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Assessment of the impact of salvaging the Costa Concordia wreck on the deep coralligenous habitats

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The coralligenous habitats found in the Mediterranean Sea are hotspots comparable in biodiversity to tropical reefs. Coralligenous reefs are vulnerable to many human pressures, thus they are among the most threatened habitats in the Mediterranean Sea. In this study, we assessed the impacts on coralligenous habitats of activities associated with salvaging the wreck of the Costa Concordia cruise ship. After its partial foundering in 2012, the Costa Concordia remained adjacent to the eastern coast of Giglio Island (Tuscany, Italy), in the Tyrrhenian Sea, for over two years. Its salvage required high-impact engineering works, during the course of which monitoring of benthic communities was undertaken. We performed Rapid Visual Assessment (RVA) sampling (using recorded video) from 17 stations located between 35 and 76 m depth and characterized by coralligenous habitats. Sampling activity was performed during the summers of 2012, 2013, and 2014. In parallel, chemical and physical water parameters were measured continuously from summer 2012 to the end of summer 2014, in order to detect any perturbation in natural conditions caused by salvage activities. We assessed the ecological quality of coralligenous habitats by applying the COARSE (COralligenous Assessment by ReefScape Estimate) index, based on the RVA approach. Slight modifications were applied to one of the descriptors of the COARSE index in order to adjust for study site features. There was clear evidence of a reduction in coralligenous habitats quality. Assemblages, slope, type of pressure, and distance from the source of disturbance played a pivotal role in characterizing bottom quality. The index was shown to have an easy and cost-effective application, even in waters deeper than its calibration specification; furthermore, the modification reported here may increase its potential applications.

Introduction

Coralligenous habitats are biogenic reef formations endemic to the Mediterranean Sea. They are primarily produced by the accumulation of encrusting algae growing in dim light conditions and, secondarily, by bioconstructor animals such as polychaetes, bryozoans, and anthozoans (Ballesteros, 2006). Coralligenous habitats have been identified as the climax circalittoral Mediterranean biocenosis (Pérès and Picard, 1964), although they may be found in shallower waters if conditions allow coralline algae development (Martì et al., 2004; Romdhane et al., 2007). Even though coralligenous reefs have been recognized as the second most important ‘hotspot’ of biodiversity in the Mediterranean Sea, after *Posidonia oceanica* meadows (Ballesteros, 2006), there are few studies and estimates of the diversity of sessile and vagile macroinvertebrate species recorded in this community type (Antoniadou and Chintiroglou, 2005; Ballesteros, 2006; Ponti et al., 2010; Bertolino et al., 2013; Bedini et al., 2014; Poursanidis and Koutsoubas, 2015). To date, Coralligenous reefs studies have mainly used non-destructive sampling methods such as photographic and visual assessments, due to the operational restrictions imposed by scuba diving, conservation purpose, and the high heterogeneity and complexity of the habitat (Parravicini et al., 2010; Kipson et al., 2011; Trygonis and Sini, 2012; Zapata-Ramírez et al., 2013; Gerovasileiou et al., 2016). Considering their slow dynamics and longevity, coralligenous reefs are among the habitats most exposed to human impacts (Ballesteros, 2006; Teixidó et al., 2011; Giakoumi et al., 2013), and as such are safeguarded under environmental protection legislation. In fact, they were incorporated into the category ‘reefs’ under the EC Habitats Directive (HD, 92/43/ EEC), and are therefore automatically included in the network of Natura 2000 sites (Council of the European Communities, 1992).

Furthermore, the contracting parties of the Barcelona Convention (1995) adopted the ‘Action plan for the conservation of the coralligenous and other calcareous bio-concretions in the Mediterranean Sea’ (UNEP-MAP-RAC/SPA, 2008). Coralligenous habitats must be monitored through assessment of the descriptors of Good Environmental Status (GES) contained in the Marine Strategy Framework Directive (MSFD, 2008/56/EC), particularly descriptors 1 (biodiversity) and 6 (sea-floor integrity).

On 13 January 2012, the cruise vessel Costa Concordia collided with a rock in the Tyrrhenian Sea, just off the eastern shore of Giglio Island (Tuscany), on the western coast of Italy. It sank few hundred metres north of Giglio Porto harbour, eventually settling at an inclined angle of 65° towards the starboard (right-hand) side, which was submerged in shallow waters, while most of the port (left-hand) side laid out of the water. Salvage operations began in May 2012 with preparations to safely rotate the wreck (www.theparbacklingproject.com). Firstly, the wreck was stabilized using a special anchoring system in order to prevent any slippage or sinking along the steep seabed slope; 15 caissons were installed, on its port side. An artificial seabed was then installed on which the wreck could rest after rotation; it consisted of grout bags (bags filled by cement) inserted in the gaps between the rocks, and six submerged iron platforms (three large and three small), with the 2-m diameter piles inserted both on granite and sandy bottoms. With these safeguards in place, it was possible to rotate the Costa Concordia wreck in September 2013, using the parbuckling procedure. Subsequently, a further 15 caissons were positioned on the starboard side, and some parts of the wreck were removed in order to reduce its weight. Two and a half years after the shipwreck, at the end of July 2014, the Costa Concordia was refloated and towed to Genoa harbour. In this context, the wreck and subsequent salvage of the ship presented potentially negative impacts on the surrounding relevant marine area. The need for environmental assessment played a pivotal role during the entire salvage operation. Monitoring was undertaken to detect any alterations in physico-chemical parameters in the water column, and resulting responses from benthic communities. In particular, baseline surveys and mapping of key and sensitive habitats, such as P. oceanica meadows and coralligenous reefs, were carried out in the area of activity from June 2012, followed by continuous monitoring during salvage activities. The major concern was for uncontrolled spillage of pollutant substances deriving from the wreck. In this context, *Mytilus galloprovincialis* was chosen as bioindicator organism through the Mussel Watch Program in order to detect variations of bioavailability and the early onset of molecular and cellular effects. Results obtained from Mussel Watch excluded serious contamination events or increases in environmental pollution (Regoli et al., 2014). On the other hand, the presence of the cruise shipwreck, together with other vessels used during the salvage operations, completely changed the natural features of the study site and promoted fouling settlement, as reported by Bacci et al. (2016), and Casoli et al. (2016). Furthermore, the aforementioned operations on the seafloor and on the wreck (i.e. grout bags filling, drilling, caissons installation and following reduction of ship weight) might have led to sedimentary alteration and debris loss.

In the wider context of monitoring the 'sea-floor integrity', the COARSE index (COralligenous Assessment by ReefScape Estimate), based on the RVA (Rapid Visual Assessment) approach, has been proposed as a suitable tool for the assessment of the ecological quality of coralligenous reefs (Gatti et al., 2012, 2015a). This index has been built using the 'structural approach', distinguishing the basal (BL), intermediate (IL), and upper layers (UL), as the coralligenous reefs show a stratified structure. Each layer is characterized by three descriptors that contribute to the assignation of a layer quality score (for a full description, we refer to Gatti et al., 2015a). The salvage of the Costa Concordia presented an opportunity to test this method. In this regard, based on the hypothesis that coralligenous quality may change if subjected to anthropogenic stressors, we pursued three main objectives: (i) to report and determine the impact of the Costa Concordia salvage operation on deep coralligenous reefs; (ii) to provide baseline data for monitoring potential modifications of coralligenous habitats subjected to multiple stressors; and (iii) to assess the sensitivity of the COARSE index, as designed by Gatti et al. (2015a), under different anthropogenic pressures and at greater depths compared to those where the index was originally applied and calibrated.

