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Towards a predictive model to assess the natural position of the *Posidonia oceanica* seagrass meadows upper limit

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ABSTRACT

The upper portion of the meadows of the protected Mediterranean seagrass *Posidonia oceanica* occurs in the region of the seafloor mostly affected by surf-related effects. Evaluation of its status is part of monitoring programs, but proper conclusions are difficult to draw due to the lack of definite reference conditions. Comparing the position of the meadow upper limit with the beach morphodynamics (i.e. the distinctive type of beach produced by topography and wave climate) provided evidence that the natural landwards extension of meadows can be predicted. An innovative model was therefore developed in order to locate the region of the seafloor where the meadow upper limit should lie in natural conditions (i.e. those governed only by hydrodynamics, in absence of significant anthropogenic impact). This predictive model was validated in additional sites, which showed perfect agreement between predictions and observations. This makes the model a valuable tool for coastal management.

1. Introduction

The problem of sliding baselines represents a major concern for the evaluation of global change impacts on ecosystems (Dayton et al., 1998; Hobday, 2011). Lack of information on pristine (or at least historical) conditions to be used as references impairs our understanding of the effects of global change on natural ecosystems and their consequences on the amount of resources a healthy ecosystem can provide. Although marine systems may seem less accessible to human uses and impacts than terrestrial ecosystems, global assessments revealed that pristine areas are lost also in the marine realm (Jackson and Sala, 2001; Stachowitsch, 2003). Seagrass meadows are among the most important elements for the functioning of marine coastal ecosystems, and represent a major focus for research and conservation (Koch et al., 2006). This paper is focused on the endemic seagrass *Posidonia oceanica,* the most important and abundant of the Mediterranean Sea. Its meadows form a key coastal habitat and strongly influence coastal features in terms of wave reduction and nearshore sedimentary patterns (Boudouresque et al., 2012). Anthropogenic pressure causes the regression of *P. oceanica* meadow upper and lower limits (i.e. the shallowest and the greatest depths reached by the plant, respectively), which implies a reduction in its extension and therefore a functional loss for the coastal ecosystems (Montefalcone et al., 2010a, 2010b; Boudouresque et al., 2012). Assessing the natural position, i.e. the baseline, of seagrass meadow limits is crucial to define their reference status in order to distinguish the impact of natural processes as opposed to anthropogenic factors (Pergent et al., 1995; Montefalcone et al., 2010b). Recent efforts have been invested worldwide for the preservation of coastal ecosystems, also from a legislative point of view (Ricketts and Harrison, 2007; Barnes and McFadden, 2008; Borja et al., 2008). In Europe, both the Water Framework Directive (WFD, 2000/60/EEC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EEC) recognize as mandatory the maintenance of seafloor integrity, which has to be assessed by comparison with reference conditions (Duarte et al., 2008). In general, reference conditions can be defined in three ways: (i) historical information, when available and reliable, which is not always the case (Leriche et al., 2004; Montefalcone et al., 2013; Lyons et al., in press); (ii) data collected in pristine areas, still scarce worldwide and often insufficiently enforced (Stachowitsch, 2003; Montefalcone et al., 2009); (iii) modelling (Valle et al., 2011; Parravicini et al., 2012; Downie et al., in press).

The *P. oceanica* meadow upper limit usually occurs within the most dynamic region of the seafloor (Boudouresque et al., 2012). Recent literature highlighted that coastal dynamics strongly

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influence the shallowest meadow portions (Folkard, 2005; Infantes et al., 2009; Vacchi et al., 2010). This paper explores the relationship between the position of the meadow upper limit and the morphodynamic domain of the beach (i.e. the distinctive type of beach created by the interplay of topography, wave climate and sediment composition, Benedet et al., 2004) on a wide spatial scale in the NW Mediterranean Sea. We hypothesized that, in absence of major human pressures, the structure (i.e. shoot density and seagrass cover) of the upper limit of *P. oceanica* meadows and its position along the region of the underwater beach profile mostly reworked by wave action, are mainly controlled by local nearshore hydrodynamics. An innovative predictive model was developed: it can accurately identify the seafloor portion where the meadow upper limit should lie in natural conditions (i.e. conditions defined by hydrodynamics alone) and could provide the proper tool to define reference conditions for healthy meadows.

2. Methods

2.1. Study area

The study was carried out in Liguria, an administrative Region of NW Italy, where virtually all existing *P. oceanica* meadows have been included within Sites of Community Importance (SCIs) according to the European Community Directive of 1992 (EEC, 1992). We investigated 10 coastal areas (Fig. 1) where *P. oceanica* meadows occur on sedimentary seafloor, according to the detailed cartography provided by Liguria Region (Diviacco and Coppo, 2007). Selected coastal areas show different geomorphologic setting and wave exposure and were historically subject to low anthropic pressure (Diviacco and Coppo, 2007; Montefalcone et al., 2010a, 2010b).

