demarcations in the Atlantic Ocean (Fig. 7A, B) exhibit similar values regarding the proportion inside the Natura 2000 area.

*Figure 7. Carbon stored inside and outside Natura 2000 in tonnes of CO<sub>2</sub> eq. in present and future scenarios per marine demarcation. Percentages represent the proportion of the total per marine demarcation.*

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. 7A). The Canary Islands demarcation did not show significant changes inside and outside the Natura 2000 sites (Fig. 6B). 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. 6C). 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.

The monetary value of the total coastal blue carbon currently stored in Spain is 8,634 million € (227,000,000 tonnes of CO<sub>2</sub> 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<sub>2</sub> 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 € in the business-as-usual scenario and 500 million € in the sustainable scenario.

## 4 Discussion

### 4.1 The importance of marine phanerogams for carbon sequestration

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 (Pettersson and Lubchenko 1997; Nordlum and Gullström, 2013; Nordlum et al., 2018). However, considering the current scenario of climate change, three of these ES, related to the physical structure of the ecosystem, are considered of special importance: their ability to act as carbon sinks (sequestering 20% of global carbon despite occupying just 0.1% of the ocean surface (Duarte et al., 2005)), their capacity to reduce erosion, and their role as coastal protectors from disturbances associated with the rise in sea level (Ondiviela et al., 2014). In this study, we assessed the capacity to sequester carbon in marine phanerogams, but the protection of these ecosystems would widely improve the other ES. Seagrasses form thick belowground organic deposits from the accumulation of rhizome and root debris. These deposits can be several meters thick and persist for thousands of years (Mateo et al., 1997; Serrano et al., 2012; Monnier et al., 2020).

The canopy is also vital for carbon sequestration because it acts as a filter that retains particles suspended in the water column and traps them in the sediments. Moreover, the canopy significantly reduces the current velocity and wave intensity, making the sedimentation process more efficient and long-lasting (Duarte et al., 2013a; Duarte et al., 2013b). The filtering process also increases water clarity, enabling the plants to grow and reproduce under improved conditions (Van der Heide et al., 2007).

Some preliminary estimates suggest that the size of the carbon sink associated with European seagrass meadows could be approximately 7.5 Gt CO<sub>2</sub>/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; Pendelton et al., 2012; Duarte et al., 2013b).

In this study, 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 phanerogam habitat) and enhancing desirable strategies (i.e., conserving hotspots of carbon sequestration areas under Natura 2000 sites to assure).

Carbon stock differences among Spanish marine demarcations are a consequence of three combined factors: total surface occupied by seagrass meadows, specific composition of those meadows, and 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, Russel et al., 2013; Ondiviela et al., 2014).

However, a set of limitations to this strategy has been identified (Duarte et al., 2013a): (1) a lack of accurate estimates of seagrass cover and a need for better carbon stock and sequestration estimates over time and space, (2) a better explanation of the fate of the carbon exported by seagrass is necessary; (3) more knowledge is needed regarding the high variability of the seagrass carbon sink capacity, (4) improved models for potential areas suitable for new and growing of already existing meadows, and (6) a better assessment of the impacts of seagrass loss on the fate of the carbon stocks.

#### 4.2 Protected areas and future scenarios for conservation

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<sub>2</sub> 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. *C. nodosa* both forms single species meadows and occurs with *P. oceanica* (it is out-competed by this species) in sandy habitats in the Mediterranean and eastern Atlantic (Short et al., 2007). It is especially sensitive to water pollution and turbidity (OSPAR Commission, 2010). In addition, a considerable threat to this species in the Mediterranean is the competition with exotic species, such as *C. taxifolia* and *C. racemosa* (Short et al., 2010a). *Z. noltii* is a fast-growing species with a

wide geographical range of distribution: northern and eastern Atlantic, and the Baltic, Mediterranean, Black, and Caspian Seas. Due to its small size, it is extremely sensitive to burial and erosion (4 to 8 cm) and to eutrophication, shading, and competition with *C. racemosa* (Short et al., 2010b). 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, and the presence and management of the Natura 2000 sites need to coordinate with other measurements that tackle water pollution and quality.

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 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., 2010c). 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. The scenario 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.

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. 7). 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 ([http://ec.europa.eu/environment/water/marine/index\\_en.htm](http://ec.europa.eu/environment/water/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](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 EU's 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 sequestration and storage 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.

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 20<sup>th</sup> century (de los Santos et al., 2019). This surface reduction is attributed to impacts as such 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<sup>-1</sup>) (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

for management purposes, and it is a powerful tool to communicate conflicts between pressures and human well-being.

