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# A predictive model based on multiple coastal anthropogenic pressures explains the degradation status of a marine ecosystem: Implications for management and conservation

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## ABSTRACT

During the last fifty years, there has been a dramatic increase in the development of anthropogenic activities, and this is particularly threatening to marine coastal ecosystems. The management of these multiple and simultaneous anthropogenic pressures requires reliable and precise data on their distribution, as well as information (data, modelling) on their potential effects on sensitive ecosystems. Focusing on *Posidonia oceanica* beds, a threatened habitat-forming seagrass species endemic to the Mediterranean, we developed a statistical approach to study the complex relationship between human multiple activities and ecosystem status. We used Random Forest modelling to explain the degradation status of *P. oceanica* (defined herein as the shift from seagrass bed to dead matte) as a function of depth and 10 anthropogenic pressures along the French Mediterranean coast (1700 km of coastline including Corsica). Using a 50 × 50 m grid cells dataset, we obtained a particularly accurate model explaining 71.3% of the variance, with a Pearson correlation of 0.84 between predicted and observed values. Human-made coastline, depth, coastal population, urbanization, and agriculture were the best global predictors of *P. oceanica*'s degradation status. Aquaculture was the least important predictor, although its local individual influence was among the highest. Non-linear relationship between predictors and seagrass beds status was detected with tipping points (i.e. thresholds) for all variables except agriculture and industrial effluents. Using these tipping points, we built a map representing the coastal seagrass beds classified into four categories according to an increasing pressure gradient and its risk of phase shift. Our approach provides important information that can be used to help managers preserve this essential and endangered ecosystem.

## 1. Introduction

Ecosystems are globally threatened by anthropogenic pressures (Halpern et al., 2008; Hoekstra et al., 2005; Jackson et al., 2001; Stachowitsch, 2003; Vitousek et al., 1997). The increasing impact of humans on ecosystems is accompanied by an increasing demand on ecological services (e.g. production of edible biomass or nutrient cycling). In this context, concerns are emerging about our capacity to manage the balance between human impacts, ecosystem status and the provision of ecological services (United Nations Environment Programme, 2006). These concerns affect the vast majority of the human population, but they are particularly pressing for coastal ecosystems which concentrate high levels of marine biodiversity (Halpern et al., 2008). Therefore, the development of new predictive tools to support decision makers to maintain healthy ecosystems, despite increasing pressures, are urgently needed (Mouquet et al., 2015).

The relationship between the intensity of anthropogenic pressures and the status of ecosystems is largely acknowledged (Wilkinson, 1999). Well-known examples include the 'phase shift' (or regime shift) which implies a dramatic change from a healthy to a degraded ecosystem status after a tipping point is reached (Hughes, 1994; Scheffer et al., 2001). The existence of non-linearity in an ecosystem's response to disturbance adds complexity and challenges for the development of predictive statistical tools. For example, diverse methods, from

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experiments to time series analyses have been used to study a decrease and/or an unexpected resurgence of seagrass in a non-linear way (Connell et al., 2017; Gurbisz and Kemp, 2014; Hughes et al., 2017; Lefcheck et al., 2017). However, non-linearity also opens new possibilities for ecosystem management if thresholds and tipping points are identified (Folke et al., 2004). Indeed, the same variation in pressure intensity could have either a negligible or dramatic effect on ecosystems, according to the nature of the system-pressure relationship, and the position of the ecosystem status relative to the tipping point. It also means that different ecosystem "states" (e.g., bare sediment, dead seagrass beds and sediment colonized by alive seagrass or submersed aquatic vegetation) can exist under the same set of environmental conditions (e.g., turbid and clear water) (Gurbisz and Kemp, 2014). Therefore, the development of tools able to quantify the nature of the system-pressure relationship and the relative distance to tipping points is essential so that managers can understand how their decisions impact ecosystems (Graham et al., 2015).

In this study, we developed a spatially explicit statistical approach to: (i) characterize the system-pressure relationship for multiple pressures, (ii) identify tipping points and (iii) use the distance from these tipping points to classify an ecosystem according to its risk of phase shift. Seagrass ecosystems were chosen because they provide many ecosystem services such as nursery, spawning, feeding and oxygenation, and they also aid coastal protection and sediment trapping (Borum et al., 2004; Campagne et al., 2015). However, they are threatened by many human activities such as shoreline alteration, anchoring, wastewater release and climatic changes (Orth et al., 2006, 2017a; Waycott et al., 2009). We chose the most common Mediterranean seagrass meadow (*Posidonia oceanica* (L.) Delile) as a model system. *P. oceanica* is a protected plant (Pergent et al., 2010) which forms extensive meadows from the surface to depths of 40 m (depending on water transparency and temperature). Over the last 100 years, a global decline with losses exceeding 25% worldwide has been observed for most species of seagrass (Waycott et al., 2009), including *P. oceanica,* whose loss of area has been evaluated to be 10% (Boudouresque et al., 2012; Marbà et al., 2014). A recent study led along the French South-Eastern coast specified that 73% of the shallow seagrass limits had declined over the last 85 years, with a loss of 13% of the initial shallow meadow areas (spatial extent between 0 and 15 m deep) (Holon et al., 2015a). Lost areas were mainly found along human-made coastlines such as harbours (Holon et al., 2015a). Coastal infrastructures were also recently recognized as a major threat to the *P. oceanica* food web (Giakoumi et al., 2015).

