Application of the generic DPSIR framework to seagrass communities of Ria de Aveiro: a better understanding of this coastal lagoon

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ABSTRACT

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Seagrasses are rooted flowering plants, forming dense and highly productive meadows in transitional and coastal waters, which assure major functions and services contributing to the ecosystems health. However, the increased decline and fragmentation of seagrass meadows lead to the loss of the associated benefits. In Ria de Aveiro coastal lagoon (Portugal), seagrass meadows showed a marked decline during the past three decades. In this context, the DPSIR framework (Drivers-Pressures-State-Impacts-Response) arises as an useful tool for environmental assessments. The objective of this study was to apply the DPSIR conceptual model to the seagrass communities in the Ria de Aveiro lagoon, to identify the main drivers, pressures, state and impacts resulting in its decline. Lastly, it was intended to propose possible management responses towards the maintenance of the functions and services provided by the seagrass communities in the Ria de Aveiro. This framework provided an integrated view of the past-present information considering the background data available. The results obtained by the application of the DPSIR framework to the seagrass communities of Ria de Aveiro lagoon structured the existing data from the point of view of a multiple-effect chain, and it was suggested that seagrasses decline in this coastal system have been mainly due to anthropogenic pressures. In conclusion, this work is a relevant contribution from an ecological-scientific perspective of seagrass meadows in the Ria de Aveiro lagoon, with succinct information potentially useful to be integrated in management tools applied to the overall coastal lagoon.

ADDITIONAL INDEX WORDS: *Seagrass decline, ecosystem services and function, Zostera noltii, climate change*.

INTRODUCTION

In coastal ecosystems, seagrasses provide important and valuable services, since they play a major role in the environmental health and biodiversity, contributing to the well-being of the vicinity populations. However, the increased anthropogenic activities are responsible for higher direct and/or indirect pressures, resulting in a worldwide decline of these ecosystems quality and biodiversity (Pérez-Domínguez *et al.*, 2012). In fact, several studies have shown that seagrass habitats are declining due to local environmental disturbances, such as habitat disruption and fragmentation, eutrophication, climate change, water turbidity, pollutants, coastal development, and new species introduced (Lillebø *et al.*, 2011 and references therein). Therefore, seagrasses were included in the list of threatened and/or declining species and habitats, in the context of international conventions (Short *et al.*, 2011).

Seagrasses habitats, constituted by marine rooted flowering plants, are among the most productive systems in coastal zones, providing key ecological services, which reflect their significant functions (Duarte, 2000; Duarte, 2002; Orth *et al.*, 2006). Their important role in stabilizing sediments, reducing water currents, and providing habitat for ecological and economical valuable species of invertebrates and fishes, are some of the contributions/inputs for maintaining the ecosystems health (Duarte, 2000; Lillebø *et al.*, 2011).

Seagrasses are the only true marine angiosperms, being used as bioindicators of ecosystem change and health (Martínez-Crego *et al.*, 2008; Montefalcone, 2009) due to their sensibility to human induced disturbances. Angiosperms (seagrasses) are one of the "biological quality elements" to be used in defining the ecological status of transitional and coastal waters (Annex V - WFD, European Commission, 2000; OSPAR Commission, 2005; Lillebø *et al.*, 2007)), highlighting the importance of these ecosystems. During the last decades, conservation and restoration of coastal areas, including seagrass communities, has become a priority (Lillebø *et al.*, 2011). In this context, the DPSIR framework (Drivers-Pressures-State-Impacts-Response) resulted from a further extension of the PSR (pressure-state-response) model (European Environmental Agency, EEA) and has been recognized as an important environmental assessment tool to develop and sustain appropriate and adaptive management responses (Rogers and Greenaway, 2005). Therefore, this framework has been successfully applied in studies on coastal systems (e.g. Elliott, 2002; Atkins *et al.*, 2011).

Following a global trend, the seagrass meadows in Ria de Aveiro lagoon showed a noticeable decline during the past three

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decades (Silva *et al.*, 2004). Besides the ecological importance of seagrasses, the associated social-economic component was also relevant in the Ria de Aveiro lagoon due to the high yields and harvested amount of "moliço", a mixture of seagrasses, namely *Zostera noltii* and *Zostera marina*, with green and red macroalgae namely *Ulva* sp. and *Gracillaria* sp. (Santos and Duarte, 1991).