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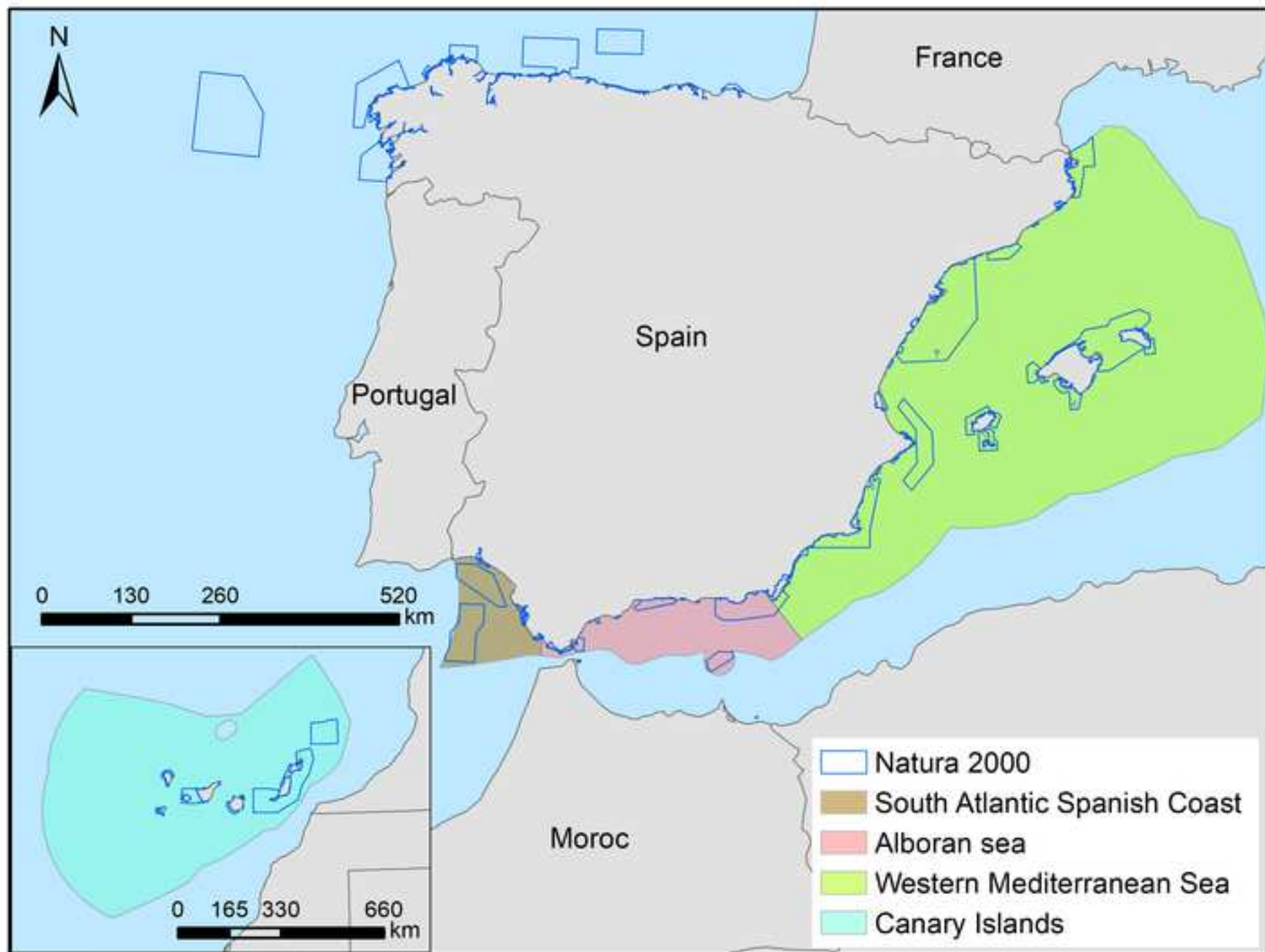
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Figure1

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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).

#### 4.3 Caveats and limitations

As mentioned above, we consider our approach to be a substantial improvement to estimate and assess marine carbon sequestration services at the national level. However, we acknowledge that the use of this approach has certain limitations. First, the approach for developing future scenarios focuses on identifying the separate effects of individual drivers instead of the synergetic effect of multiple drivers (Hauck et al., 2015). Second, the approach could be improved by including new components of analysis (i.e., human benefits that estimate values beyond its monetary valuation) for the full application potential of the ES framework (de Groot et al., 2012). Third, the level of resolution of the indicators used at the national scale could be improved, which will require fine-tuning the models and access to better data sources at the regional level (i.e., individual marine demarcation areas). Fourth, the transition from 2020 to 2050 in the InVEST model requires data that show the changes occurring in the different parts presented in Table 3. This means that one pressure can alter the carbon in the aboveground living/dead biomass but not in carbon below living/dead biomass. Finally, the effect of alien species in our study has been considered in one of the 11 pressures used in the scenarios; consequently, areas that currently present *C. racemosa* will disappear in the future scenarios. This simplification of the effects of alien species and other pressures needs to be improved in future studies because the effects of these pressures are not static but include the progressive invasion of marine phanerogam ecosystems. All these caveats highlight the limitations of the model and the need for improvement in future versions.

