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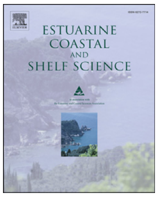

Decadal changes in the structure of *Cymodocea nodosa* seagrass meadows: Natural *vs.* human influences

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ABSTRACT

Seagrass meadows are deteriorating worldwide. However, numerous declines are still unreported, which avoid accurate evaluations of seagrass global trends. This is particularly relevant for the western African coast and nearby oceanic archipelagos in the eastern Atlantic. The seagrass *Cymodocea nodosa* is an 'ecological engineer' on shallow soft bottoms of the Canary Islands. A comparative decadal study was conducted in 21 *C. nodosa* seagrass meadows at Gran Canaria Island to compare the structure (shoot density, leaf length and cover) between 2003 and 2012. Overall, 11 meadows exhibited a severe regression, while 10 remained relatively stable. During this period, natural influences (sea surface temperature, Chlorophyll-a concentration and PAR light, as well as the number of storm episodes detaching seagrasses) had a low predictive power on temporal patterns in seagrass structure. In contrast, proximity from a range of human-mediated influences (e.g. the number of outfalls and ports) seem to be related to the loss of seagrass; the rate of seagrass erosion between 2003 and 2012 was significantly predicted by the number of human-mediated impacts around each meadow. This result highlights promoting management actions to conserve meadows of *C. nodosa* at the study region through efficient management of local impacts.

1. Introduction

Seagrasses constitute a key habitat on shallow soft bottoms worldwide, where they profoundly influence the physical, chemical, and biological environments – acting as 'ecological engineers' (Wright and Jones, 2006) – providing numerous 'goods and ecological services' to humans. Seagrasses, in fact, alter water flow, nutrient cycling, and food web structure, stabilize sediments and produce large quantities of organic carbon (Hemminga and Duarte, 2000), some of which is exported to other coastal and deep-sea habitats, hence providing an important supply of organic matter. Moreover, much of the organic carbon produced is buried in sediments, promoting the C sequestration in the biosphere (Duarte et al., 2005).

The location of seagrasses on shallow waters, and their vulnerability to altering environmental conditions, exposes seagrasses to different types of human-induced disturbances, which frequently leads to habitat loss and eventually local/regional extirpation. In fact, large-scale seagrass losses have been reported in many coastal areas, mainly due to intense human-related activities, what has caused a worldwide declining trend (Orth et al., 2006; Duarte et al., 2008; Hughes et al., 2009; Waycott et al., 2009; Short et al., 2011). Importantly, when seagrasses disappear, the 'goods and ecological services' they provide are eroded, affecting the coastal ecosystem (i.e. loss of water quality, reduction of primary and secondary production, biodiversity, artisanal fisheries decline, etc.). The conservation of these valuable habitats must be a priority in any environmental policy programme. There is, however, sparse information on seagrass distribution and abundance patterns from most coastal areas of the world and so many losses remain unreported, leading to inaccurate evaluations of seagrass global trends (Duarte et al., 2008). This is particularly relevant for the western African coast (Cunha and Araújo, 2009) and nearby oceanic archipelagos.

Cymodocea nodosa (Ucria) Ascherson is a seagrass distributed across the Mediterranean Sea and adjacent eastern Atlantic

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coasts, including the Macaronesian archipelagos of Madeira and the Canaries, all the way down to Senegal in the western African coast (Alberto et al., 2006; Mascaró et al., 2009; Cunha and Araújo, 2009). Meadows constituted by *C. nodosa* are often the dominant vegetated communities on shallow soft substrates of the Canaries (Reyes et al., 1995a; Pavón-Salas et al., 2000; Barberá et al., 2005; Tuya et al., 2013a), where they support a high number of algal species (Reyes and Sansón, 1997), providing food and shelter for diverse invertebrates and fish assemblages (Tuya et al., 2001, 2006; Espino et al., 2011a). These meadows are generally located along the eastern and southern coasts of the islands, sheltered from the dominant oceanic swells from the north and north-west, forming extensive, but often fragmented, subtidal meadows. At within-meadow scales, high-energy swells may remove seagrass vegetative fragments, particularly in winter, deteriorating seagrass vitality. In the Canary Islands, *C. nodosa* shows a clear seasonal pattern, with a summer peak in shoot density and biomass (Reyes et al., 1995a, 1995b; Tuya et al., 2006), similar to what has been observed in the Mediterranean Sea (Terrados and Ros, 1993).

Recently, Short et al. (2011) considered the population trend of *Cymodocea nodosa* as 'stable' along the temperate North Atlantic and Mediterranean, and categorized *C. nodosa* – according to criteria from the IUCN Red List of Threatened Species – as 'least concern'. In the Canary Islands, there is scarce data to support the conservation status of *C. nodosa*; indeed, the Canarian Autonomous Government recently enacted a new environmental law, which reduced its protection status (BOC *n*° 112, Law 4/2010 of the Canarian Catalogue of Protected Species). This seagrass is exclusively protected within marine protected areas, e.g. 'Special Areas of Conservation' under the EU 'Natura 2000' network. A recent study found a severe decline in the presence of this seagrass at 5 meadows from Gran Canaria Island when data from 1995 was compared with 2011 (Tuya et al., 2013b). However, it is essential to encompass a wide range of meadows under distinct environmental scenarios to adequately assess temporal trends of any seagrass (Montefalcone et al., 2007), including estimations of the effects of natural disturbances (Boudouresque et al., 2009), to support proper management actions by coastal resources managers.

