Bioerosive and bioprotective role of barnacles on rocky shores

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Abstract

Bioerosion and bioprotection (bio-remodeling) is the action exerted by biota colonizing rocky shores. It represents an important component among processes responsible for shaping coastal landforms, and a clear evidence of interaction between the biosphere and the solid earth. Barnacles extensively colonize the midlittoral belt of rocky shores in the Mediterranean Basin. Previous research, mostly based on laboratory evidence, suggests that barnacles are bioprotectors, in that they protect the rock surface from different types of physical and chemical weathering. In this paper, we present the results of a field experiment carried out at different spatial scales at two study areas along the moderately energetic and microtidal coast of NW Italy. Barnacles were removed from the sandstone bedrock in replicated plots (manipulated plots) arranged according to a hierarchical spatial design. After four months rock hardness was tested on each plot with both Schmidt hammer and Equotip Piccolo devices, as well as on a corresponding number of control plots. Data were processed by means of a multifactorial analysis of variance (ANOVA). In control plots, rock hardness tested with Schmidt hammer exceeded that measured in previously manipulated plots. Testing with Equotip yielded the opposite results. This experimental evidence confirmed that barnacles play a bio-protective role in the midlittoral at sub-surficial level, while adding the key aspect that this effect is generalizable to spatial scales ranging from a few centimeters up to tens of

kilometers. In addition, our results showed, for the first time, that at surface level they can simultaneously act as bioeroders, likely causing corrosion of the rock surface by fostering dissolution of the sandstone carbonate matrix.

Keywords: rocky shores, bioerosion, bioprotection, barnacles, durometer, NW Mediterranean.

1. Introduction

Rocky shores evolve under different geomorphic processes that are driven both by marine and subaerial agents (Stephenson et al., 2013; Kennedy et al., 2014). A huge amount of work has been done in order to assess, rank and quantify the effect of such processes (Trenhaile, 1987; Sunamura, 1992; Naylor et al., 2010; Moses and Robinson, 2011; Naylor et al., 2014) and to relate their relative efficiency to the development of specific coastal landforms (Gomez-Pujol et al., 2006a; Moura et al., 2006; Stephenson and Kirk, 2000a,b; Kennedy et al., 2011; Ogawa et al., 2011; Feal-Pérez and Blanco-Chao, 2012; Dickson et al., 2013; Trenhaile, 2015).

Among the most relevant processes acting on coastal rock surfaces are also those operated by the biota colonizing rocky shores (Spencer, 1992; Radtke et al., 1997; Viles, 1988; Kázmér and Taboroši, 2012; Naylor et al., 2012). We refer to bio-remodelling to indicate those actions exerted by marine and terrestrial biota on rocky shores (Pappalardo et al., 2016), and different from the contribution of physical and chemical weathering in shaping the coastline. Bio-remodelling includes bioerosion (Viles, 1988), i.e. the action of biological agents directly removing inorganic particles from the rock surface or weakening it, or indirectly fostering weathering processes, and bioprotection (Carter and Viles, 2005), i.e. the sheltering of rock surfaces directly exerted by biota and effective in preventing or retarding weathering processes.

A number of papers have examined the effect of grazing organisms, such as *Gastropoda* (limpets) and *Echinoidea* (sea urchins) (Mc Lean, 1967; Torunski, 1979; Schneider and Torunski, 1987; Trudgill, 1987; Trudgill et al., 1987; Abensperg-Traun et al., 1990; Andrews and Williams, 2000; Gómez Pujol et al., 2006a; Fornós et al., 2006; Naylor et al., 2011; Vidal et al., 2013), as well as the role of seaweeds (Morrison et al., 2009; Coombes et al., 2013a) and, in the mid and supra-littoral, biofilm (Coombes et al., 2011; Coombes and Naylor, 2012; Mayaud et al., 2014). Also the role of lichens has been investigated (Moses and Smith, 1993; Chen et al., 2000;Carter and Viles, 2003; 2004), but only in specific coastal areas (Gómez Pujol et al., 2007; Pappalardo et al., 2016). Among the most controversial is the role of barnacles as bio-remodelers. These organisms have been traditionally considered bioprotectors, as they form physically protective crusts on the rock surface (Laborel and Laborel-Deguen, 1996; Spencer and Viles, 2002; De Waele and Furlani, 2013). Their effect has been recently investigated through studies carried out along oceanic coasts (Naylor et al., 2012), as well as in the Mediterranean Sea, characterized by different wave, climate and tidal regimes (Pappalardo et al 2016). Laboratory simulations have proved barnacles to play a bioprotective effect, as they reduce sub-surface temperatures in the rock (Coombes et al., 2012, 2017). However, preliminary field experiments showed a moderate, mostly indirect, bioerosive or neutral role of barnacle cover over coastal rocks (Pappalardo et al., 2016). The apparent contrasting effects observed under laboratory or field conditions emphasize the possible complex and spatially variable role of barnacles as bio-remodelers on rocky shores. Presence and abundance of barnacles, in fact, are influenced by the topography of the bedrock and exposure to wave action (Erlandsson et al., 2005); the consequent variability in their spatial distribution might therefore turn out into a variable influence on physical and chemical weathering at multiple spatial scales. Moreover, barnacles are involved in both positive and negative interactions with other potential bio-remodelers, such as biofilm and grazing gastropods (Maggi et al. 2015 and references therein), which could result in variable protective/erosive effects of barnacles on the rock surface.