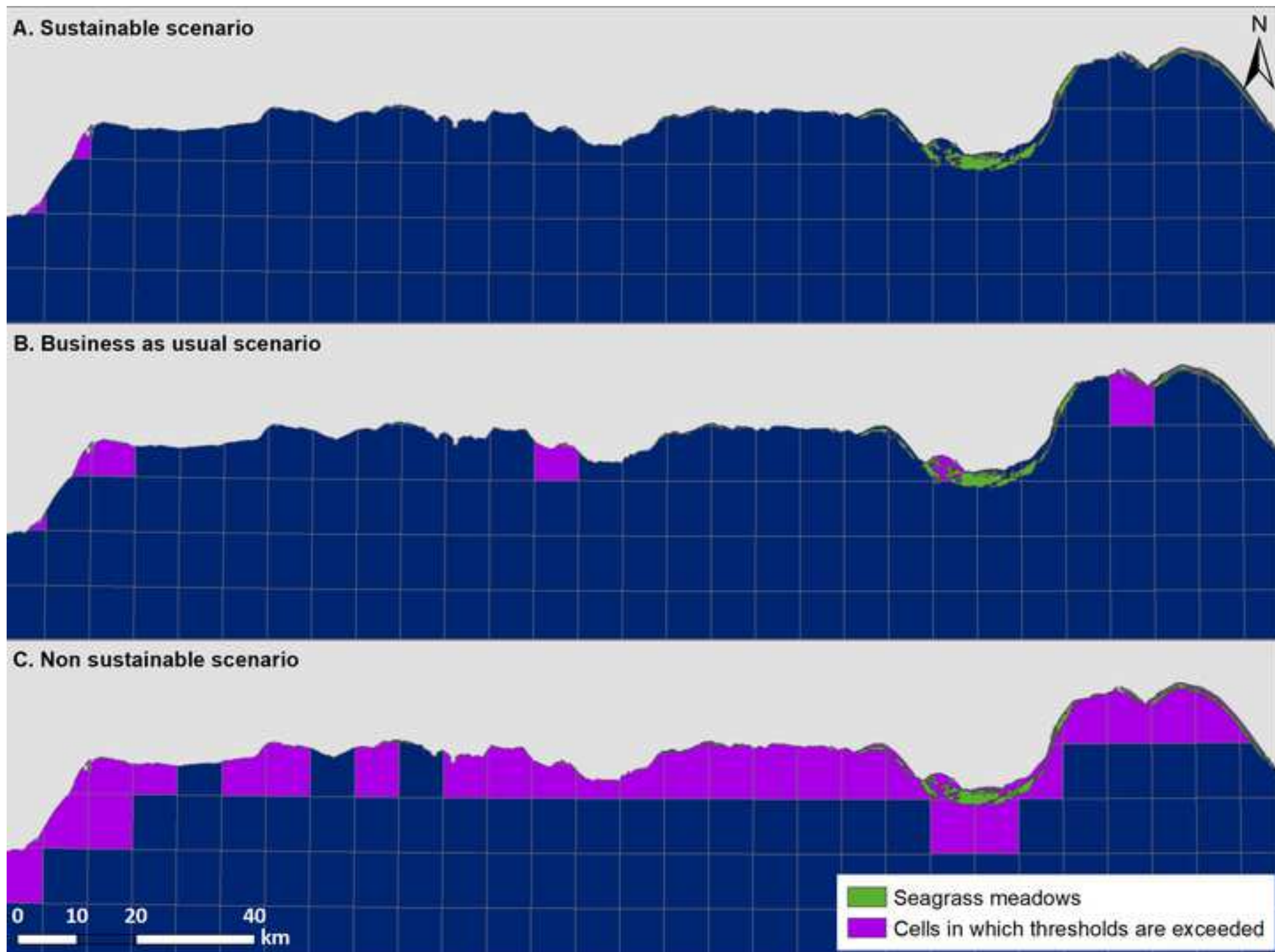
The main data sources used in this research were obtained from official and contrasting sources, such as Spanish authorities (Atlas of Marine phanerogams and pressures) or projects in which field data were obtained (LIFE BLUE NATURA). Nevertheless, some caveats and limitations must be acknowledged regarding the data processing. First, the Atlas of marine phanerogams of Spain (Ruiz et al., 2015) presents the data for species that occur in association with other species, but the proportion of each species is not considered. Thus, the estimation of carbon storage in these associations has been