In this context, the objective of this study was to apply the DPSIR framework to the seagrass communities of Ria de Aveiro lagoon, in order to identify the main Drivers for its decline, as well as the resulting Pressures, State and Impacts in the seagrass community. Finally, we propose some potential Responses foreseen the ecosystem ecological quality status.

METHODS

Ria de Aveiro lagoon - case study

Ria de Aveiro (Figure 1) is a shallow lagoon (average depth of 1 m) with a complex geometry, located on the northwestern Portuguese coast (40º38'N, 8º45'W). It is connected to the Atlantic Ocean by a single artificial tidal channel, and has four main channels: S. Jacinto, Espinheiro, Mira and Ílhavo.

Its location and characteristics provide conditions for harbour, navigation and recreation facilities (Dias *et al.*, 2001). With 45 km long and 10 km wide, this coastal system has 83 km^2 and 66 km^2 of water covered area, for high and low tide spring conditions, respectively (Dias *et al.*, 2001). Semidiurnal tidal regime is responsible for the main forcing of circulation within the lagoon, with a mean tidal range of about 2 m, being the minimum and maximum tidal ranges of 0.6 m (neap tide) and 3.2 m (spring tide), respectively, assigning Ria de Aveiro as a mesotidal coastal lagoon (Dias *et al.*, 2000). Consequently, this system has large intertidal areas, with extensive areas of salt marshes and mud flats exposed during low tide.

Until approximately the last two decades of the 20^{th} century, seagrass meadows were present in the subtidal and intertidal areas of Ria de Aveiro, namely in the Ovar and Mira channels, contributing to its high primary productivity and, providing suitable conditions for nursery and habitat of several fishes and invertebrates' species. During the late 19^{th} and early 20^{th} centuries this leaded to the exploration of lagoon's resources and to the development of a wide range of other human-related activities. Used as fertilizer for agricultural fields, the "moliço" was formerly and intensively harvested in Ria de Aveiro lagoon (Santos and Duarte, 1991). These authors estimated that in late 19^{th} century, one-year income could reach about US $3,000,000 (value corrected for inflation for 1991). In addition, based on the number of "moliceiros", the typical boats exclusively used to the "moliço" harvesting activity, the average yield of "moliço" between 1883 and 1967 could reach 274 600 t. However, increasing pressure conducted to the regulation of this activity, such as the requirement of licenses to the harvesters and boats, the establishment of a harvest season and the definition of the used tools and selling prices (Santos and Duarte, 1991). According to Silva *et al.* (2004) the seagrass harvesting decreased after the 1960's, due to changes in agricultural practices (i.e. increased use of chemical fertilizers), rather than due to the seagrass depletion, resulting in a consequently loss of its economic value. In 1998, the commercial harvesting of seagrass was totally ceased, after a noteworthy decrease in the subtidal populations (Silva *et al.*, 2004). Reviewing the changes in Zosteraceae meadows of the Ria de Aveiro lagoon reported in the literature (Table 1), it is highlighted the reduction in seagrasses cover distribution and biomass (*Z. noltii* and *Z. marina)* over the years. Several causes were pointed out by the authors to explain the seagrass decline, which will be addressed in thorough detail.

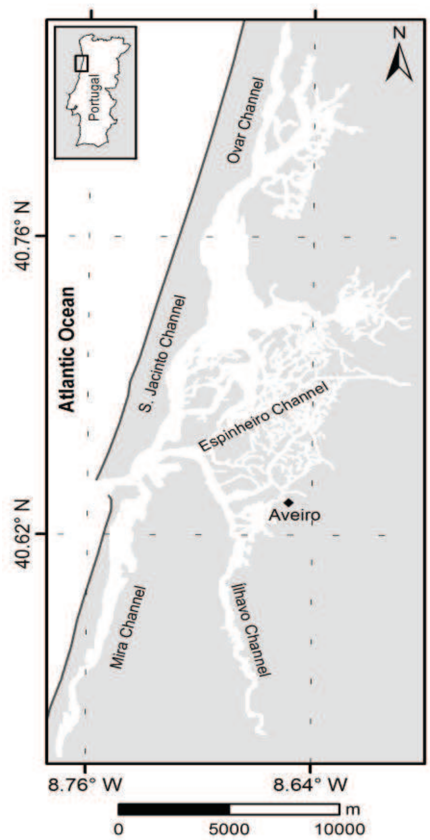

Figure 1. Geographic map of Ria de Aveiro lagoon.

