Economic mapping and assessment of *Cymodocea nodosa* meadows as nursery grounds for commercially important fish species. A case study in the Canary Islands

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Abstract

Cymodocea nodosa seagrass meadows provide several socio-economically ecosystem services, including nurseries for numerous species of commercial interest. These seagrasses are experiencing a worldwide decline, with global loss rates approaching 5% per year, mainly related to coastal human activities. *Cymodocea nodosa*, the predominant seagrass in the Canary Archipelago (Spain), is also exposed to these threats, which could lead to habitat loss or even local disappearance. In this case study, we estimated the potential economic value of *Cymodocea nodos*a seagrass meadows for local fisheries at an archipelago scale. Habitat suitability maps were constructed using MAXENT 3.4.1, a software for modelling species distributions by applying a maximum entropy machine-learning method, from a set of environmental variables and presence and background records extracted from historical cartographies. This model allows characterising and assessing the *C. nodosa* habitat suitability, overcoming the implicit complexity derived from seasonal changes in this species highly dynamic meadows and using it as a first step for the mapping and assessment of ecosystem services. In a second step, value transfer methodologies were used, along with published economic valuations of commercially-interesting fish species related to *C. nodosa* meadows. We estimate that the potential monetary value of these species can add up to more than 3 million euros per year for the entire Archipelago. The simplicity of the proposed methodology facilitates its repeatability in other similar regions, using freely available data and hence, being suitable for data-scarce scenarios.

Keywords

Cymodocea nodosa, seagrass meadows, habitat suitability mapping, ecosystem services, value transfer methodology, Canary Islands.

Introduction

Seagrasses are important coastal and marine habitats in temperate and tropical regions around the globe (Green and Short 2003). They provide several ecological functions and ecosystem services (ES) (Cullen-Unsworth and Unsworth 2018, Nordlund et al. 2018), such as habitat and spawning ground, coastal protection, carbon sequestration and food and nursery for a great variety of marine organisms, including several commercially-important species (Cullen-Unsworth and Unsworth 2018, Espino et al. 2011, Jimenez-Ramos et al. 2017).

Seagrass meadows are experiencing a world-wide decline, with global loss rates estimated at 2-5% year^{-1}, compared to 0.5% year^{-1} for tropical forests (Duarte et al. 2008, Hughes et al. 2009, Orth et al. 2006, Short et al. 2011, Waycott et al. 2009). Seagrass declines have been attributed to the five most serious threats to marine biodiversity, often in combination: over-exploitation, physical modification, nutrient and sediment pollution, the introduction of non-native species and global climate change (Waycott et al. 2009, Tuya et al. 2014a). Even though global scale phenomena may partly explain seagrass distribution decline (Jorda et al. 2012), the accumulation of local threats seems to be amongst the main causes of seagrasses regression as well (Gonzalez-Correa et al. 2007).

Cymodocea nodosa (Ucria) Ascherson, 1870, the predominant phanerogam species in the Canary Islands, is exposed to different threats, mainly related to coastal human activities, leading to habitat loss or even to their disappearance at a local scale (Tuya et al. 2014a, Tuya et al. 2014b). However, spatial information on the distribution and conservation status of *Cymodocea nodosa* meadows in the Canary Islands, needed for the evaluation of goods and services provided by these ecosystems, is scarce. *C. nodosa*'s distribution has been already assessed in the Archipelago in the past (e.g. Barbera et al. 2005, Barquin-Diez et al. 2005, Reyes et al. 1995, Tuya et al. 2014b, Wildpret et al. 1987,Martín-Garcia et al. 2004). Nevertheless, these one-time attempts presented limitations in terms of spatial coverage with some areas of the Archipelago not covered due to technical infeasibility. At the same time, temporal discrepancies could be found in *C. nodosa*'s historic distribution datasets as many cartographies were built within a few years' time difference. These discrepancies result in an especially significant handicap, as this community presents a high seasonal variability (Guidetti et al. 2002) which makes it even more difficult to establish an accurate mapping of the real distribution of the species.