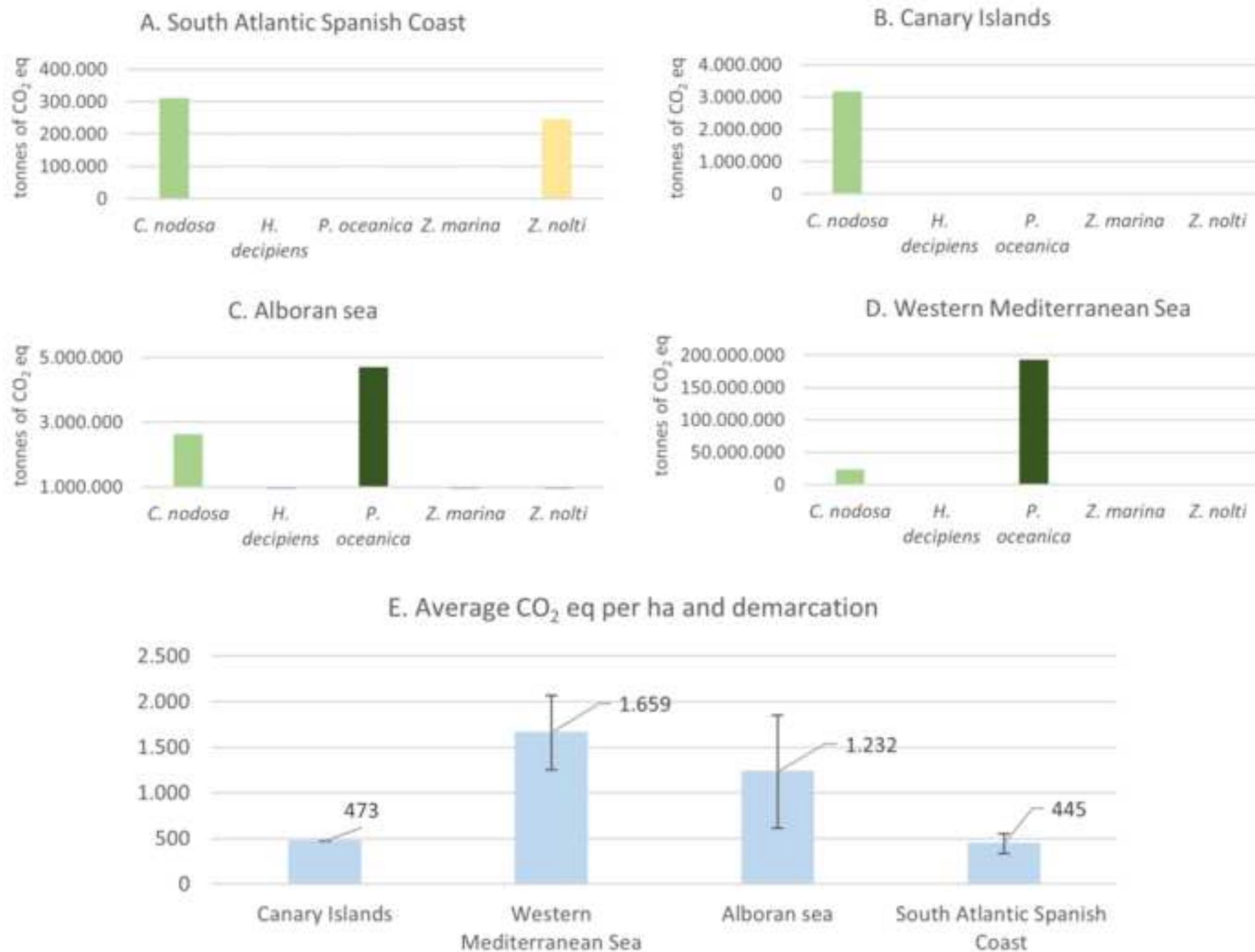
generalized, increasing the uncertainty. Moreover, this database is not homogeneous enough regarding the way data were collected. In this sense, the different regions of Spain collected data using a variety of methods, which suggests that accuracy levels will differ.

Second, we used data from the field estimations of the Andalusian project that provides carbon storage and sequestration values of marine phanerogams in the Mediterranean Sea. We assumed that the same species would store the same carbon in other areas, but different conditions could lead to differences in the amount of carbon stored, which has occurred in Australia due to the carbon input coming from coastal forests (Lavery et al., 2013; Serrano et al., 2019). Moreover, we used the average CO<sub>2</sub> eq. of plots of the same species provided in Mateo et al. (2018), which slightly increases uncertainty in some species (i.e., *C. nodosa* presents values between 104 and 1,224 tonnes of CO<sub>2</sub> eq h<sup>-1</sup>). Nevertheless, because 98% of the coastal blue carbon is in Mediterranean Sea marine demarcations, this generalization does not provoke significant caveats. Further, regarding the pressures, more studies concerning how specific pressures could affect marine seagrass are needed (Pergent et al., 2014). In this research, we considered 11 pressures with little data regarding how they provoke the destruction of marine phanerogams, especially concerning the thresholds in which those pressures could be irreversible. Finally, we have assessed only one ES related to marine phanerogams but multiple values should be included in future research for enhance the management and sustainable use of coastal and marine ES (Chakraborty et al., 2020).