According to Silva *et al.* (2004), until 1960 there was a dense coverage of Submerged Aquatic Vegetation (SAV), including *Potamogeton pectinatus, Rupia cirrhosa, Z. noltii and Z. marina*. However, recent assessments (e.g. Silva *et al.*, 2009; Cunha *et al.*, 2013) indicate that, currently, it is only verified the presence of *Zostera noltii* restricted to the intertidal zones.

DPSIR framework

The DPSIR framework provides cause-consequence connection between the anthropogenic activities and the environmental processes in a descriptive simple method, organizing the collected data. Afterwards, the analysis might give to scientists, stakeholders and managers a better understanding of the importance of natural systems in decision-making processes, and the consequences of economic activities. This framework includes the Driving forces, which emerge from people's needs to their welfare. These drivers lead to Pressures on the environment, as a result of production and consumption activities/processes. In turn, pressures result in State, which represents the degree of environmental quality, reflected in physical, biological and chemical conditions. The changes in those conditions induce environmental and economic Impacts on ecosystems. In order to minimize them as much as possible, the Responses present a set of societal, scientific/academic and policy maker's prioritizations by affecting any part of the chain between the drivers and the impacts (Sekovski *et al.*, 2012).

In the frame of this study, a literature review and systematisation concerning the seagrass assessments in the study area was made followed by the DPSIR framework application to the Zosteraceae

Table 1. Chronological changes of seagrass meadows in Ria de Aveiro lagoon.*(seagrass+macroalgae)

Species	*Period*	*Location*	*Cover distribution*	*Biomass data*	*Causes of seagrass decline/Obs.*	*Reference*
Zostera noltii	1984	Ovar channel	8 km^2 (subtidal+intertidal)	300-600 $gDW.m^{-2}$ *	Resuspension, turbidity, sedimentation	Silva *et al.* (2004)
Zostera noltii	1998 vs 2005	Ria de Aveiro	Large intertidal areas with unvegetated sediment, new areas colonised by *Z. noltii*	Aerial photographs (1998) vs field observations (2005)	Apparent slowly ecosystem adjustment to the new tidal conditions	Silva and Duck (2007)
Zostera noltii	2003	Ovar channel	1 km^2 (intertidal)	100-300 $gDW.m^{-2}$ *; Sept.2002-June 2003: 154±142 $gDW.m^{-2}$ (Zostera)	Resuspension, turbidity, sedimentation	Silva *et al.* (2004)
Nano-zostera noltii	2002-2004	10 intertidal sampling points with *N. noltii* + adjacent areas with sparse macroalgae coverage	3 km^2 (2004) (intertidal)	110±50 g m^{-2} (AFDW)	Erosion, increased water current, loss of fine sediments and nutrients	Silva *et al.* (2009)
Zostera noltii & Z. marina	2008	Mira channel	*Z. marina*: 10 patches (<2m); *Z. noltii*: 0.130 km^2 (intertidal)		Patches of *Z. marina* found in 2009 in Ovar channel and in front of Costa Nova do Prado; May 2010: those patches had disappeared	Cunha *et al.* (2013)
Zostera noltii	2010	Ovar channel	0.431 km^2 (intertidal)			

seagrass communities in Ria de Aveiro coastal lagoon. Thus, all the steps of DPISR framework were followed considering the information gathered from the available literature. First, the past and present Driving forces were identified, as well as the past and present Pressures, the present State, considering the background information and the potential Impacts, namely those associated with functions and services provided by seagrass meadows. Then, there were outlined possible Responses from the scientific/academic point of view in the scope of the maintenance and preservation of the functions and services provided by the seagrass communities in Ria de Aveiro lagoon.

RESULTS AND DISCUSSION

The direct application of the DPSIR framework to the seagrass communities of Ria de Aveiro (Figure 2) pointed out the harbour activities as the main Driving forces for seagrasses decline (Duck and Silva, 2012). The continuity of the harbour activities and related actions are essential to satisfy human requirements for welfare, being an important input to the local economy. However, it results in several Pressures to the natural system such as the need for artificial and permanent channel opening (Silva *et al.*, 2009). Thus, dredging activities are demanded, in order to maintain the requirements of deep and wide channel for a safe navigation (Silva and Duck, 2001). Other identified Pressures to the seagrass communities of the Ria de Aveiro lagoon are the fishing activities involving motor boating and bait digging from the tidal flats (Silva *et al.*, 2005). These activities have a high potential for disturbing sediment, intensifying the decline of their diversity and abundance (Silva *et al.*, 2005).