The main objective of this study is to evaluate the potential ecosystem services provision of the phanerogam meadows in the Canary Islands to aid policy-making in terms of coastal spatial planning and conservation policies, exploring the capabilities of Mapping and Assessment of Ecosystem Services (MAES) at an archipelago level. For this purpose, a *C. nodosa*'s potential distribution model and a value transfer methodology of the main commercial species, associated with the presence of this habitat, were used.

Methodology

Study area

The Canarian Archipelago comprises eight main islands located in the North-east Atlantic Ocean between latitudes 27° and 30° N and longitudes 18° and 13° W, approximately (Fig. 1). It is an oceanic archipelago of volcanic origin, progressively formed from a long-lasting source of magma for about 60 million years.

The Canary Islands present a sub-tropical climate with warm temperatures and small seasonal variations. The main large-scale oceanic flow is the Canary Current, a relatively cold surface current following SSW direction (Fiekas et al. 1992). Oligotrophic waters are found all around the year, although coastal upwelling along the eastern boundary of the North Atlantic subtropical makes eutrophic waters in the eastern side of the Archipelago (Aristegui et al. 2009, Barton et al. 1998) with much higher biomass volumes and respiration levels found in eddies around the Islands.

Three species of seagrasses are present: *C. nodosa* (Afonso-Carrillo and Gil-Rodriguez 1980), *Nanozostera noltii* (Hornemann) (Tomlinson and Posluzny 2001) and *Halophila decipiens* Ostenfeld 1902 (Gil-Rodriguez et al. 1982). *C. nodosa* is not only the most common (Fig. 2), forming the most important marine ecosystem in sandy bottoms, but also proves to be a suitable bioindicator of ecosystem health because of its sensitivity to changes in the environment (Mascaró et al. 2012). It can be found forming extensive monospecific meadows, varying in density, in sandy and muddy bottoms in bays, harbours and sheltered areas along the eastern and southern coasts of the Islands (Barquin-Diez et al. 2005, Reyes et al. 1995).

Habitat suitability mapping

As a first step, to characterise the habitat suitability of *C. nodosa* in the Archipelago, a model using MAXENT 3.4.1 (Phillips et al. 2006) was constructed with a set of environmental variables and presence and background records extracted from historical cartographies. Species habitat suitability was modelled, based on only-presence records without consideration for human pressure whatsoever. This procedure allowed us to identify potential suitable areas for *C. nodosa* to grow and thrive, rather than modelling current species distribution, influenced by the proximity of coastal human activities and better suited when real absence data are available. *KUENM R* package (Cobos 2019) was used to find optimal *MAXENT* setting parameters to construct the model (Fig. 3) and only open-source datasets were used for modelling purposes, advocating for the replicability of this methodology in data-scarce scenarios.

Environmental variables

A set of 11 environmental variables were considered (Table 1). Northness, Eastness, Depth (m) and Slope (°) were derived from a Digital Terrain Model (DTM) with an original resolution of 5 m x 5 m. These data were provided by the Spanish Ministry of Environment (M.M.A. 2001b, M.M.A. 2001a, M.M.A. 2003, M.M.A. 2004, M.M.A. 2005b, M.M.A. 2005a), processed using *QGIS 3.4.1 Madeira* and resampled to 100 m x 100 m resolution. The Fetch (m), a measure of coastal exposure derived from spatial proximity to shorelines, was calculated using *R studio 1.1.463B* (Yesson et al. 2015). Chlorophyll concentration ($mg*m^{-3}$) was derived from NASA Level-3 MODIS-Aqua monthly chlorophyll concentration (https://oceancolor.gsfc.nasa.gov/l3/). Mean annual values were calculated for a period of time ranging from 2010 to 2019 and resampled to 100 m x 100 m resolution. Finally, a series of variables, providing information of Sea Surface Temperature (SST), were processed from the NASA GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (https://podaac.jpl.nasa.gov/dataset/JPL-L4UHfnd-GLOB-MUR). SST values were considered for a period of time ranging from 2010 to 2019. Mean SST values of annual hottest months (September and October) and coldest (February and March) were calculated as well as mean SST annual maximum and minimum. All these variables were resampled to 100 m x 100 m resolution.