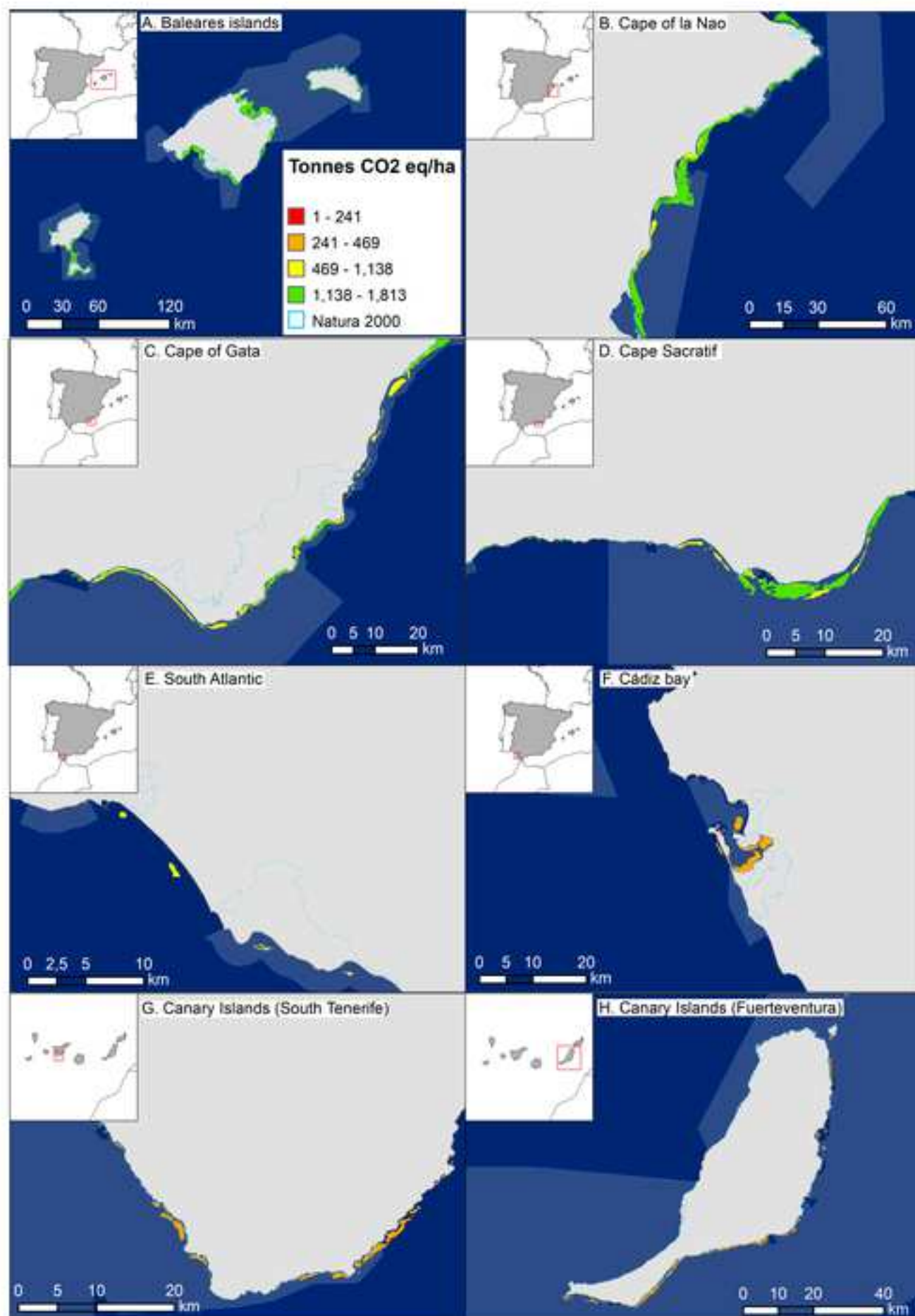
## 5 Conclusions

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 wellbeing. 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. Finally, mapping and assessing the ES and future scenarios provide highly relevant information