The State of the seagrass communities have been changing over time, as a result of the mentioned pressures, and notably reflected by a decrease in the biomass and species richness of seagrasses (Silva *et al.*, 2004). Formerly subtidal and intertidal areas were vegetated/colonized by *Zostera* (both *Z. marina* and *Z. noltii*) and nowadays the seagrass meadows are restricted to the intertidal area and to the *Z. noltii* species (Silva *et al.*, 2004; Silva *et al.*, 2009; Cunha *et al.*, 2013). The changes in the system hydrodynamics are detected by an increase in tidal wave penetration (Araújo *et al.*, 2008), which induces noticeable modifications in the sediment dynamics (Silva *et al.*, 2004). Thus, resuspension, transportation and redistribution of coarser, sandy sediment have been observed (Silva *et al.*, 2004). Alterations in physicochemical parameters, light penetration, nutrient cycling and seagrass decline (Silva *et al.*, 2004; Silva *et al.*, 2009) were also determinant to the State of the seagrass communities.

Changes in these processes and State of the seagrass meadows have had environmental negative Impacts. In Ria de Aveiro lagoon the boats used for traditional activities, such as the harvesting of "moliço", were quite abundant. Nevertheless, they were characterised by a small draft and sail- or oar-propelled, having a very low impact in the ecosystem (Silva *et al.*, 2005). This traditional activity declined after the 1960's contrasting with an accentuate increase in commercial and recreational navigation. However, the new boats in the Ria de Aveiro usually have outboard engines with a high potential for disturbing the sediment of the shallow tidal flats (Silva *et al.*, 2005).

Other Impacts, resulting from the hydrodynamic changes, are related with the water current velocity and tidal circulation increase. This is reflected by the transport and redistribution of coarser, sandy-sediments and increased resuspension and turbidity in the water column. In turn, the light that reaches the seagrasses is reduced and sedimentation in vegetated areas increases (Silva *et al.*, 2004), resulting in a decreased plant productivity (Erftemeijer and Lewis, 2006). Besides alterations in sedimentary regimes in Ria de Aveiro lagoon, the increased salinity was also pointed out as an important factor to explain the seagrass decline in this coastal system (Silva *et al.*, 2004). A recent experimental study focused on the response of *Z. noltii* to changes in salinity concluded that growth and survival of this species was significantly affected but by hyper-saline conditions, i.e., results showed that the mortality rate increased at salinity levels above 43, reaching 50% at salinity of 50 and 100% at salinity above 57 (Fernández-Torquemada and Sánchez-Lizaso, 2011). So, this