Materials and methods

Study area

The study area was located along the east coast of Giglio Island, in the Tuscany archipelago, central Tyrrhenian Sea, few hundred metres north of Giglio Porto harbour (Fig. 1). This area corresponds to the area of restricted access during the salvage operation; in order to avoid any disturbance during the wreck removal phases, and to maximize safety in the case of an accident, the operational area was clearly defined, and any touristic or recreational activity (i.e. diving, sailing, swimming) was forbidden. The sea bottom at this location was characterized by two monzogranite rocky ridges (identified as the S and N ridges), developing from a few metres up to 80 m depth, separated from each other and surrounded by sandy sediments. Very high-resolution (0.20 m) multibeam sonar imagery (RESON Seabat 7125 sv2 multibeam system) was collected during the summers of 2012 and 2014, during baseline surveys and once salvage activities were completed, respectively. The bathymetric profiles were processed using the PDS2000 swath editor tool, which provided a high quality digital terrain model (DTM, 20 × 20 cm grid size), which was then imported into ArcGIS 10.2.2.
Remotely operated vehicle (ROV, Prometeo-Elettronica Enne Savona) surveys were carried out as part of the baseline monitoring in the early summer of 2012 and detected coralligenous habitats below 40 m depth.

Monitoring of water features

Water features were monitored throughout the salvage operation, in order to capture any alterations in the physico-chemical parameters of the water column. In particular, 13 fixed monitoring stations distributed across the area impacted by the salvage activities were monitored using from the surface down to 30–50 m depth (Fig. S2). Turbidity (Tu; values in Formazine Turbidity Units, FTU) daily measurements (using probes MAR-330 and IP010D, IdromarAmbiente) in stations 3, 5 (because these were located close to the rocky outcrops here studied), and 9 (as control site) were taken into account. In addition to measurements from the fixed water monitoring stations, the principal turbidity events caused by programmed salvage operations were monitored using mobile stations following the development of the plume and its extension. We have reported three cases as examples of considerable sediment release in 2013; these occurred during the drilling phase before installation of the platforms and filling of the grout bags. Two of these releases, which occurred on 31 January and 18 February 2013, were monitored using a station time series; the third sediment release on 3 May 2013 was monitored using stations carried by a vessel in the turbidity diffusion area.

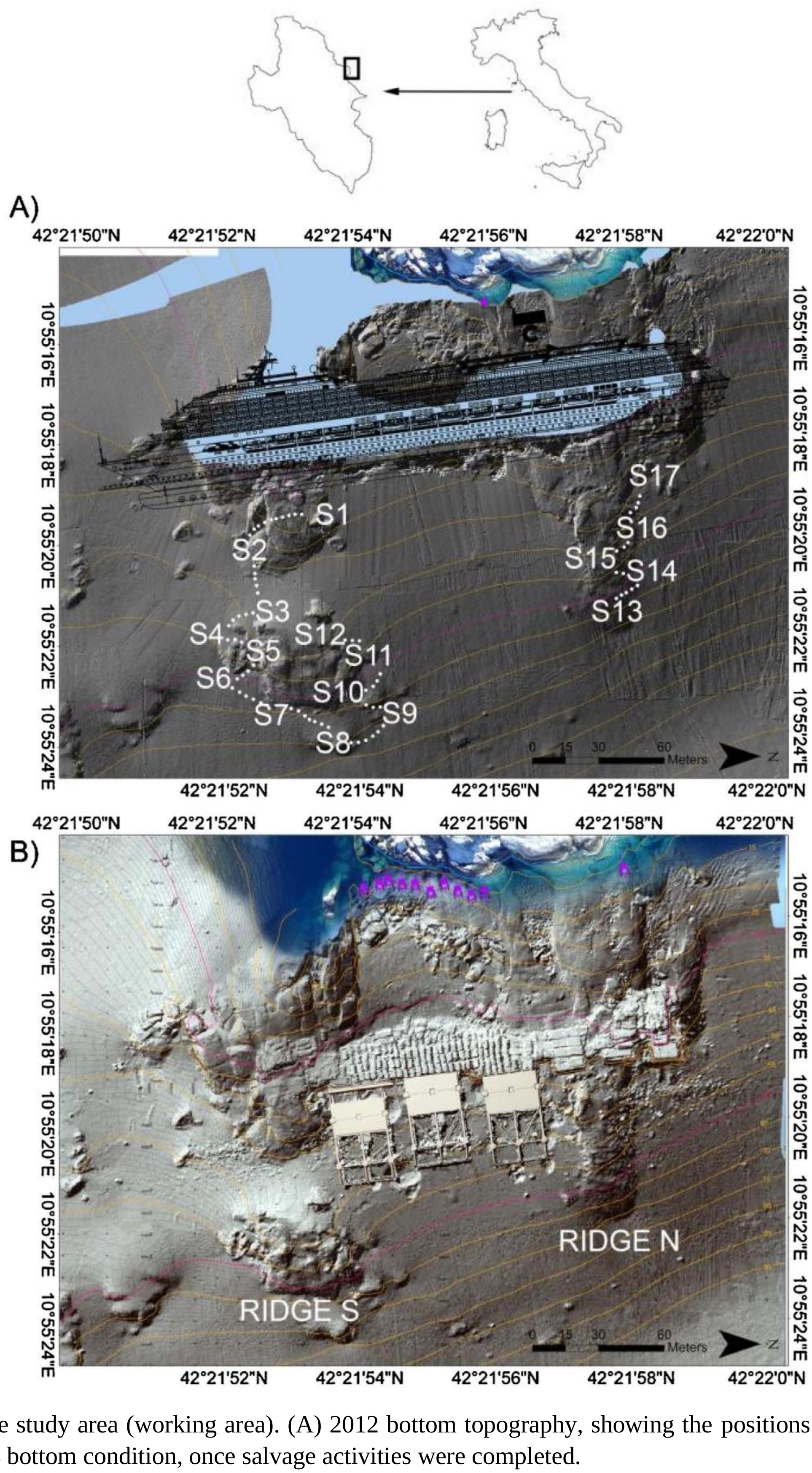

Fig. 1. Map of the study area (working area). (A) 2012 bottom topography, showing the positions of the monitoring stations. (B) 2014 bottom condition, once salvage activities were completed.

Data collection

A total of 17 sampling stations were selected for monitoring the quality of the coralligenous habitats (Fig. 1A and Table 1; named S1–S17). Samplings were carried out by CCUBA divers in summer 2012 (during the baseline surveys), 2013 (before parbuckling), and 2014 (once the Costa Concordia was refloated and towed to Genoa harbour). Divers covered the same route every year, swimming and filming at a distance of 1 m above the substratum. The divers made detailed recordings of three replicates of the sea floor (measuring approximately 2 m^2) on each sampling stations. High quality videos were recorded using a close up zoom lens (Canon C500 with SEACAM housing) in order to investigate concretion portions. Positional information was obtained from an Ultra-Short Base Line (USBL, MicronNav) tracking system attached to the diver. The position of each replicate was imported into a geographical information system (ArcGIS 10.2.2). The following information was collected for each replicate: • Depth: the z-value indicating the height of the corresponding cell, reported in metres.