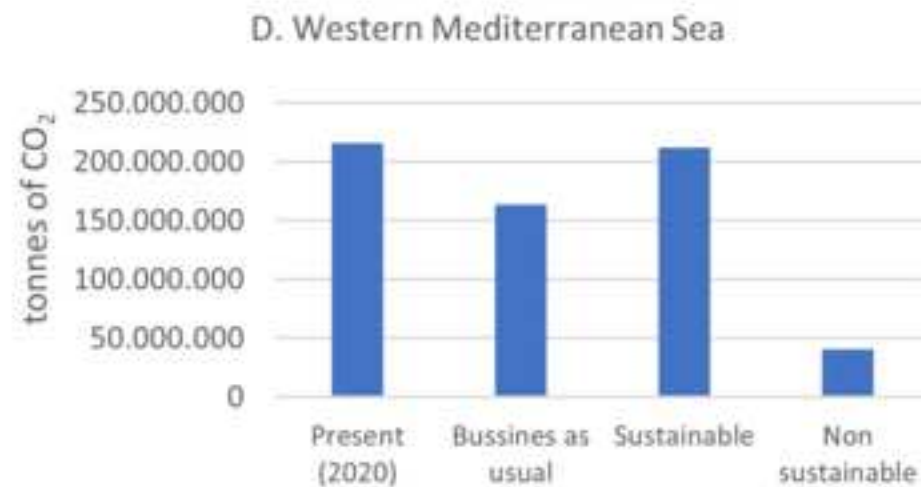
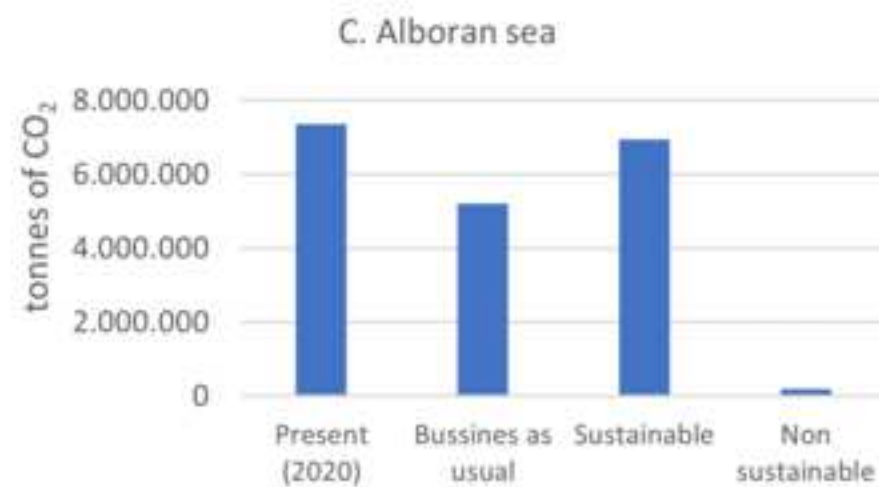
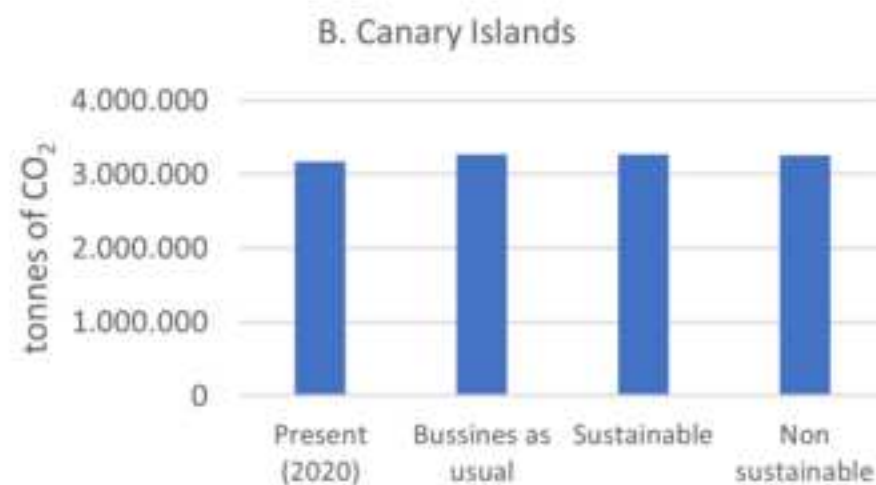
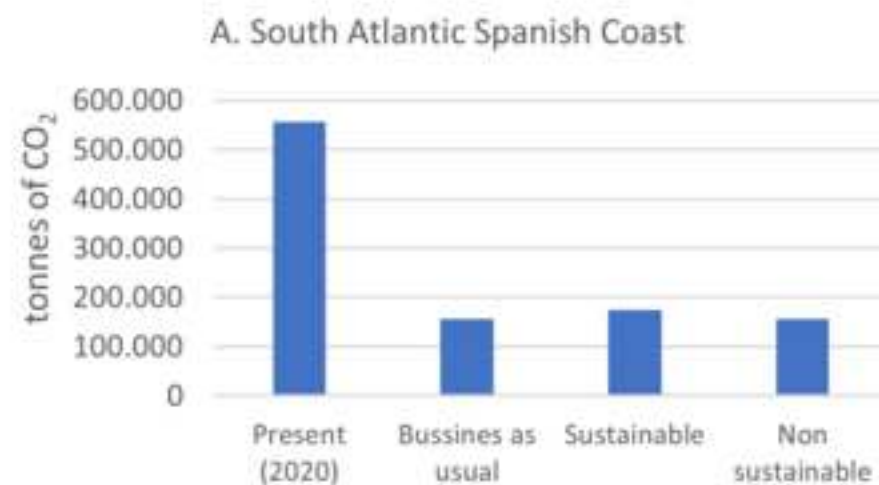