In this study, we (i) compared the structure of *Cymodocea nodosa* seagrass, through 3 key seagrass structural descriptors: seagrass shoot density, leaf length and cover, at 21 meadows along the coastal perimeter of Gran Canaria Island between summer 2003 and summer 2012. To determine whether natural and/or human influences may have contributed to explain temporal trends from 2003 to 2012, we (ii) analysed temporal patterns in natural influences, here Sea Surface Temperature (SST), surface Chlorophyll-a concentration (Chl-*a*) and Photosynthetically Active Radiation (PAR) above seagrass canopies, as well as wave-induced disturbances (number of storms detaching seagrasses), and (iii) estimated whether proximity from number and types of human impacts, in conjunction with natural influences, explained rates of change in the structure (shoot density, leaf length and cover) of meadows between 2003 and 2012. The combination of these approaches allowed us to discriminate whether natural and/or human influences may explain temporal trends at the island scale between 2003 and 2012.

2. Materials and methods

2.1. Study area and seagrass sampling

Twenty one seagrass meadows were sampled across the entire distribution area of *Cymodocea nodosa* in Gran Canaria Island (27°58′ N, 15°36′ W, Fig. 1, Table 1; Espino et al., 2003). Each meadow was, at least, between 0.5 and 10 km apart from the adjacent meadow, so we encompassed all range of conditions across the island perimeter where *C. nodosa* is present. At each meadow, two sites were randomly selected during the summer 2003 and again in summer 2012 (hereafter 2003 *vs.* 2012). On each sampling time, three seagrass structural descriptors were assessed *in situ* through SCUBA divers at each site: (1) shoot density (by counting seagrass shoots in $n = 6$, 25 × 25 cm, quadrats), (2) leaf length (by measuring average leaf length in 20 shoots randomly selected) and (3) seagrass cover (by registering the distance under a 1 cm × 25 m flexible line transect covered by *C. nodosa* to the nearest cm, and subsequent calculation of percentage cover, $n = 6$). It is worth noting that this descriptor does not refer to the total area occupied by each meadow at large-scales, but to a local-scale measure of seagrass fragmentation. These descriptors have been previously used at the study region to describe the physical structure of *C. nodosa* meadows (Reyes et al., 1995a,b; Tuya et al., 2002; Espino et al., 2003; Barberá et al., 2005; Tuya et al., 2006; Espino et al., 2011a, 2011b). All measurements were standardized to m^2 to facilitate comparisons with other studies.

2.2. Natural influences: satellite-derived data

Environmental data (SST, Chl-*a* and surface PAR) were acquired from monthly level-3 standard mapped image (SMI) files derived from the Aqua MODIS (MODerate-resolution Imaging Spectroradiometer) sensor, available on NASA's Ocean Color Web (oceancolor.gsfc.nasa.gov/). Satellite-derived data for SST correlate with temperature above the bottom on nearshore habitats, typically at <20 m depth (Smale and Wernberg, 2009). The SST4 product was selected for SST data, which corresponds to SST derived from near infrared bands detected by the MODIS sensor during nighttime. Monthly data files in HDF format were selected and then extracted from pixels that encompassed each seagrass meadow as shown in Fig. 1. The period of satellite data extraction covered from January 2003 to December 2012. By taking into account the depth (z, Table 1) and the surface PAR (I_o) derived from satellite imagery, we calculated the PAR above seagrass canopies (I_z) at each meadow via the equation: $I_z = I_o\, e^{-kz}$. We assumed an average k(PAR) light attenuation coefficient of 0.15 for the study region; this value was previously reported for the water column above a seagrass meadow in the Canary Islands (Tuya et al., 2002). Values of k(PAR) may have been alternatively derived from remote sensing using the K(490) product data for offshore waters (Morel et al., 2007). However, remote sensing derived k(PAR) is not suitable for coastal waters. Despite this approach ignores among-seagrass fluctuations in k(PAR), it provides a proxy to light intensity at each seagrass. Means, variances and coefficients of variation (CV) for each environmental variable at each seagrass meadow were calculated from January 2003 to December 2012 for further statistical analyses and graphical purposes.

2.3. Natural influences: temporal trends in swell-induced disturbances

To describe the wave climate, we derived data (wave height and period) from 2 WANA datasets from the south-west and south-east off Gran Canaria Island (WANA-1017010 and WANA-1019011, respectively, Fig. 1; hereafter WANA-10 and WANA-11, respectively), freely provided by the national '*Puertos del Estado*' port authority (www.puertos.es). To define a storm episode as that event potentially detaching *Cymodocea nodosa* plants from the bottom, we took advantage of two previous studies that determined the tolerance of *C. nodosa* to wave-induced (swell) orbital velocities (v_o). According to Infantes et al. (2011), plants from the Mediterranean