- Elevation from the bottom: the difference between the replicate depth and the depth of the closest sandy bottom, reported in metres. • Slope: the maximum rate of change in z-value from one cell to its neighbours. Essentially, the maximum change in elevation over the distance between the cell and its neighbours corresponded to the steepest downhill descent from the cell. Three slope classes were defined: 0°–29° (Low), 30°–59° (Medium), and 60°–90° (High).

- Orientation: downslope direction of the maximum rate of change in z-value from each cell to its neighbours. The values of each cell in the output raster indicated which compass direction the surface faced at that location, reported as cardinal points.

- Distance from the wreck: linear distance from the bow and stern water lines for the southern and northern stations, respectively. Five radius classes were defined: 30 m, 60 m, 90 m, 120 m, and 150 m.

Table 1 - Features of the 17 sampling stations. Station ID refers to each station’s identification code.

Station ID	Mean depth (± sd)	Mean elevation (± sd)	Ridge	Slope	Orientation	Assemblages	Distance
S1	36.6 (± 1.5) m	2.1 (± 0.3) m	S	High	NW	As 3	30 m
S2	44.8 (± 1.4) m	1.1 (± 0.2) m	S	High	S-SE	As 1–As 3	60 m
S	48.6 (± 1.2) m	2.1 (± 1.6) m	S	High	W-SE	As 1	90 m
S4	53.4 (± 2.2) m	2.3 (± 0.8) m	S	Low	SE-N	As 2	90 m
S5	54.3 (± 0.5) m	3.0 (± 0.8) m	S	Med-High	S-E	As 1–As 2	120 m
S6	58.3 (± 1.4) m	1.6 (± 0.5) m	S	High	E-NE	As 1–As 3	120 m
S7	62.9 (± 1.3) m	0.8 (± 0.5) m	S	Low	E-SE	As 2	120 m
S8	70.3 (± 2.9) m	2.8 (± 2.0) m	S	High	E-NE	As 3	150 m
S9	65.3 (± 1.4) m	1.6 (± 0.7) m	S	Low-Med	E-NE	As 2–As 3	120 m
S10	60.3 (± 2.1) m	1.6 (± 0.9) m	S	Low-Med	E-N	As 1–As 2	120 m
S11	54.6 (± 1.2) m	2.2 (± 0.7) m	S	Med-High	N	As 2–As 3	120 m
S12	52.0 (± 1.7) m	2.1 (± 1.2) m	S	Low	E-N	As 2	120 m
S13	63.7 (± 2.3) m	1.8 (± 1.3) m	N	Low	NE	As 2–As 3	120 m
S14	56.9 (± 1.6) m	1.3 (± 0.5) m	N	Low	NE	As 2	90 m
S15	57.0 (± 4.1) m	1.7 (± 0.7) m	N	Low	NE	As 2	90 m
S16	50.0 (± 1.3) m	1.8 (± 0.9) m	N	Low-Med	NE	As 2	90 m
S17	43.7 (± 2.0) m	1.5 (± 0.0) m	N	High	NE	As 1	60 m

Furthermore, the replicates were biologically characterized in accordance with the European Nature Information System (EuNIS) codification (Davis et al., 2004), and the Relini and Giaccone (2009) habitats classification. The following assemblages (As.) were identified: facies with *Eunicella c*avolini and *Paramuricea clavata* (EuNIS codes: A4.26B, A4.269) (As. 1); association with *Flabellia petiolata* and *Halimeda tuna* (EuNIS codes: A3.23J, A4.267) (As. 2); communities of circalittoral caves and overhangs (EuNIS code: A4.71) (As. 3) (Fig. S3). Moreover, a 'pressures' category, based on visual estimations, was assigned to each replicate, where: None – absence of visible pressure; Net – presence of lost fishing nets; Debris – debris from the wreck; Fine Sediments – fine sediment produced during salvage activities; Mix – patches of debris and fine sediment. Following the environmental assessment plan, both debris and sediment distributions were mapped in detail at the end of summer 2014, once the wreck was towed to Genoa. The map was drawn based on ROV survey and visual estimations (Fig. S4). In order to assess potential changes in the quality of coralligenous habitats (indicated by an overall quality score, Q_O), the COARSE index was applied (Gatti et al., 2015a) through analysis of the images acquired by the CCUBA divers. A brief description of the index components is given in the supplementary material (Table S1). Only two descriptors (instead of three) were used for computation of the basal layer quality score (Q_{BL}). This was because the sampling strategy did not allow the estimation of Thickness and consistency of calcareous layer. However, the quality scores for both the intermediate and upper layers (Q_{IL} and Q_{UL}, respectively) were characterized using all descriptors (three for each layer) included in the COARSE index. Furthermore, the cover percentage provided by the tallest species (TS, belonging to the upper layer, mainly gorgonians and erect sponges), and *F. petiolata* and *H. tuna* (F & H) was assessed for each replicate. Due to the study site features, slight modifications were applied to the first descriptor of Upper Layer (UL), and Q_{UL} was renamed 'Adjusted upper layer quality score' (Q_{AUL}). Consequently, Q_O was renamed 'Adjusted overall quality score' (Q_{AO}). These modifications are described in the Results section.

Statistical analyses

Beta regression models (Ferrari and Cribari-Neto, 2004) were fitted in order to assess both TS and F & H cover data from 2012 in relation to assemblages and slope classes. Percentage values were reported to the (0,1) interval and no other transformation was applied to the dependent variable. The relationship between TS and F & H cover data in the studied assemblages was investigated by Pearson's correlation analysis. A Wilcoxon–Mann–Whitney test was carried out in order to assess significant differences between Q_O and Q_{AO}, calculated from the 2012 samples (Siegel and Castellan, 1989). A two-way ANOVA was used to verify COARSE index (i.e. the 'adjusted' overall quality scores – Q_{AO}) variations between years and stations. The three-layer quality scores
(Q_{BL}, Q_{IL}, and Q_{AUL}) were separately evaluated in relation to years and stations. A Hill–Smith multivariate analysis (Hill and Smith, 1976) was used to perform a sampling stations ordination, which mixed quantitative and qualitative variables. The dataset was built by associating each replicate with the quantitative variables of Q_{AO}, year, depth, and elevation from the bottom, and the qualitative variables of slope (three categories: Low, Medium, and High), type of pressure (five categories: None, Net, Sediment, Mix, and Debris), and distance from the wreck (five radius categories: 30 m, 60 m, 90 m, 120 m, and 150 m). Finally, a linear model was fitted in order to test the efficiency of the modified COARSE index in the context of the Costa Concordia impact assessment. The Q_{AO} was the dependent variable, while the independent variables were Assemblages, Depth, Slope, Pressures, and Distance from the wreck.
In both the ANOVA and linear model, data were log-transformed [log(x + 1)] in order to respect the assumption of normality and homogeneity of variances; a level of significance of 0.05 (p-value <0.05) was selected.

Water features and debris distribution

Trends in Tu measured at the fixed stations did not reflect any visible alteration caused by salvage activities (Fig. S5), it mostly showed values of < 1 FTU. In both the most important sediment releases that occurred on 31 January 2013 (Fig. 2a) and on 18 February 2013 (Fig. 2b), Tu showed values above the normal range, reaching a maximum of 26.9 and 8.6 FTU, respectively. Values of Tu during the sediment release that occurred on 3 May 2013 (Fig. 2c) reached up to 10.0 FTU. In all of these events, the increase in Tu affected the whole water column, from the surface to 50 m depth. No similar events were detected during 2014. The map of debris and sediment distribution in the late summer of 2014 clearly highlights how the whole study area was affected by salvage operation Fig. S4. Abundant debris covered the seafloor on the shallower sections of the two aforementioned rocky ridges sited closer to the wreck position. On the other hand, patches of debris and sediments mainly affected rocks situated deeper than 50 m and 60 m, in the case of the S Ridge and N Ridge, respectively.