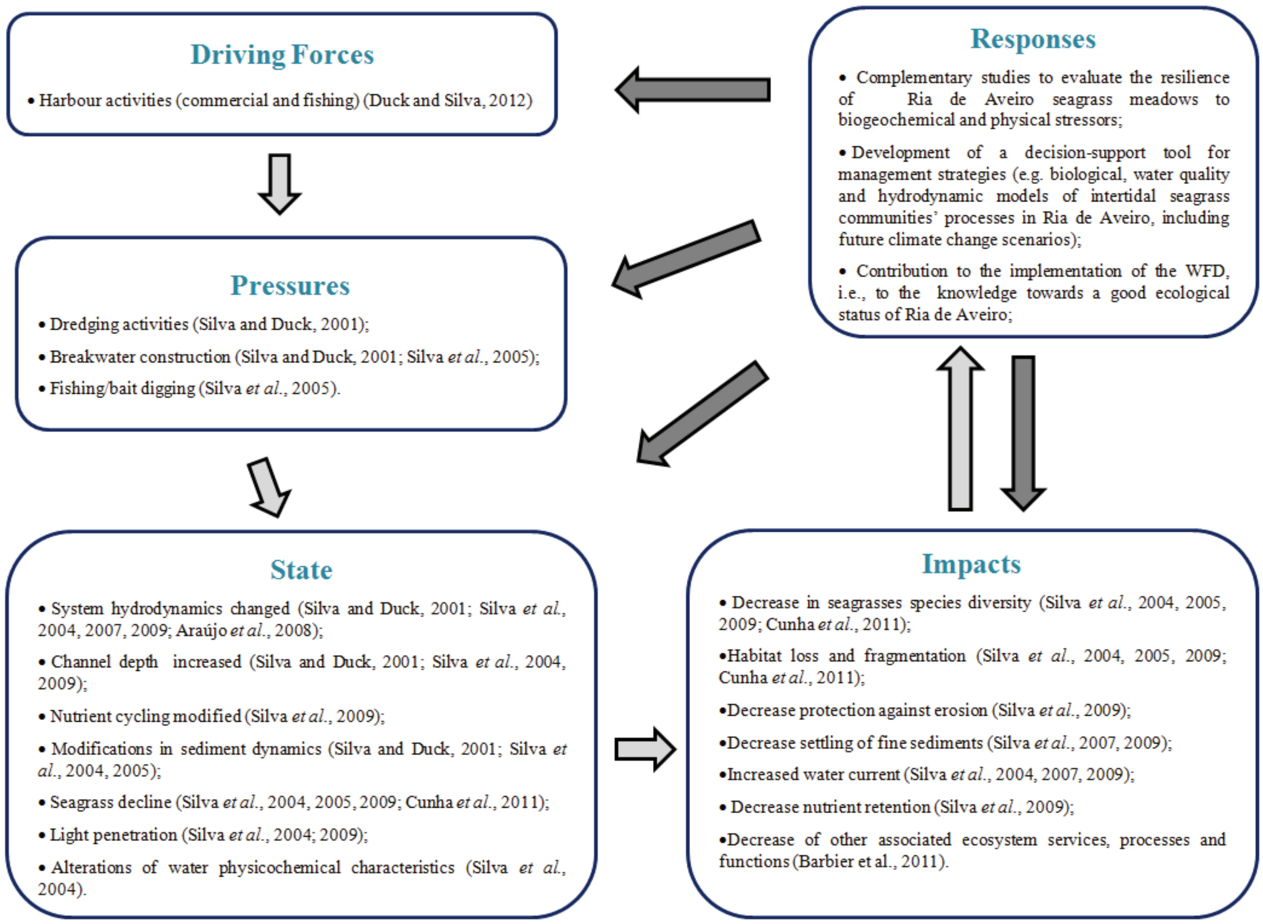

Figure 2. Application of DSPIR framework to the Zosteraceae seagrass communities of Ria de Aveiro.

might not be the major factor responsible for the sharply decline of *Z. noltii* in Ria.

The decline of seagrasses due to the increased sedimentation in vegetated areas (siltation) is usually related with the partial burial of the plants, namely if disturbances become too frequent or intense (Han *et al.*, 2012). On the other hand, the erosion and the combined action of increased water current, loss of fine sediments and decrease in nutrients retention are also important states that might conduct to seagrass decline (Silva *et al.*, 2009). Seagrass decline results on the loss of several ecosystem services, processes and functions (Barbier *et al.*, 2011): loss of raw materials and food, which are responsible for generating biological productivity and diversity and providing suitable habitat for diverse fauna and flora; loss of coastal protection and erosion control, which attenuate waves propagation providing sediment stabilization; degradation of water purification, through nutrient and pollution uptake reduction; carbon sequestration decrease, modifying biogeochemical activity and sedimentation; and decrease of recreational and educational potentiality, due to the loss of exceptional and aesthetic landscape. (Barbier *et al.*, 2011).

Considering this, the proposed academic/scientific contribution to Responses to the seagrass meadows decline at Ria de Aveiro lagoon are 1) Complementary studies to evaluate the resilience of Ria de Aveiro seagrass meadows to biogeochemical and physical stressors (the knowledge of the processes that lead to seagrass decline is obviously the key to remedial measures targeting the re-establishment or protection of seagrass communities); 2) the development of a decision-support tool for management strategies (e.g. biological, water quality and hydrodynamic models of intertidal seagrass communities' processes in Ria de Aveiro, including future climate change scenarios); and 3) Contribution to the implementation of the WFD, i.e., to the knowledge towards a good ecological status of Ria de Aveiro. Regarding modelling developments as a decision-support tool for seagrass management strategies, it is important to highlight that the already existing ones are still undeveloped, requiring some adaptations to simulate more realistic situations (improvements concerning the inclusion of additional parameters/variables and several scenarios response in the scope of the climate change context, among others).