Presence/Background data

C. nodosa presence records were extracted from historic benthic maps (Barbera et al. 2005, Barquin-Diez et al. 2005, Reyes et al. 1995, Tuya et al. 2014b, Wildpret et al. 1987, Martín-Garcia et al. 2004). Records were identified as established and stable meadows and, hence, representative of optimal environmental conditions. A total of 148 presence records were gathered and a series of background records were selected following the methodology by Elith (2006) and Phillips et al. (2009).

Model fitting

Three steps were followed: Variance inflation factor (VIF), Model setting parameters optimisation and Jackknife analysis.

The VIF analysis provided information regarding spatial collinearity amongst predictors. This analysis showed a spatial correlation between “Hottest months mean” and “Annual maximum SST”, as well as “Coldest months mean” and “Annual minimum SST”, meaning that both “Annual minimum SST” and “Annual maximum SST” were left outside of the model.

For parameter optimisation, 426 MAXENT models were generated using the *KUENM R* package (Cobos 2019) with *R studio* 1.1.463. MAXENT optimal parameters and environmental predictors were selected, based on Partial Receiver Operating Characteristic (ROC), Omission rates and Akaike’s Information Criterion (AIC) assessments (Table 2). Once optimal MAXENT parameters were set, a total of 40 models were run and evaluated with bootstrap analysis with 50% presence records random selection to test model performance, based on Area Under the Curve (AUC) values.

The Jackknife approach, an iterative variable subsampling method that evaluates the variable permutation importance in the model, was used. This test allowed us to assess the species' response to changes in environmental variables and to find spatially non-correlated predictors to feed the model. This test is already implemented in MAXENT 3.4.1 (Phillips et al. 2006).

Once the three previous analyses were carried out, a set of spatially non-correlated predictors best explaining species potential distribution was selected, along with the most optimal MAXENT paremeters.

Value transfer approach

Value transfer methodologies rely on the estimation of ES values by extrapolating an available valuation of a similar ecosystem (Troy and Wilson 2006). These methodologies are gaining exponentially in importance in literature when it comes to ES monetary valuation (Niccolucci et al. 2021, Rizzo et al. 2021, Sinclair et al. 2020, Zhou et al. 2020). Following this procedure, the monetary value of eight fish species (Table 3), estimated in Tuya et al. 2014a, were extrapolated to the potential *C. nodosa* modelled distribution at an archipelago level. To transfer the monetary valuation, values were multiplied by an index expressing the relative suitability of the species. The same calculations were performed with each habitat suitability class to construct a spatially explicit ES assessment for the entire Canarian Archipelago.

To generate the total economic value, published monetary values (€*ha^{-1}) were multiplied by the total area of distribution (ha), taking into consideration the whole extent of *C. nodosa* 's potential habitat at an archipelago level.

Results

Habitat suitability mapping

The Jackknife approach allowed determining variables' capability to predict and explain *C. nodosa*'s potential distribution. Higher values of variable permutation importance represent higher capability for a certain environmental variable to affect species habitat suitability in a given area and, hence, to predict the species habitat. Depth, with 76.5% of variable permutation performance, was the variable best explaining *C. nodosa* 's potential distribution. Aspect, (specifically Northness) also plays an important role, presenting 12.3% of variable permutation importance. On the contrary, mean SST of the annual hottest months and Fetch play the least predictive capabilities with 6.4% and 4.7%, respectively (Table 4).

The selected model (Fig. 4) showed excellent performance with a mean AUC value of 0.94 and a standard deviation of 0.01.

Nursery grounds economic assessment

Results of potential economic estimation of commercially-interesting species are presented in Table 5. Fishing activities are of great importance to the Archipelago, with many municipalities depending on this sector. Based on value transfer methodology, it was estimated that the *C. nodosa* meadows support a potential fish population valuated in 3,060,501 €*year^{-1}.

Amongst the eight assessed species, *S. cretense* and *M. surmuletus* present the highest economic value with 1,280,959 and 1,267,976 €*year^{-1}, respectively, accumulating 83% of the total economic production of fishing activities related to *C. nodosa* meadows.