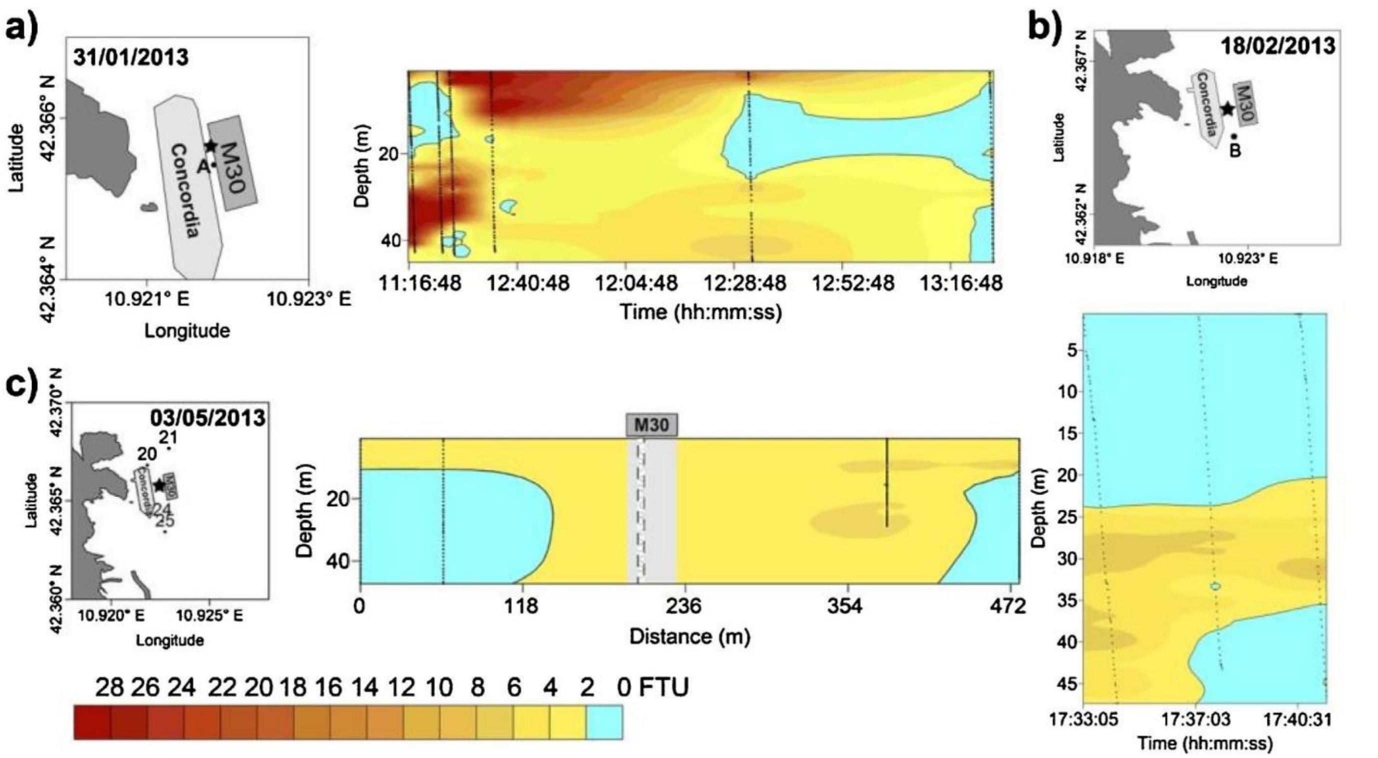

Fig. 2. Temporal (a–b) and spatial (c) turbidity distributions in three different cases of turbidity plumes (31 January 2013, 18 February 2013, and 3 May 2013, respectively). Values are reported in FTU. The star symbol shows the sediment release point. M30 was a heavy lift/accommodation barge where platform installation and grout bag positioning were carried out.

Results

COARSE index application, and following modification

The overall quality scores (Q_O) generally decreased with time in all the sampling stations (Fig. S6), even though great variability was found among stations in 2012. In fact, low scores (0.7–1.2 Q_O) were reported for stations S4, S7, S10, S12, S13, S14, S15, and S16, whereas moderate and high scores were reported for the other stations. Associations with *F. petiolata* and *H. tuna* (As. 2) and low or moderate slopes characterized stations that displayed low Q_O scores (Table 1), although no pressures were detected at these locations in 2012. The three layer quality scores for 2012 (Fig. S6) revealed that the low scores of the aforementioned stations were mainly attributable to the scarce contribution of the

UL (upper layer). Total cover of species, with a score generally < 10%, was the lowest in score of the three descriptors for Q_{UL}.

According to the beta regression models, cover by TS and F & H significantly differed for both assemblages and slope (Table 2). Intercepts were significant in both models, and were defined by the As. 3 and high slope class. In particular, lower but not significant TS cover values were associated with As. 2, whereas significantly lower values were reported for the low slope class. In contrast, F & H cover significantly increased in relation to the low and medium slope classes. An inverse correlation could be detected by plotting TS against F & H (Pearson's correlation between TS and F & H, r = −0.566, p = < 0.001); the assemblages dominated by filter feeders (As. 1 and As. 3) were clearly separated from those covered by sciaphilic green algae (As. 2; Fig. 3).

Table 2 Output of beta regression model performed on untransformed cover data for the tallest species (TS) and associations with *Flabellia petiolata* and *Halimeda tuna* (F & H); significant values are highlighted in bold.

Coefficient	Estimate	Std. Error	z-value	p-value
TS (Intercept)	−1309	0.209	−6.241	<0.001
As 1	1419	0.28	5.062	<0.001
As 2	−0.233	0.608	−0.384	0.701
L slope	−1524	0.633	−2.406	0.016
M slope	−0.098	0.481	−0.204	0.838
Log-likehood: 75.86 on 6 DF; Pseudo-R squared: 0.730 F & H (Intecept)	−4621	0.336	−13.769	<0.001
As 1	0.674	0.374	1804	0.057
As 2	2073	0.55	3.767	<0.001
L slope	1909	0.579	3.294	0.003
M slope	1823	0.53	3.441	0.001

Log-likehood: 158.70 on 6 DF; Pseudo-R squared: 0.707.

According to the beta regression models, cover by TS and F & H significantly differed for both assemblages and slope (Table 2). Intercepts were significant in both models, and were defined by the As. 3 and high slope class. In particular, lower but not significant TS cover values were associated with As. 2, whereas significantly lower values were reported for the low slope class. In contrast, F & H cover significantly increased in relation to the low and medium slope classes. An inverse correlation could be detected by plotting TS against F & H (Pearson's correlation between TS and F & H, r = −0.566, p = < 0.001); the assemblages dominated by filter feeders (As. 1 and As. 3) were clearly separated from those covered by sciaphilic green algae (As. 2; Fig. 3).