Based on an extensive collection of high resolution field data, we propose a framework to quantify the role of multiple anthropogenic pressures in shaping the status of coastal ecosystems, such information can then be used to map their risk of degradation. We used a fine resolution (scale 1:10000) spatial dataset covering the entire French Mediterranean coastline (1700 km), combining the distribution of *P. oceanica* and 10 anthropogenic pressures in a statistical modelling framework. Our approach comprised four main steps: (1) mapping human pressures and their intensities for three different grid cell sizes using a geographic information system (GIS), (2) mapping living and dead *P. oceanica* beds, (3) modelling and predicting the relationships between the distribution of human pressures and the degradation status of *P. oceanica* (4) use of the best model to build maps highlighting priority areas for management, according to the tipping point values (identified by step 3) of the 10 anthropogenic pressures.

## 2. Materials and methods

### 2.1. Study area and seagrass bed maps

Our study considers the French Mediterranean coastline (1700 km including Corsica) between 0 m and 40 m deep, i.e. the bathymetric range of *P. oceanica* in France (Boudouresque et al., 2012). Two ecosystem states were taken into account: living *P. oceanica* seagrass beds and dead matte covering (what remains of the plant after its death), which account for 70,641 ha and 5693 ha of seabed, respectively (Holon, 2015). Maps of these marine habitats and bathymetric data were obtained during previous work and are freely available after free registration at http://www.medtrix.fr (DONIA expert project, see Holon et al., 2015a, 2015b for details concerning data and map building). Briefly, after compiling a bibliographic synthesis, we gathered and homogenized data from 1:10000 habitat maps; these data were collected by different organizations and programmes (see Acknowledgements). Campaigns were led between 2005 and 2014 using classical methods: aerial or satellite photography, side-scan sonar survey, sonar survey and validation through direct observations ("ground-truth points") based on classical dives and/or towed dives. A final 1:10000 continuous habitat map was realized, comprising 11 habitat classes including *P. oceanica* seagrass and dead matte. For this study, all habitats other than *P. oceanica* and its dead matte were removed. To find the scale that allowed for the best model, the original vector map was rasterized using three different grid cell sizes: 20 × 20 m, 50 × 50 m and 100 × 100 m. For each cell size, the degradation status of *P. oceanica* meadows was calculated as the percentage of dead matte cover (interpreted as a decline rate, see Moreno et al. (2001)); the higher the percentage of dead matte cover, the higher the degradation status.

### 2.2. Anthropogenic pressures

We considered 10 relevant pressures for which data were available (Holon et al., 2015b): (1) agriculture (land cover), (2) aquaculture (total area of the farms), (3) coastal erosion (land cover), (4) industrial effluents (chemical oxygen demand), (5) human-made coastline (big harbours/harbours/artificial beaches, ports of refuge/pontoons, groynes, landfills and seawall areas), (6) boat anchoring (number and size of boats observed during summer), (7) fishing (traditional and recreational fishing areas estimated from the observation of buoy nets, pleasure fishermen and fishing boats i.e. passive fishing), (8) coastal population (size and density considering the inhabitants/residents), (9) urban effluents (capacity and output) and (10) urbanization (land cover). It is thought that these pressures impact the seagrass by modifying water clarity and/or current, and/or by causing direct physical damage (Boudouresque et al., 2012). Coastal populations often include consumers which can lead to an increased demand on resources (water, energy, raw material) and natural areas for recreational activities, and can also increase the emission of various pollutants in the water, soil and air (Savage et al., 2010). By definition, human-made coastline, coastal population and urbanization were somewhat correlated (Spearman correlation coefficient 0.57–0.62), but not enough ($< 0.8$) to discard any of them. Moreover, Random Forests, i.e. the method that we used, are unaffected by multicollinearity. All other predictors were poorly correlated (Spearman correlation coefficient $< 0.27$). Details concerning data and map building have previously been described in Holon et al. (2015b). Briefly, data concerning the origin and intensity of these pressures came from published databases: MEDAM, CORINE land cover, INSEE and MEDOBS data, but were also provided by Agence de l'Eau RMC and IFREMER. Satellite-aerial pictures and unpublished data from Andromède océanologie were also analysed. Models of the spatial extent of the pressures were built using ArcGIS 10 (ESRI, Redlands, California, USA), with a 20 m distance matrix. We applied a pressure curve (type $y = a.\exp(-bx)$) considering the distance (but not the current) to the source with a negative exponential shape ranging between 100% (origin) and 0% (no more impact) to each type of pressure. We also included bathymetry to model the spread of each pressure (Holon et al., 2015b). Please note that for a given pressure, grid cells with equivalent pressure values could correspond to different types of origin and intensity, for example for human-made coastline, the pressure at a large distance (15 km) from a large harbour may correspond in