The total economic valuation for the assessed species is presented in Fig. 5 and Fig. 6, obtained by the summation of per species valuation. Higher economic values are closely related to areas presenting higher habitat suitability of *C. nodosa*, with values between 75 and 95 €*ha*year^{-1}. These can be found in southern coasts of the Islands in the western area of the Archipelago, where substrate availability and shelter conditions favours the establishment of the species. These values decrease along habitat suitability, reaching 28 to 45 €*ha*year^{-1} in areas where those criteria are not met for the species to thrive.

It was also found that the decrease in habitat suitability (and, hence, in economic valuation of potential fish catch) follows an east-west and a north-south direction. The lowest values are found on the Islands of La Palma and El Hierro.

Discussion

This study represents one of the first attempts to model and assess the potential distribution of *C. nodosa* meadows in the Canarian Archipelago, following the methodological approach in Martín-García et al. 2014, entirely based on species' response to environmental and climatic variables, regardless of the influence of human coastal activities and infrastructure. This model represents the geographical distribution of suitable areas for the species to thrive in a hypothetical pristine scenario with no human influence and, hence, its realised ecological niche. Historical cartographies of *C. nodosa* are available in the Canary Islands (Barbera et al. 2005, Barquin-Diez et al. 2005, Reyes et al. 1995, Tuya et al. 2014b, Wildpret et al. 1987, Martín-Garcia et al. 2004). These cartographies, built with in-situ measures, depict the real distribution of this seagrass, presenting much more limited areas than the potential distribution, probably reflecting the influence of human activities and infrastructure that occupies optimal areas for the species. This modelling approach allowed us, on the one hand, to study the response of the species to solely environmental characteristics and, on the other hand, to overcome the spatial and temporal limitations of in-situ cartography, as the seasonal changes of highly dynamic meadows of *C. nodosa* (Marbà and Duarte 2001). Potentially suitable predicted areas show a clear difference with the real distribution of the species, helping to understand the paramount importance of human pressure jeopardising this phanerogam distribution (Grech et al. 2012, Orth et al. 2006, Sweatman et al. 2017, Tuya et al. 2014b, Waycott et al. 2009, Tuya et al. 2013, Cabaço and Santos 2014) in the Archipelago and hence, the provision of ES.

Other attempts of modelling the distribution of *C. nodosa* have been carried out in broader scales (Chefaoui et al. 2016), trying to capture, in concordance with our methodologies, the species response to environmental variables with no consideration of human pressure whatsoever. Contrary to our findings, highlighting the importance of depth and northness, different responses to those variables were obtained in this other study, assessing SST as the key variable for the species distribution. SST plays an important role in the distribution of marine species when considering its distribution on a global scale. However, at a local or regional scale, the importance of the variables changes considerably, as observed in the present work. In the Canary Islands, SST has an important variation range between the eastern and western zones, which can reach 5ºC (Santana-Falcon et al. 2020) due to the influence of the upwelling of the African coast (Barton et al. 1998. Therefore, the importance of temperature in the species distribution models applied in this region can greatly vary, as different variable responses are found due to the scale of the models (Graham et al. 2004, Guisan et al. 2007).

In a second step, an estimation of the economic value of this seagrass as nursery grounds for commercially-interesting fish species was provided. This estimated economic value does not represent the extractive economic value of fish species hosted by this phanerogam, but rather, the value of habitat of *C. nodosa* to fish populations. Actual value of coastal fisheries, related to these species, represent a small fraction of the estimation presented in this study (https://www.gobiernodecanarias.org/agp/sgt/galerias/doc/estadisticas/pesca/2007_2021- especie_meses-valor.ods), as the economic value of fisheries relate to only the market value of the fishable extracted fraction of fish populations. Other coastal habitats present in the Archipelago (e.g rocky reefs) could represent higher extractive economic valuations, as those habitats host better valuated species in the market, like serranid species as *Epinephelus marginatus* or *Mycteroperca fusca*. The comparison between these habitat's value for fisheries and *C. nodosa* estimated economic valuation as nursery grounds is extremely difficult to assess, as these values relate to different ecosystem functions and services. *Cymodocea nodosa* meadows also play a key role as nursery grounds for species that will migrate to and establish trophic links with other habitats, representing an added value to these phanerogam meadows, unlikely to be captured in explicitly economic terms. In addition to the mentioned complexity, regional particularities should be considered when comparing market values of commercially-interesting fish species. Most fishery activities take place at a local scale and many species related to *C. nodosa* are caught and sold within the Archipelago market, with no exportation whatsoever, meaning that cultural added value to some species plays a key role for the local market.

