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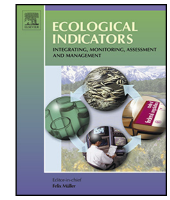

Detecting the impacts of harbour construction on a seagrass habitat and its subsequent recovery

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ABSTRACT

Managing coastal development requires a set of tools to adequately detect ecosystem and water column degradation, but it also demands tools to detect any post-disturbance improvement. Structural seagrass indicators (such as shoot density or cover) are often used to detect or assess disturbances, but while they may be very sensitive to the impact itself, it is unclear if those indicators on their own can effectively reflect recovery at time scales relevant to managers. We used the construction of a harbour affecting a nearby *Posidonia oceanica* seagrass community to test the ability of a set of indicators (structural and others) to detect alterations and to evaluate their sensitivity to recovery of environmental quality after harbour construction was complete and the disturbance ceased. We used a Beyond Before After Control Impact (BBACI) design to evaluate effects on one impacted and three control meadows where we used structural, morphological, community and physiological indicators (26 in total) to asses disturbance impacts. Additionally, we measured some of the potential environmental factors that could be altered during and after the construction of the harbour and are critical to the survival of the seagrass meadow (light, sediment organic matter, sediment accrual).

Harbour construction caused a clear increase in sediment organic matter and in sediment deposition rates, especially fine sand. Light availability was also reduced due to suspended sediments. Sediment and light conditions returned to normal levels 5 and 15 months after the construction began. As expected, seagrass structural indicators responded unequivocally to these environmental changes, with clear reductions in shoot density. Additionally, reduced light conditions quickly resulted in a decline in carbohydrate content in affected meadows. Unexpectedly, we also recorded a significant increase in metal content in plant tissues. No response was detected in the physiological indicators related to eutrophication (e.g. N and P content in tissues) and in morphological (shoot biomass) and community (epiphyte biomass) indicators. More than three years after the completion of the harbour, structural indicators did not show any sign of recovery. In contrast, physiological indicators, mainly heavy metal and carbohydrates content, were much better in detecting the improvement of the environmental conditions over the fairly short period of this study. These results indicate that while structural indicators are critical to evaluate the immediate effect of disturbances and the recovery on impacted systems, specific physiological indicators may be much better suited to determining the timing of environmental quality recovery. The design of impact and monitoring protocols in the wake of coastal developmental projects need to consider the differential effectiveness and time–response of measured indicators carefully.

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1. Introduction

Coastal zones around the world have been and are still facing intensive development that includes the construction of marine infrastructures such as harbours and breakwaters (Short and Wyllie-Eciieverria, 1996; Waycott et al., 2009). These large, physical structures modify the interface between the sea and the land, can destroy valuable marine habitats (Inglis and Lincoln-Smith, 1995) and alter currents and sediment dynamics (Morales et al., 2004). In addition, the process of construction itself also produces several associated effects that may have extended areas of influence. Specifically, the construction of harbours has been associated with increases in the fine sediment fraction and in water turbidity (Erftemeijer and Robin Lewis, 2006) and with changes in current dynamics that can affect sediment deposition (Morales et al., 2004; Anfuso et al., 2011) among other effects. Detecting the appearance of ecological impacts, assessing their consequences and understanding the time course for natural conditions to re-establish following cessation of the disturbance are some of the main challenges for environmental management in the coastal zone.

Indicators are among the most important tools used by managers to detect changes in ecosystems due to anthropogenic impacts or improvements due to successful management actions (Heink and Kowarik, 2010). Their present-day importance is reflected by the huge effort devoted to develop a large array of indicators in many different environments, from forest ecosystems (Brooks et al., 1998) to freshwater (Harig and Bain, 1998; Munné and Prat, 2009) and coastal water marine systems (Carignan and Villard, 2002; Ballesteros et al., 2007; Martínez-Crego et al., 2008). According to Heink and Kowarik (2010), an indicator in ecology and environmental planning is defined as something used to depict or evaluate environmental conditions or changes or to set environmental goals, where this *something* can be either a component or a measure of environmentally relevant phenomena. For the present work, we use the term “indicator” only in the second sense, that is, a measure of environmentally relevant phenomena.