The ~350 km long Ligurian coastline (Fig. 1) is mainly characterized by rocky headlands alternating with sandy to gravelly beaches, especially along the Eastern Riviera: soft coasts are relatively less developed and are typically found adjacent to small coastal plains along the Western Riviera (Rovere et al., 2010, 2011). Ligurian coastline wave regime is mainly influenced by winds blowing from southwest, with small differences between the two Rivieras (Fig. 1, Corsini et al., 2006; www.idromare.it). The SW (220–240° N) is the dominant wave direction, with a fetch longer than 800 km and an offshore wave height of more than 4 m. The SE (130–150° N) and the S (180° N) wave directions, both characterized by fetches of about 200 km and waves of about 2 m height, have comparatively lower impact.

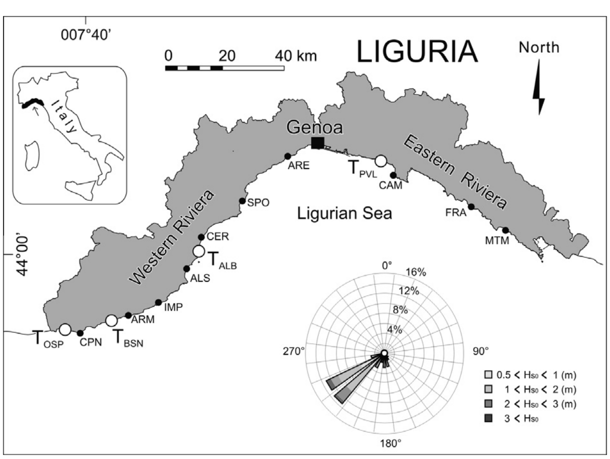

Fig. 1. Study areas along the Ligurian coastline. Black dots individuate the 10 *Posidonia oceanica* meadows investigated: Alassio (ALS), Arenzano (ARE), Arma di Taggia (ARM), Camogli (CAM), Framura (FRA), Imperia (IMP), Monterosso al Mare (MTM), Spotorno (SPO), Capo Nero (CPN) and Ceriale (CER). White dots represent the 4 meadows where the predictive model was tested: Albenga (T_{ALB}), Bussana (T_{BSN}), Pieve Ligure (T_{PVL}) and Ospedaletti (T_{OSP}). The annual wave climate is also indicated (data from Corsini et al. (2006), modified). H_{S0} is the significant offshore wave height (m) recorded by the La Spezia buoy (43.92917° N, 9.82778° E).

2.2. Hydrodynamic study

Two hydrodynamic limits along the underwater beach profile represent important boundaries to be considered in coastal engineering design (Sorensen, 2006): (i) the breaking depth, i.e. the depth where waves break (Smith, 2003); and (ii) the closure depth, i.e. the depth where wave action on the seafloor becomes negligible (Dean and Dalrymple, 2004). Intense alongshore and onshore–offshore transports take place only in depths shallower than the closure, whereas horizontal water particle velocity reaches its maximum values at breaking depth and increases its movement towards the shoreline.

In each area a detailed bathymetric survey was carried out with a single-beam echo-sounder (single frequency, error ± 0.1 m, 1 point every 5 s) and differential GPS to define the morphology of seafloor where meadows grow. A detailed 2D bathymetric map (1:5000) was produced for each of the 10 areas; together with the local wave parameters (Table 1), it allowed identifying the two hydrodynamic boundaries along the underwater beach profile. The breaking depth (d_b) was calculated using the formula (Smith, 2003)

$$d_b = H_b/\gamma_b \tag{1}$$

where $H_b = H_0 K_{sh}\sqrt{(\varphi_o/\varphi_b)}$; ($K_{sh}$ = shoaling coefficient, φ_o and φ_b = offshore and nearshore waves approach angle, respectively); and $\gamma_b = b - (aH_b)/(gT_0^2)$ (a and b being empirical coefficients depending on the beach slope, Smith 2003). Annual offshore wave parameters (return time 1 year) were preferred to daily average waves as the latter could underestimate the effect of annual extreme events on the meadow (Infantes et al., 2009; Vacchi et al., 2012a).

The closure depth (d_c) was computed using the following formula (Sorensen, 2006)

$$d_c = 6.75 H_s \tag{2}$$

where H_s is the mean annual significant wave height.

2.3. Underwater surveys

We assessed the structure of the upper portion of the *P. oceanica* meadows and the sedimentary features of the seafloor by scuba diving surveys carried out on three different sites (A, B and C), which were selected at least 100 m apart from each other in each coastal area (Fig. 2). In each site, five stations were located along the underwater beach profile in order to encompass both breaking and closure depth (Fig. 2); in particular, the location of station 1

Table 1
H_0, T_0, and L_0 values (return time 1 year) in the 10 study areas (Corsini et al., 2006, www.idromare.it). See Fig. 1 for the codes of each areas. H_0 is the offshore wave height, T_0 is the offshore wave period and L_0 is the offshore wave length.

Area	H_0 (m)	T_0 (m)	L_0 (m)
ALS	2.6	5.8	52.4
ARE	4.0	7.5	87.7
ARM	4.0	7.5	87.7
CAM	4.2	7.8	94.9
CER	2.6	5.8	52.4
CPN	4.0	7.5	87.7
FRA	4.2	7.8	94.9
IMP	4.0	7.5	87.7
MTM	4.2	7.8	94.9
SPO	2.6	5.8	52.4

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