As stated, the presence of coastal human activities and infrastructure pose a paramount threat to phanerogam meadows in the Archipelago and they should be considered in future research lines, allowing the comparison between potential and realised ES provision and aiding management, marine spatial planning and conservation of this important habitat.

Conclusions

In the Canary Islands and in the entire Macaronesian bioregion where this Archipelago is located, there is a certain lack of effort in the characterisation and quantification of fishery resources, with serious limitations in the databases related to this ecosystem service. The proposed methodology would be a cost-effective tool for Mapping and Assessment of Ecosystem Services in this region.

As a starting point, we relied on habitat suitability models as an alternative to existing historical mapping in the Archipelago. This allowed us to assess habitat suitability in areas not yet mapped or not conveniently updated and to build a spatially-explicit dataset with a consistent methodology at an archipelago level. This type of habitat mapping could also be developed in other regions where mapping is even more limited.

The presented value transfer methodology, relied on previously-published monetary estimations, estimated that the *C. nodosa* meadows support a potential fish population valued at more than 3 million € year^{-1}. Local specificities of fish communities may have been overlooked and, hence, the results may have been affected by the accuracy of the economic assessment. Nevertheless, we can assume that the populations of the species studied share sufficient similarities across the Archipelago to make this extrapolation.

Future studies should consider including the potential risks and adverse effects of coastal human activity on coastal communities, as well as their influence on the ecosystem services they provide, by constructing distribution models that include such activities.

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Author contributions

E. Casas, L. Martin-Garcia and M. Arbelo conceived, designed, applied the methodology and obtained the results. E. Casas, in collaboration with L. Martin-Garcia and M. Arbelo, drafted the manuscript. All authors analysed and discussed the results and revised the manuscript critically.

Conflicts of interest

The authors declare no conflict of interest

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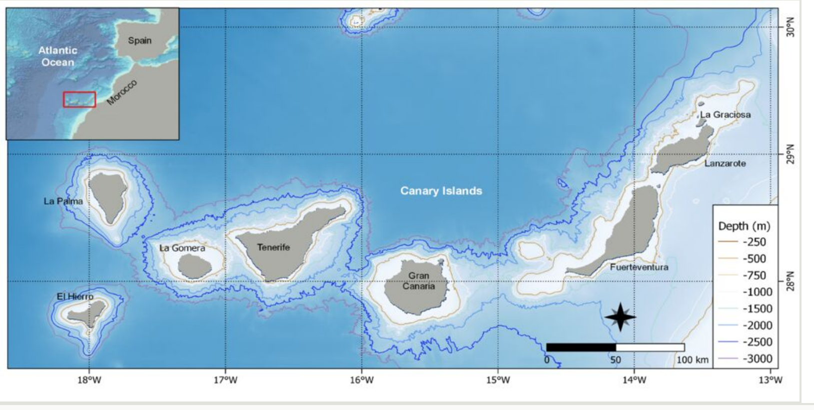

Figure 1.

Canarian Archipelago.