The increased knowledge and awareness of the seagrass meadows values are quite important for the accomplishment of successfully seagrass restoring areas (e.g. Bastyan and Cambridge, 2008; Bologna and Sinnema, 2012), not only in terms of vegetation biomass and coverage area, but also the respective fish and decapod faunal abundance and composition (Hemminga and Duarte, 2000). However, there are also recovering attempts that have not been fully successful, even with considerable efforts. In fact, recovery might become very difficult to achieve if the system reaches an alternate stable state (e.g. Lillebø *et al.*, 2011). It is also recognized that where seagrasses are abundant, human populations benefit directly or indirectly from the presence of this marine vegetation (Barbier *et al.*, 2011). However, the Responses suggested should be accompanied by a regular monitoring of the seagrass meadows, in line with the requirements of the Water Framework Directive. This kind of monitoring programs involves the determination of the areal cover and density of seagrasses in order to detect declines in the meadows. The satellite or airborne remote sensing is a common technique used to monitor changes in large meadows and was already successfully applied to Ria de Aveiro lagoon by Silva and Duck (2007), providing important information for the evaluation if vegetation change over time. Ideally, monitoring techniques should be able to forecast losses before they occur (Hemminga and Duarte, 2000), although seagrasses are a vulnerable resource and easily lost in coastal areas facing environmental changes.

The seagrasses decline in Ria de Aveiro lagoon is suggested to be mainly due to human-induced disturbances, although other factors should not be neglected, such as the potential natural decline due to the abandon of "moliço" harvesting activity. Thus, the application of the DPSIR framework is obviously an important approach to lately establish the most appropriate mitigation measures targeting the re-establishment or protection of seagrass meadows in this coastal lagoon. Besides the direct value of seagrass meadows, the services provided by these ecosystems to the overall functioning of coastal zones are even more important reinforcing the necessary efforts for its protection. In this context, for future directions, and as a Response of the present application of DPSIR framework, the development of a model of intertidal *Zostera noltii* seagrass processes in Ria de Aveiro lagoon is planned. This will aim to represent supportive information to integrate management tools, recognizing these ecosystems services and functions, in a climate change context, and considering the previous events but also taking into account future scenarios. It is also expected to evaluate the response of these communities considering the resilience of the system to multiple stressors, namely anthropogenic pressures in the context of climate change. This factor is an emerging concern worldwide and some studies pointed out the Ria de Aveiro as a potential susceptible area in Portugal mainland to some climate change effects, namely sea level rise (Ferreira *et al.*, 2008; Lopes *et al.*, 2011).

Presently, several factors are important to consider when studying the general climate change effects in the coastal systems. Besides sea level rise, the shifts in salinity and water temperature (Michener *et al.*, 1997; Nielsen and Brock, 2009), which are translated in ecosystem losses and economic impacts (Nicholls *et al.*, 1999; Allison *et al.*, 2009), are some of the concerns. These alterations should be taken into account because they affect the seagrass distribution, productivity, and community composition, inducing deep alterations in the local and regional biota and biogeochemical cycles (Short and Neckles, 1999). Additionally, some of the alterations due to the climate changes are also reflected by an increase of extreme events such as floods or storm surges, which may increase the turbidity of the coastal waters. In turn, increasing floods of the adjacent agriculture fields of Ria de Aveiro (Silva and Duck, 2001) may contribute with organic and nutrient input. Consequently, several physical and chemical changes may occur, including a reduction of the water transparency (diminishing the light available for the plants) with negative effects on seagrass functioning and following decline.

CONCLUDING REMARKS

Seagrass meadows are threatened ecosystems and the well reported losses clearly justify the need of developing scientific-based studies that will contribute to the sustainability and preservation of the existing seagrass meadows and lately, potentially re-establish those meadows that were already lost. The proposed Responses resulting from the application of the DPSIR framework to the seagrass meadows of Ria de Aveiro showed that more research efforts are required, in order to find the best and adequate management practices that would help the preservation and recover of these meadows. The results obtained from the application of the DPSIR framework to the seagrass communities of Ria de Aveiro lagoon structured the existing literature data from the point of view of a multiple-effect chain. Thus, this work is a relevant contribution from an ecological-scientific perspective of seagrass meadows in the Ria de Aveiro lagoon, with succinct information potentially useful to be integrated in management tools applied to the overall coastal lagoon.

Future research will focus on the development of a modelling tool for the study of the processes related with intertidal seagrass communities in Ria de Aveiro, considering future quantitative scenarios in a global climate change context. This way, the model will not consider solely the previous events but also will take into account several future scenarios. The ecological applications of this development will be the assessment and identification of areas with favourable conditions, for both hydrodynamic and water quality parameters, obtaining supportive information to integrate management tools and regarding the preservation of ecosystem's services and functions.

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