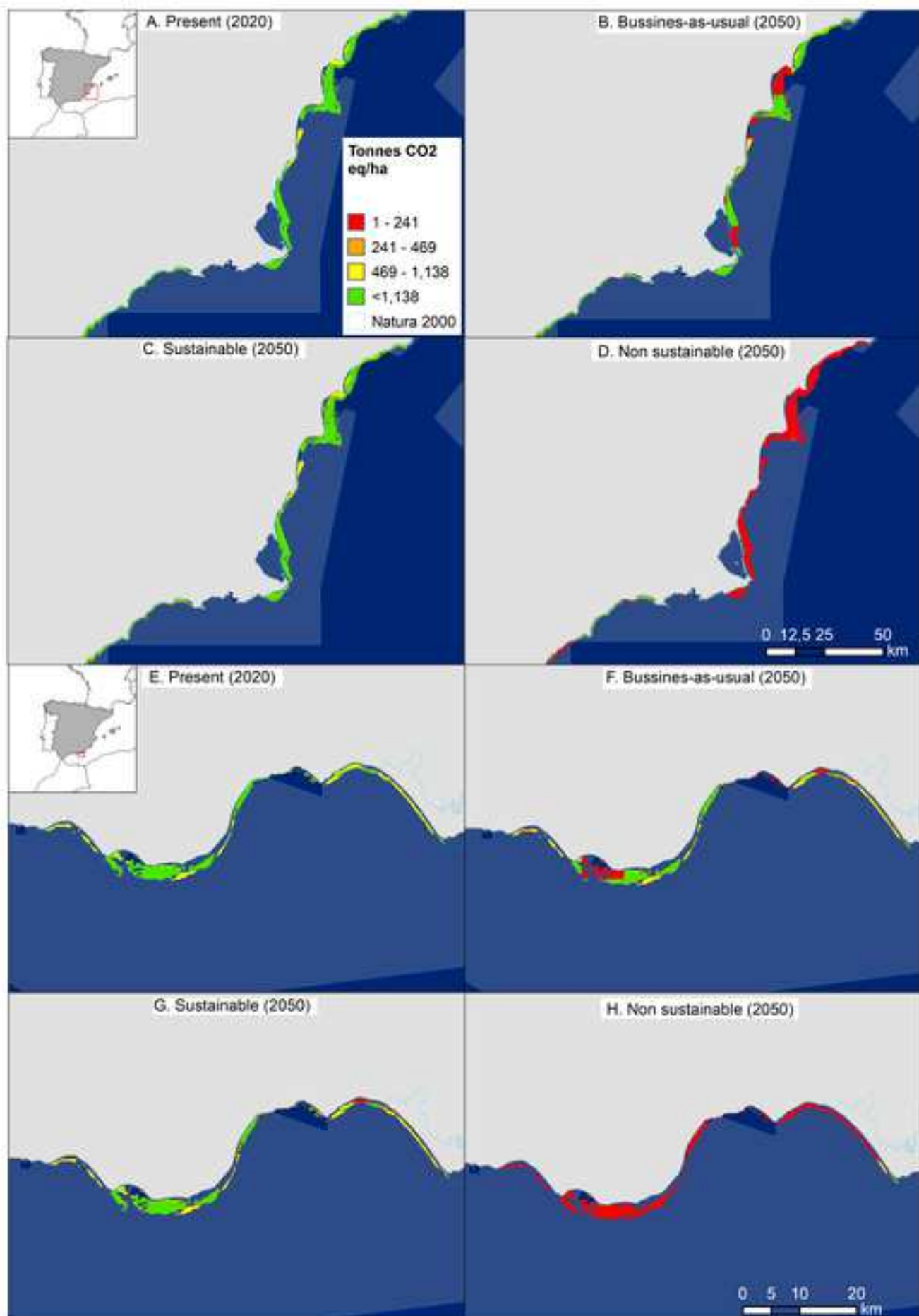


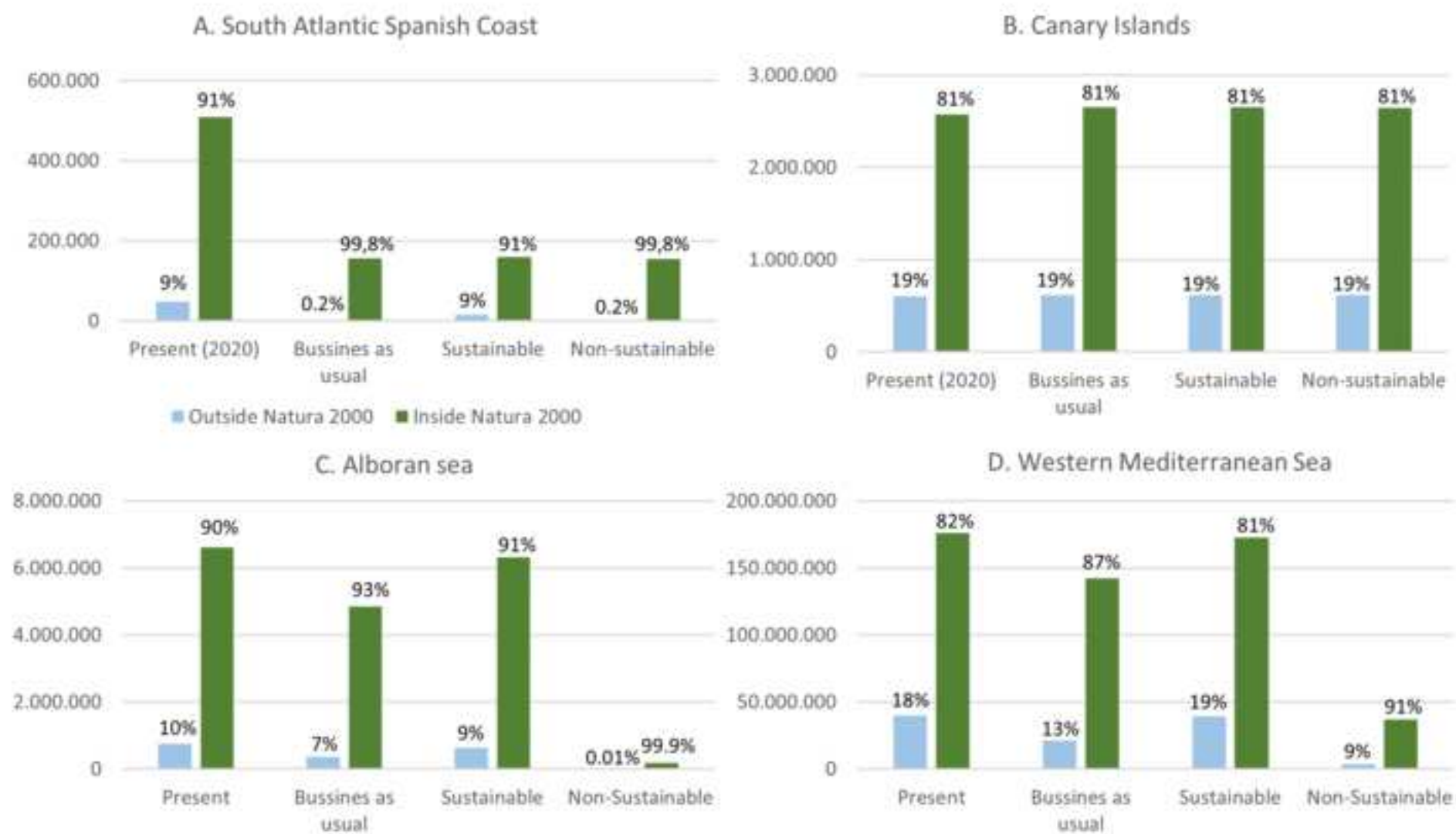












Marine demarcation	Total surface (km <sup>2</sup> )	Total 2000 surface (km <sup>2</sup> )	Natura surface	Number of Natura 2000 sites	Spp.	Surface (ha)
South Atlantic Spanish Coast	14,070	5,579		SCI: 7	<i>C. nodosa</i>	1,151
				SPA: 7	<i>Z. noltii</i>	912
				SAC: 4	<i>Z. marina</i>	0.09
Canary Islands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

Atlas classes	tCO <sub>2</sub> /ha aboveground living/dead biomass	tCO <sub>2</sub> /ha belowground living/dead biomass	Total t CO <sub>2</sub> /ha	Yearly accumulation tCO <sub>2</sub> /ha
NS	NA	NA	NA	NA
CN	1.63	469.3	470.93	0.48
CNZN	1.175	243.95	245.125	0.39
DdPO	8.06	900	908.06	0.6
PO	8.06	1,813.91	1,821.97	1.81
ZN	0.72	18.6	19.32	0.11
DPO	8.06	1,560.69	1,568.75	NA
POR	8.06	1,560.69	1,568.75	1.14
POCN	4.84	1,137	1,141.84	1.81
POCR	NA	NA	NA	NA
CR	NA	NA	NA	NA
HD	NA	NA	NA	NA
CNCR	NA	NA	NA	0.24
ZM	0.72	18.6	19.32	0.11

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