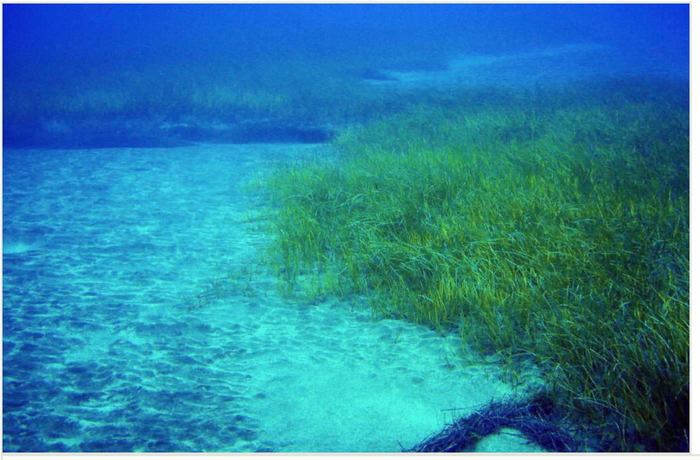

Figure 2.

Cymodocea nodosa. *Author:* Laura Martín-García

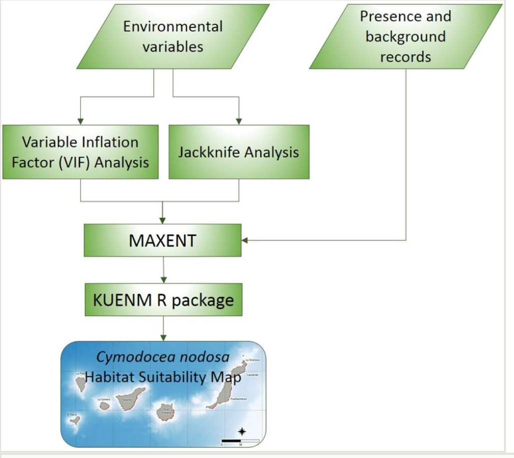

Figure 3.

Cymodocea nodosa habitat suitability modelling methodology.

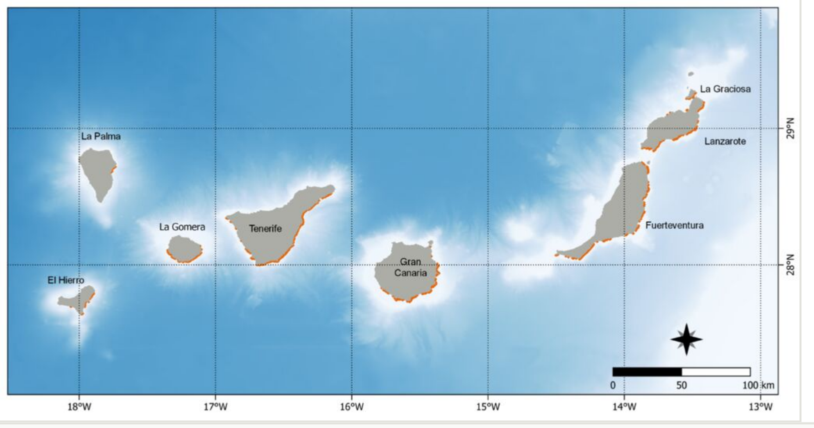

Figure 4.

Cymodocea nodosa's potential distribution. Orange colour depicts Cymodocea nodosa potential distribution.

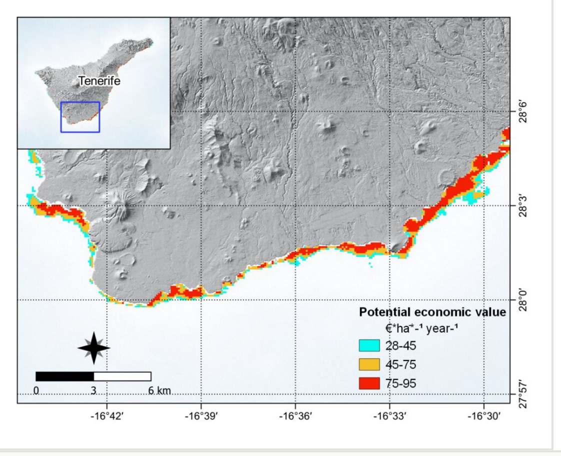

Figure 5.

Cymodocea nodosa's potential fish economic value. Zoom in south of Tenerife.