The rate at which the indicators respond to degradation and improvement in physical environmental conditions is therefore, a key aspect for their use and interpretation, yet it is often overlooked (Donangelo et al., 2010). Indeed, most of them have been validated only to track trajectories of ecosystem degradation. Few have proven successful in tracking recovery, since recovery is often more protracted and, in many cases, may follow complex, nonlinear trajectories (Scheffer et al., 2001; Carstensen et al., 2011). This is especially true for ecosystems with slow-growing species, where recovery processes are typically slow, often occurring over significantly longer time periods than standard monitoring programs are funded for. The failure to detect recovery in these systems may result in the erroneous conclusion that disturbance has persisted or that remedial actions were inadequate, both of which may have important consequences for long-term management.

Seagrass meadows are one of the dominant ecosystems in shallow coastal marine waters over the world with important contributions to their goods and services (Cullen-Unsworth and Unsworth, 2013). Additionally, seagrass ecosystems are extremely sensitive to changes in water quality and to other human induced disturbances (Short and Wyllie-Echevarria, 1996; Krause-Jensen et al., 2005; Lopez et al., 2010). As a result, seagrass ecosystems have been used in many monitoring programs (Marbà et al., 2012) to obtain reliable indicators. Among them, structural ones are the most widely used because of their ease of measurement and their clear links to ecosystem structure and services. Likewise, morphological parameters have been used worldwide as a good measure of plant health and stress (Marbà et al., 2012). Finally, physiological indicators are increasingly being used in monitoring programs as they are reported to be efficient tools for early detecting of anthropogenic disturbances (Martínez-Crego et al., 2008).

Posidonia oceanica (L.) Delile is the most important and widespread seagrass in the Mediterranean sea, where it forms extensive meadows from the surface down to 40 m depth (Bouduresque et al., 2006). *P. oceanica* is a foundation species (sensu Dayton and Hessler, 1972) that performs important ecological functions in the ecosystem but is also extremely sensitive to changes in environmental conditions. This makes *P. oceanica* one of the species from which the largest number of indicators have been described so far (Montefalcone, 2009). In particular, with a set of structural, physiological, morphological and community indicators, this plant has been observed to effectively detect changes in light availability, sediment characteristics and increases in organic matter – the most frequent physical changes associated with coastal development (Ruiz and Romero, 2001, 2003; Erftemeijer and Robin Lewis, 2006; Frederiksen et al., 2006; Pérez et al., 2007; Serrano et al., 2011). Of these, physiological indicators are well known to have driver-specific responses and this specificity has been used as a tool to identify the causal factors behind deterioration in the ecosystem or in water quality (Martínez-Crego et al., 2008). Nevertheless, there is still little known about the rate of response of these indicators to improvements in the physical environment once the disturbance has ceased (i.e. how they track recovery). As already stated, the inability to track the timing and form of response to improved environmental conditions can lead to erroneous management decisions, with potentially negative economic, social and ecological consequences. In this context, we examined the response of a range of indicators within a *P. oceanica* seagrass ecosystem to the construction of a harbour (discrete disturbance) in NW Catalonia, Spain. Our main objective was to test the ability of 26 commonly used indicators to detect alterations during the construction of the harbour and their sensitivity to potential recovery in environmental conditions over three years after the construction had been completed.

2. Materials and methods

2.1. Study design

The study was designed to detect the impacts of a harbour construction on a nearby *P. oceanica* meadow and its potential recovery when the construction had been completed. We employed a Beyond-BACI design (BBACI, Underwood (1992), measuring responses from a *P. oceanica* meadow close to an expanding harbour (‘impact’ location) and at three distant (non-impacted) meadows before, during and after harbour construction ceased, see (Table 1). At each location we measured 26 commonly used seagrass indicators to test their ability to track the time course of recovery. In parallel, we also measured the main environmental drivers associated with the ecological impacts of harbour construction: water transparency, sediment deposition and sediment grain size, produced during and after the construction (Erftemeijer and Robin Lewis, 2006).

2.2. Study area and harbour construction

The study area is situated in the NE coast of Spain between two localities, Blanes and Lloret de Mar, both with intense tourism development. Blanes had one of the biggest harbours in the area, with a mooring capacity for 59 fishing vessels and 684 recreational boats. In March of 2010 (Table 1) construction began to add a new external breakwater to the harbour. This meant the occupation of 42,037 m^2 of sea surface, dredging 40,000 m^3 of sediment from the seafloor and using several tonnes of sand and stones to stabilize the