In light of these findings, we proposed a partial modification of the UL descriptors; these changes were applied only in the cases defined by a combination of associations with *F. petiolata* and *H. tuna* (As. 2) and the Low-Medium slope class, according to the beta regression models. The first descriptor of UL (Total cover of species) was replaced by Total cover of *F. petiolata* and *H. tuna* (F & H), while retaining the percentages defining the score assignation (Table S1). This modification allowed a reduction of the index variability displayed during the 2012, and increased the mean quality score (Fig. 4); the statistical comparison (Wilcoxon–Mann–Whitney test) detected significant differences between Q_{O2012} and Q_{AO2012} (V = 0; p-value = 0.005).

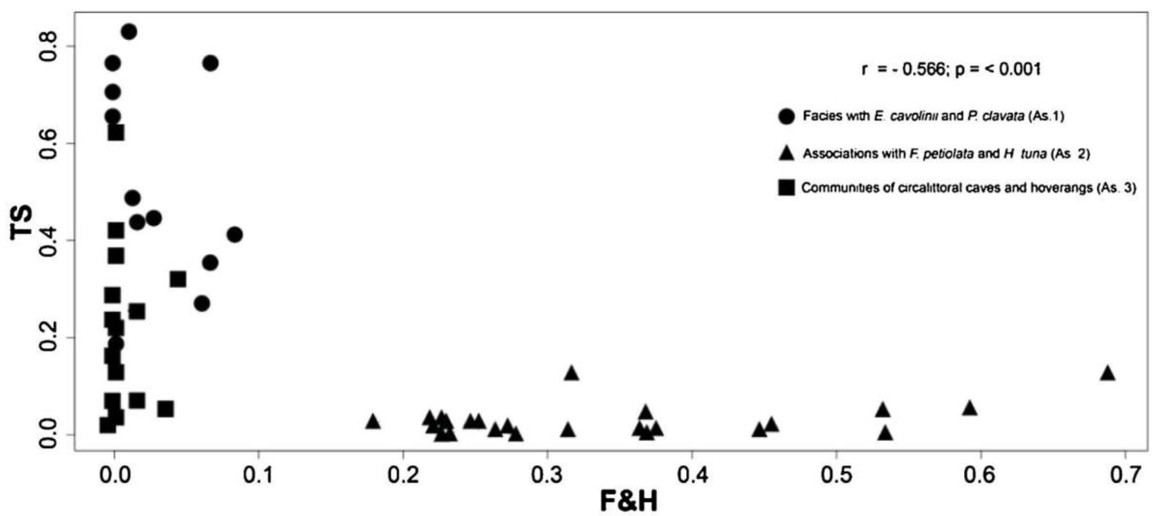

Fig. 3. Distribution of 2012 replicates defined by cover values of the tallest species (TS) and associations with *Flabellia petiolata* and *Halimeda tuna* (F & H). Pearson's correlation is reported as r.

Assessing impacts of Costa Concordia salvage operation

Applying Q_{AO} did not alter the temporal pattern revealed by the application of Q_O (Fig. 5). Q_{AO} calculated in 2012 exhibited moderate or high quality scores ($1.3 < Q_{AO2012} < 2.4$). In both 2013 and 2014, Q_{AO} was mainly characterized by low or at least moderate quality scores ($0.0 < Q_{AO2013} < 1.4$; $0.0 < Q_{AO2014} < 1.2$). Coralligenous reefs quality did not decrease equally at all the stations: in fact S1, S2, and S17 showed scores of 0.0 (Q_{AO2014}) that indicated the disappearance of coralligenous reefs. A general decreasing trend was reported in stations S3, S4, S6, S7, S9, S10, S12, S13, S14, S15 and S16, with lower scores calculated in 2014. On the other hand, stations S5, S8 and S11 showed stationary or slight increasing trends between 2013 and 2014; S5 and S11 maintained moderate scores in 2014, whereas S8 showed low quality score in both 2013 and 2014. The basal layer quality scores calculated for 2013 and 2014 (Q_{BL2013} and Q_{BL2014}) maintained a moderate or at least high quality score in stations S3, S4, S5, S6, S8, and S11 ($1.2 < Q_{BL2013}$–$2014 < 2.1$). High or moderate quality scores were reported for the intermediate layer at stations S8 and S11 during the 2013 and 2014 surveys ($1.4 < Q_{IL2013}$–$2014 < 2.7$). The adjusted upper layer quality scores (Q_{AUL}) did not differ from the patterns shown by Q_{UL}; quality scores increased in 2012, whereas a reduction in quality scores remained discernible in 2013 and 2014. Stations S3, S5, S6, and S11 maintained moderate quality scores in 2013 and 2014 ($Q_{AUL2013}$ and $Q_{AUL2014}$), ranging from 1.0 to 1.7. All other stations showed clear patterns of Q_{BL}, Q_{IL} and Q_{AUL} decreasing with time (Fig. 5). These changes were evident on the factorial plane of the Hill–Smith analysis, where 2012 samples resulted clearly separated from those of 2013 and 2014 (Fig. 6). The former were distributed in quadrants 2 and 3, and the latter in quadrants 1, 3, and 4. The first two Hill–Smith factorial axes explained 36.06% of the total variance. The ANOVA indicated that there were significant differences in all the quality scores (Q_{AO}, Q_{BL}, Q_{IL}, and Q_{AUL}) for time (years) and stations (Table 3).

In the linear model, the intercept was significant and was defined by As. 1 (facies with *E. cavolini* and *P. clavata*), high slope class, no pressure condition (None), and a distance of 30 m from the wreck (Table 4). In terms of assemblage types, only communities of circalittoral caves and overhangs (As. 3) exhibited significantly lower values when compared to the conditions defined by the intercept.

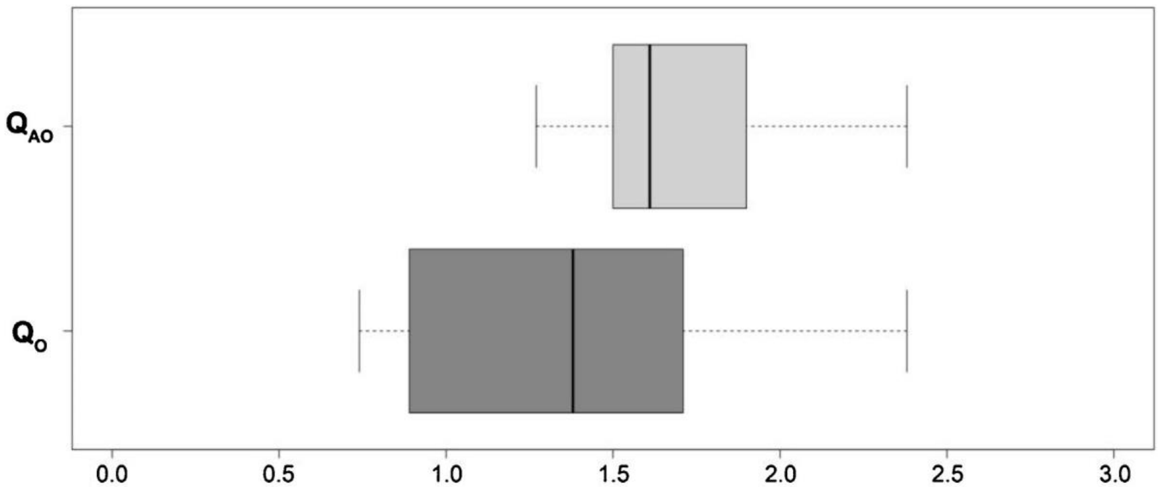

Fig. 4. Whisker plot showing Q_O and Q_{AO} scores reported for 2012.