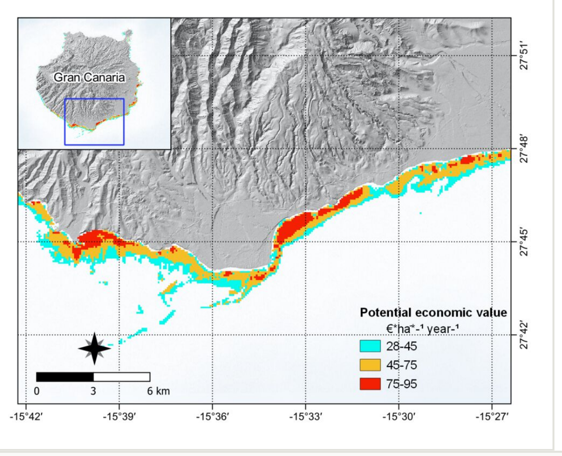

Figure 6.

Cymodocea nodosa's potential fish economic value. Zoom in south Gran Canaria.

Table 1.
Environmental variables.

Variables	Data Source	Original Data Resolution
Depth (m)	Digital Terrain Models (DTM)* resampled to 100 m x 100 m	5 m x 5 m
Aspect (Northness and Eastness) (dimensionless)	DTM Tool in QGIS 3.4.1 Madeira. Then translated into radians and calculated sine (for Eastness) and cosine (for Northness)	100 m x 100 m
Fetch (m)	Calculated using *R studio* 1.1.463 as in Yesson et al. (2015)	100 m x 100 m
Slope (°)	DTM with *Slope* Raster Tool in QGIS 3.4.1 Madeira	100 m x 100 m
Mean Sea Surface Temperature (SST) (°C) of September and October (hottest months)	NASA GHRSST Level 4 MUR Global Foundation SST Analysis (v.4.1) and resampled to 100 m x 100 m. Mean values were calculated using *Cell Statistics* Tool in QGIS 3.4.1 Madeira	1 km x 1 km
Mean SST (°C) of February and March (coldest months)		
Annual maximum SST (°C)		
Annual minimum SST (°C)		
Mean Annual SST (°C)		
Mean Chlorophyll concentration (mg*m^{-3})	NASA Level-3 MODIS-Aqua monthly chlorophyll concentration and resampled to 100 m x 100 m	4 km x 4 km
*(M.M.A. 2001b, M.M.A. 2001a, M.M.A. 2003, M.M.A. 2004, M.M.A. 2005b, M.M.A. 2005a)		

Table 2.

C. nodosa's MAXENT parameter settings

Beta Multiplier	**0.8**
Hinge features threshold	**0.5**
Beta threshold	**1.75**
L/Q/P* features	**0.346**
**Linear, quadratic and product features*	

Table 3.

Monetary assessment of fish species with commercial interest on *C. nodosa* seagrass meadows (Tuya et al. 2014a).

Fish species	**Monetary value (€·ha^{-1}) for 2013**
Sparisoma cretense	40.08
Mullus surmuletus	39.67
Xyrichtys novacula	5.54
Pagellus erythrinus	4.88
Spondyliosoma cantharus	2.73
Diplodus annularis	1.67
Bothus podas	1.09
Dicentrarchus punctatus	0.09

Table 4.

C. nodosa's MAXENT variable contributions based on the Jackknife method.

	Variable contribution (%)	**Variable Permutation Importance (%)**
Depth	70.9	76.5
Northness	12.3	12.3
Fetch	8.7	4.7
Mean SST of hottest months	8	6.4

Table 5.

Potential economic value of fish production at archipelago level.

	Min (€*ha^{-1}*year^{-1})	Max (€*ha^{-1}*year^{-1})	Total (€*year^{-1})
S. cretense	16.03	40.08	1,280,959
M. surmuletus	15.87	39.67	1,267,976
X. novacula	2.22	5.54	176,926
P. erythrinus	1.95	4.88	155,906
S. cantharus	1.09	2.73	87,209
D. annularis	0.67	1.67	53,419
B. podas	0.44	1.10	35,061
D. punctatus	0.03	0.09	3,045
Total	**38.3**	**95.76**	**3,030,501**