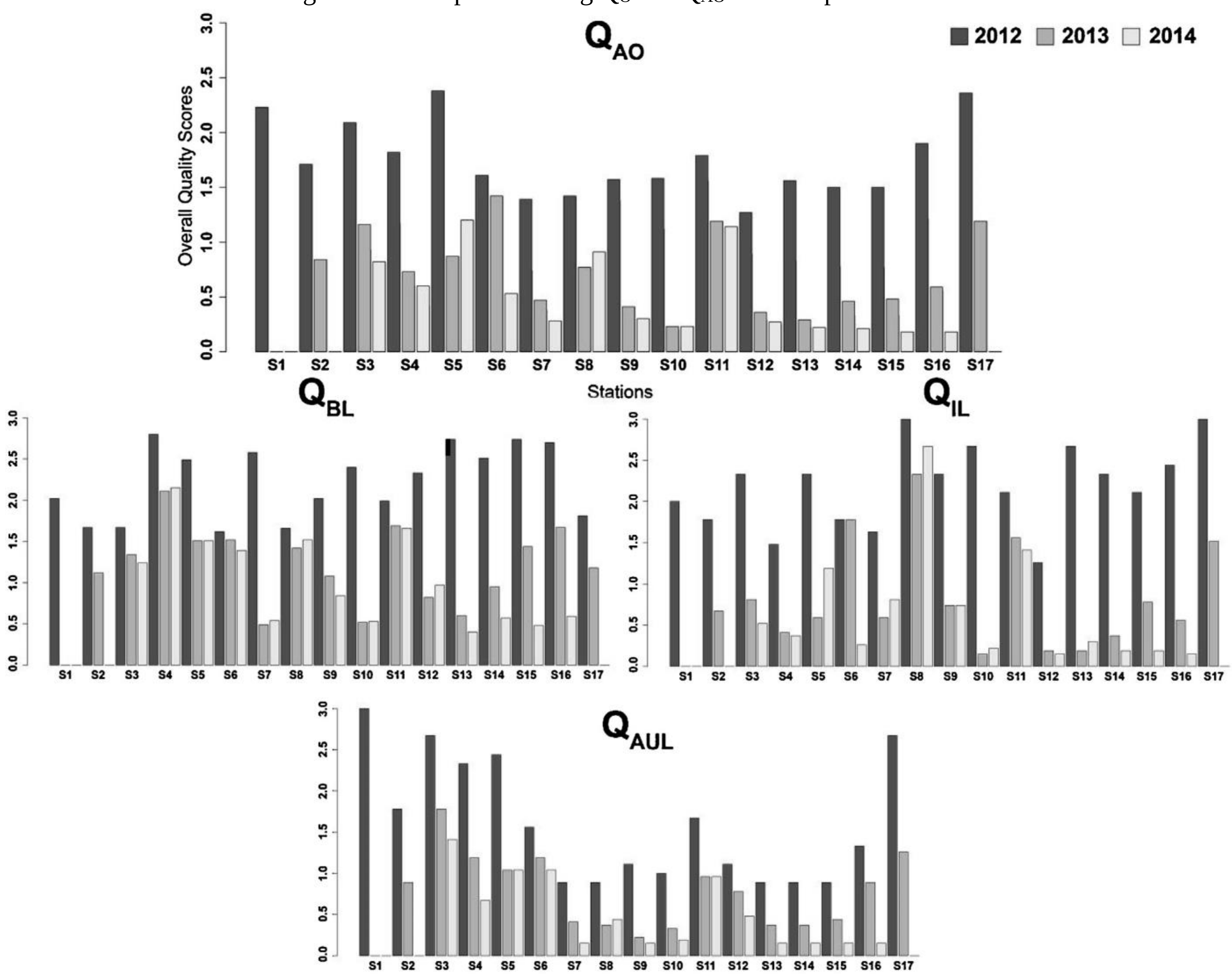

Fig. 5. Temporal trends in the Adjusted Overall Quality Scores (Q_{AO}) and Layer's Quality Scores (Q_{BL}, Q_{IL} and Q_{AUL}), for each station.

The quality score did not change significantly with depth. Low slope substrates were characterized by significantly lower scores, whereas no significant differences were reported for the medium slope class. It is notable that the different pressures contribute differently in terms of the quality scores decreasing: no significant reductions were highlighted for Net, a medium reduction was reported for both the Fine sediments and Mix, whereas a high reduction was related to Debris, when compared to the combination defined by the intercept. Distance from the wreck contributed to an increase in scores; no significant differences were highlighted for the 60 m distance class from the combination defined by the intercept, whereas more distant stations (90 m, 120 m, and 150 m distance classes) were characterized by significantly higher quality scores. The present model has an adjusted $R^2 = 0.759$.

Discussion

Indices are tools capable of assessing the quality and condition of biological systems, in order to assist managers responsible for applying environmental directives. As highlighted by Diaz et al. (2004) and Borja et al. (2009), the development of indices over the last few decades should now be followed by validation and application of these tools in the context of situations different from those originally used for their calibration. In the first decade of the twenty-first century, several indices were developed for different Mediterranean benthic communities, such as soft bottom communities (Borja et al., 2000; Simboura and Zenetos, 2002), infralittoral algal belts (Ballesteros et al., 2007), and seagrass meadows (Romero et al., 2007; Gobert et al., 2009).

Recently, indices for both shallow and deep coralligenous habitats have also been developed (Deter et al., 2012; Cecchi et al., 2014; Gatti et al., 2015a; Cánovas-Molina et al., 2016). The COARSE index was selected for our study mostly based on its seascape approach, combining geomorphological and biological features (Gatti et al., 2012). Furthermore, the coralligenous habitats in the study area were similar to those studied by Gatti et al. (2015a) along the French coast (i.e. As. 1, and As. 2), and the visual assessment approach (carried out by video filming) minimized the time spent underwater, which is a major restriction in deep benthic sampling.

Is this a matter of environmental features?

The results obtained in this study suggested that the COARSE index is a suitable methodology for identifying impacts and stresses on coralligenous habitats, even below 40 m depth, although consideration must be given to the existence of some limitations in relation to slope and assemblage structure. High complexity and heterogeneity characterize coralligenous habitats (Balata and Piazzi, 2008; Piazzi et al., 2009; Doxa et al., 2016). In particular, low spatial scale variability has been reported in previous coralligenous studies: changes in environmental variables may lead to patchy distributions of several organisms (Ferdeghini et al., 2000; Piazzi et al., 2004; Zapata-Ramírez et al., 2016). Slope and surface orientation have a pivotal role in assemblage structure, sediment deposition, and changing light intensity, therefore determining algae vs. invertebrate spatial competition (Irving and Connell, 2002; Balata et al., 2005; Virgilio et al., 2006). In the model recently proposed by Zapata-Ramírez et al. (2016), slope is the most influential environmental variable in determining the distribution of coralligenous and cave habitats. Furthermore, this factor affected the presence and abundance of gorgonians and other erect organisms, modifying hydrodynamic and light features (Gori et al., 2011; Sini et al., 2015). Conversely, clear water together with surface orientation promoted the dominance of green algae, such as *F. petiolata* or *H. tuna*, found in our study location at up to 65 m depth, and recognized as deep algal assemblages in both Mediterranean and Atlantic waters (Blair and Norris, 1988; Joher et al., 2012; Piazzi et al., 2012). Although *F. petiolata* and *H. tuna* do not form an upper layer, they do tend to colonize substrates (characterized by low or medium slope) unsuitable for more characteristic upper layer organisms, as demonstrated by the inverse Pearson's correlation. It is likely that the absence of a dense upper layer promotes the development of extensive associations with *F. petiolata* and *H. tuna*.

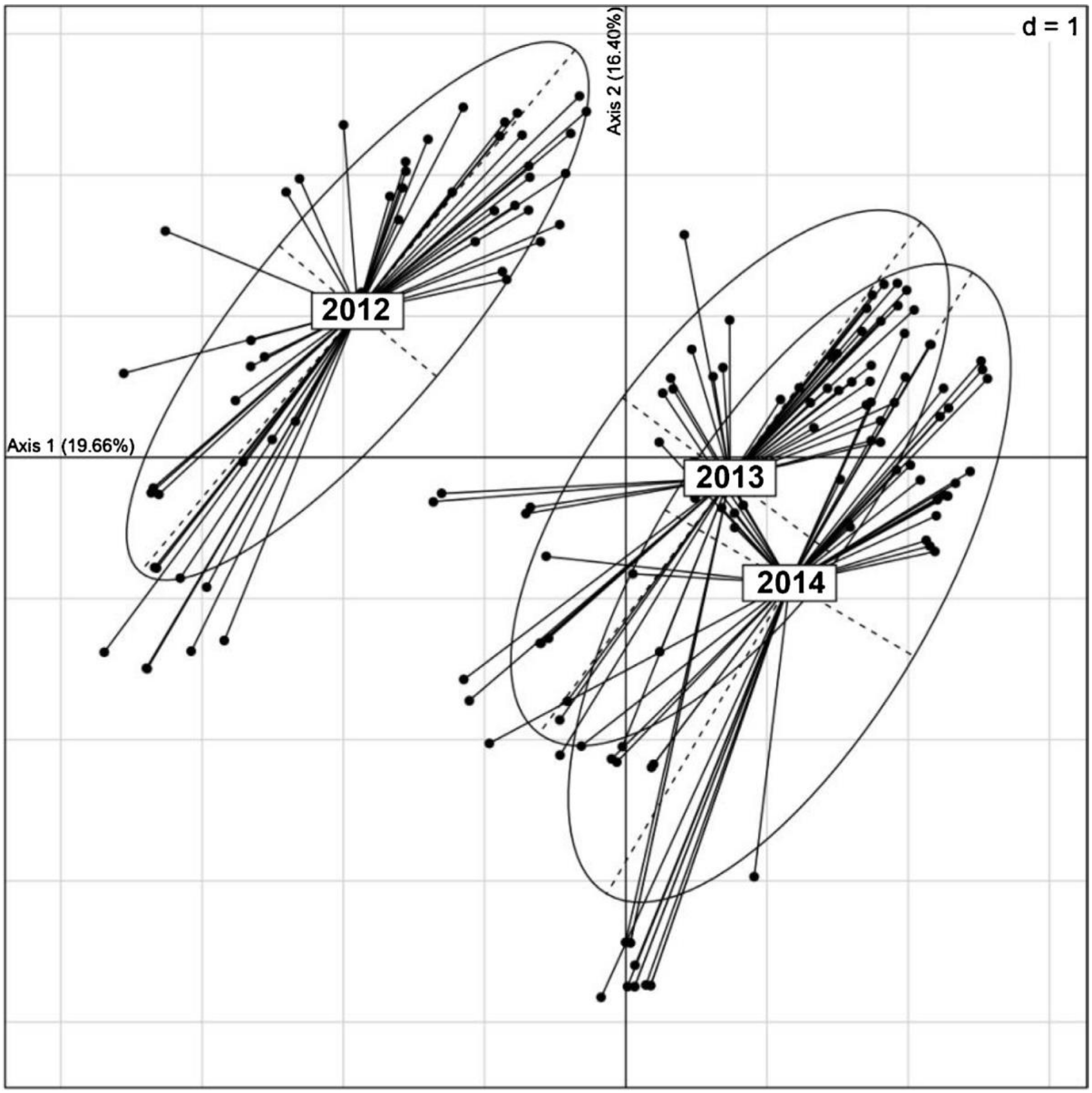

Fig. 6. Hill–Smith analysis plot of the sampling points. The replicates were distinguished on the factorial plane according to Q_{AO} score, year, depth, elevation from the bottom, slope, assemblage, distance from the wreck, and type of pressure. Explanatory variable selected: year.

Table 3 Results of the analysis of variance (ANOVA) carried out on Q_{AO}, Q_{BL}, Q_{IL} and Q_{AUL} scores. Significant values are highlighted in bold.

Source of variation	Q_{AO}			
	df	MS	F	P
Year	2	6.518	175.876	<0.001
Station	16	0.210	5.679	<0.001
Residuals	134	0.037		
	Q_{BL}			
Year	2	4.965	100.100	<0.001
Station	16	0.352	7.090	<0.001

Residuals	134	0.050		
	Q_{IL}			
Year	2	8.885	113.846	<0.001
Station	16	0.446	5.719	<0.001
Residuals	134	0.078		
	QAUL			
Year	2	4.8234.823	99.918	<0.001
Station	16	0.436	9.038	<0.001
Residuals	134	0.048		

Table 4 Output of the linear model fitted to the adjusted overall quality scores (Q_{AO}). Significant values are highlighted in bold.

Coefficients	Value	Std errors	t-value	p-value
(Intercept)	1.205	0.149	8.087	<0.001
As. 2	−0.104	0.072	-1.444	0.150
As. 3	−0.14	0.06	−2.321	0.021
Depth	−0.006	0.004	−1.674	0.096
Low Slope	−0.257	0.072	−3.562	<0.001
Medium Slope	−0.005	0.075	−0.071	0.943
Impact (Net)	−0.13	0.085	−1.529	0.128
Impact (Fine Sediment)	−0.519	0.037	−13,846	<0.001
Impact (Mix)	−0.658	0.043	−15,226	<0.001
Impact (Debris)	−0.85	0.072	−11,736	<0.001
Distance (60 m)	0.204	0.109	1.867	0.064
Distance (90 m)	0.429	0.117	3.652	<0.001
Distance (120 m)	0.417	0.130	3.202	0.001
Distance (150 m)	0.450	0.168	2.664	0.008

Residual standard error: 0.1839 on 139 degrees of freedom.
Multiple R-squared: 0.782, Adjusted R-squared: 0.762. F-statistic: 38.37 on 13 and 139 DF, p-value: < 0.001.

These two chlorophytes are sensitive species of coralligenous macroalgal assemblages, decreasing in abundance in response to human pressure (e.g. increasing sediment amounts); this was taken into account in the formulation of the Ecological Status of Coralligenous Assemblages (ESCA) index (Cecchi et al., 2014). A slight adjustment to the COARSE index structure (i.e. in the first descriptor of Q_{UL}) was proposed in order to account for the morphological and biological features of the study area. The application of Q_{AO} increased the quality status of the coralligenous habitats before impact, with no change to the pattern with time. The general shift in both upper layer organisms and associations with *F. petiolata* and *H. tuna* reflects the impacts of the salvage activities.

Modification of coralligenous habitats due to Costa Concordia salvage operation

The main pressures (i.e. sediments and debris releases) were detected in 2013 and 2014, whereas the presence of the wreck of the Costa Concordia in 2012 caused no visible alteration in the measured parameters. Changes detected by fixed stations during the monitoring period were mainly attributable to seasonal variations or natural events (such as the extreme rainfall on 12 November 2012) causing fresh water and terrigenous material to be redistributed. In 2013, the main pressure was fine sediment dispersion related to positioning of grout bags and drilling piles for platform installation (as highlighted by the turbidity data shown in Fig. 2). In contrast, debris diffusion due to parbuckling and subsequent wreck refloating was the main pressure in 2014. Our study revealed that salvage activities caused a loss of complexity, diversity, and three-dimensional structure in coralligenous habitats, although these effects were not uniform. All three layers showed a severe decrease in quality, clearly evidenced by a shift in the multivariate structure of the sampling points before and after pressures. Impacts affected the three layers differently. Encrusting calcareous algae, together with the sponges and encrusting bryozoans that characterized the basal layer, were replaced by turf-forming algae, fine sediment patches, and bare substrates. These changes alter the structure and dynamics of the community, acting on the settlement and development of the main coralligenous reef builders (Irving and Connell, 2002; Balata et al., 2007; Piazzi et al., 2012). Species loss had a strong effect on the intermediate layer, where sensitive species were impacted by both sediment (suffocation effects) and debris rolling (abrasion). Fragile tree-like bryozoans (such as Reteporella spp., *Smittina cervicornis*, and *Pentapora fascialis*), scleractinians (*Leptopsammia pruvoti*), erect sponges (*Axinella damicornis* and *A. verrucosa*), tunicates (*Clavelina lepadiformis* and *Halocynthia papillosa*), serpulids (Serpula spp. and Protula spp.), and erect algae (*H. tuna* and *F. petiolata*) were not found in most of the impacted stations. These species may be impacted by different sediment-related mechanisms: clogging of filtering apparatus, recruitment inhibition, effects on metabolic processes, and increased burial and scouring (Balata et al., 2007; Deter et al., 2012; Cecchi et al., 2014). Furthermore, sediment dispersion has also been recognized as one of the major threats to fragile and precious marine ecosystems during engineering initiatives at sea; action to reduce sediment diffusion should be mandatory (Nepote et al., 2017). In contrast, debris rolling acted to create mechanical damage, primarily affecting erect colonial species (Bo et al., 2014; Angiolillo et al., 2015). Large colonial species, such as *E. cavolini* and *P. clavata*, confirmed their role as sensitive species in the upper layer, where their cover values were severely reduced, and they suffered increased injuries (Huete-Stauffer et al., 2011; Sini et al., 2015). As reported by Ponti et al. (2014), the disappearance of gorgonians may change both the physical and biological features of the habitat, modifying spatial heterogeneity and conditioning settlement and colonization patterns.

Understanding the impact patterns affecting coralligenous habitats presents a major challenge to marine scientists. Sedimentation (Airoldi, 2003; Balata et al., 2005, 2007), weather or temperature anomalies (Garrabou et al., 2009; Teixidó et al., 2013), invasive alien species (Piazzi et al., 2012), scuba diving (Nuez-Hernández et al., 2014; Casoli et al., 2017), fishing (Bo et al., 2014), and litter (Cánovas-Molina et al., 2016) have been recognized as the main stressors acting on coralligenous habitats. Even though our research was related to an unusual and uncommon (as well as local) case study, we were able to prepare a pressure scale. The four types of pressures were found to be weighted differently in terms of their effects on decreasing quality of coralligenous reefs. The pressure magnitude was ordered as follows: from Net (i.e. lost fishing nets), which was the least destructive, passing through Sediment and Mix (patches of debris and fine sediment), to Debris (i.e. abundant anthropic materials), which was demonstrated to be the most destructive. Distance from the stress source and slope probably influenced the magnitude of the pressure; the former mainly determined the likelihood of finding debris, while the latter drove sediment and debris accumulation. As highlighted by Giakoumi et al. (2013) and Holon et al. (2015), distance from the stress source characterizes the level of human impact affecting coralligenous, as well as other benthic habitats, and therefore drives priorities for conservation actions and management plans. Sediment deposition may affect low and medium slope surfaces more than steep walls (Cocito et al., 2001; Airoldi, 2003; Balata et al., 2005) and, in this particular case, a similar result was shown for debris accumulation. Therefore, these two pressures are strictly related to bottom topography.

Conclusions

As highlighted by Halpern et al. (2008), globally there are no oceans that remain unaffected by human pressures or exploitation of natural resources; all coastal Mediterranean habitats are subject to anthropogenic impacts (Micheli et al., 2013; Holon et al., 2015). In this context, understanding and quantifying man-mediated impacts through monitoring plays a pivotal role, both for management and conservation purposes, in particular in complex, low-dynamic, and poorly investigated communities, such as coralligenous habitats (Crain et al., 2008; Claudet and Fraschetti, 2010; Gatti et al., 2015b). The ability to detect and recognize patterns driving the homogenization of coralligenous reefs is an important effort for scientists and policymakers, which could cooperate in order to protect these fragile systems.

The present work reports a case of fine-scale and mid-term environmental monitoring following the Costa Concordia wreck removal project. The results here described provide important information about deterioration of deep coralligenous habitats; taxonomical and functional homogenization may lead to the ecological role of these habitats being lost. Our study provides fine-scale spatial data and maps of marine habitats and pressures that are often lacking in the Mediterranean scenario (Giakoumi et al., 2013; Holon et al., 2015). Although several studies have focused on a specific impact, natural environments are affected by multiple stressors acting together. As stated by Micheli et al. (2013) and Holon et al. (2015), ‘field data concerning ecosystem responses to pressures and thus the relationship between cumulative impact scores and ecosystem condition should now be considered a top priority’. Our observations contribute to analyze the synergistic effects resulting from four specific disturbances, and to an understanding of the different weight that these disturbances have on coralligenous habitats. The application of the COARSE index may yield useful results and feedback in assessing sea floor integrity; this is especially so in the context of the need, under EU environmental legislation, for tools capable of quantifying how biological systems respond to a given stress. Furthermore, our modification of the COARSE index increases its potential application in the study of a broad range of coralligenous reefs characterized by different biological features.

This description of changes in communities plays a pivotal role in understanding the short-term response of marine organisms to a specific human pressure, and in providing important baseline information for the monitoring of the capacity of ecosystems to recover. In January 2015, a few months after the wreck was towed to Genoa, the site remediation phase was initiated, with the aim of removing all evidence of the accident and the following salvage operations. Debris and sediment will be removed in order to restore the seabed to its preaccident conditions as far as possible, and therefore enabling natural environmental restoration. Monitoring activities will continue to be performed in the future in order to assess habitat recovery and community.

Conflicts of interest

All the authors, as scientists of the Sapienza University of Rome and University of Genoa, were commissioned by the Titan-Micoperi Group to assess the environmental risks of engineering operations, and to monitor the environmental conditions in the impacted areas in order to protect marine habitats during salvage of the Concordia wreck. The authors’ work was controlled and continuously shared with an Italian governmental body (The ‘Osservatorio’), which fulfilled the public function of verifying the performance of the monitoring. This paper was authorized for publication by Costa Crociere S.p.A.

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