Barnacles are commonly distributed along intertidal shores under different climate conditions (Stephenson and Stephenson 1949, refs for tropical areas), developing on most natural and artificial substrates (e.g. coastal defenses). At high density, they are able to modify temperature or humidity, likely influencing the abundance and distribution of both microbial biofilm and littorinid gastropods (Cartwright and Williams, 2012; Maggi et al, 2015). Moreover, they can inhibit the movement of dominant herbivores such as limpets (Creese, 1982; Freidenburg et al., 2007). Understanding the interaction of barnacles with different types of rocks and artefacts may provide basic knowledge for solving a number of scientific problems, such as the employment of these organisms as past sea-level indicators (Bini et al., 2017), but also for practical applications. In fact, understanding how barnacles interact with the surfaces of coastal rocks may drive the selection of construction materials employed for coastal defenses, that may be improved by redesigning their chemical composition or surface texture (Coombes et al., 2015, 2017), in order to minimize the effect of bioerosion.

On the whole, it is still unclear if barnacles play a bioerosive or a bioprotective role on rocky shores, as field experimental evidence and laboratory simulations are apparently contradictory; in addition, the limited number of available case studies is insufficient to reveal a general trend. In this paper, the role of barnacles is investigated through an in situ experiment, replicated at different spatial scales and based on different approaches for rock hardness measurement, with the purpose of obtaining a more generalized, although preliminary, indication of their bio-remodeling attitude.

The experimental activities carried out in this work are aimed at determining the relative contribution of a population of Crustaceans belonging to the genus *Chthamalus* (barnacles) to bioerosion and bioprotection of littoral rocks along the coast of Tuscany, in the northwestern Mediterranean. The question posed was addressed measuring the hardness of the rock. This index, in Process Geomorphology, is considered to provide an estimate of the degree of weathering of rocks (Viles et al., 2011; Moses et al., 2014). In particular, weathering (the process to which rocks exposed to the interaction with atmosphere are subjected to) reduces the hardness of rocks, that become progressively weaker on the surface and in the shallow sub-surface. Whatever coating that is capable of sheltering the rock from weathering, produces the effect of keeping the rock harder than the case it is exposed. In the present study, rock hardness was measured using two different types of durometer on the same rock plots: the Schmidt hammer (Day and Goudie, 1977; Aydin and Basu, 2005) and the Equotip (Coombes et al., 2013b), These devices, due to the different amount of energy released by them onto the rock surface, detect hardness at two different depths inside the rock: at sub-surficial and at surface level, respectively.

The experimental design we adopted enabled us to test for possible generalizations of the effects of barnacles as bio-remodelers over spatial scales ranging from a few centimeters to tens of kilometers.

2. Methods

2.1 Study areas and methodological approach

Two study areas were selected, Calafuria and Baratti-Populonia (Fig. 1), about 50 km apart, located along the coast of Tuscany (Furlani et al., 2014), northwestern Italy, and displaying the same bedrock type (Oligo-Miocene silicic sandstone) and morphological features. They are in fact two headlands with alternating cliffs and narrow shore platforms along an indented coastline; outcropping rocks have been extensively quarried by man since Roman Age up to recent times. From the geological point of view, this sandstone belongs to the Macigno formation, a siliciclastic turbidite that represents the top formation of the Ligurian Nappe of the Apennine Chain (Carmignani et al., 2004; Falorni, 2007). This formation, being the product of a terrigenous accumulation in a shallow marine basin mostly due to submarine slumpings, displays a remarkable heterogeneity in grain size, sorting and bedding. In particular, outcrops in Calafuria and Baratti-Populonia are heterogeneous from this point of view (Gandolfi and Paganelli, 1992; Cornamusini, 2002) and affected by at least two joint systems (Sciarra et al., 2014). Both areas are exposed to an energetic wave climate and to incoming waves from the dominant direction of 240°N. The maximum coastal significant wave height is 4.5 m with a period of 11 s and the yearly mean wave power impacting the shore is about 2.5 kW/m (Vannucchi and Cappietti, 2016; Pappalardo et al., 2017).

The two areas support similar assemblages in the mid littoral; in particular, both areas are characterized by patchy populations of barnacles belonging to the genus *Chthamalus* (mostly *Chthamalus stellatus* [Poli], while individuals of *C. montagui* [Southward] are uncommon; Benedetti-Cecchi et al. 2000; Pannacciulli and Relini, 2000). These populations cover the midlittoral coastal rocks, here mainly shaped as small shore platforms (Furlani et al., 2014), reaching percentage covers close to 100% (Benedetti-Cecchi et al., 2000).

We manipulated the presence/absence of barnacles through a removal field experiment, replicated according to a hierarchical spatial approach. Where barnacles were removed, the rock surface remained exposed to physical and chemical (marine) weathering agents for 117 and 104 days in Calafuria and Baratti-Populonia, respectively (from 2015/02/08 to 2015/06/06 in Calafuria and from 2015/03/18 to 2015/06/30 in Baratti-Populonia). After that time, the effect of bio-remodeling was no more detectable on the rock as it had been deleted by physical/chemical weathering; the magnitude of biological weathering, in fact, should be considered generally lower than that of physical/chemical processes. On the contrary, where barnacles were left intact, *Chthamalus* cover was removed immediately before instrumental testing, so that effect of biological weathering could be highlighted. We therefore expected higher rock hardness in presence than in absence of barnacles, if *Chthamalus* exerted a bio-protective role; on the contrary, a bio-erosive effect should be detected trough greater values of rock hardness where barnacles have been removed for 4 months, in comparison to control conditions.

2.2 Experimental design

Within each area, we randomly selected three Localities about 2 km apart, all characterized by extensive covers of barnacles and with similar aspect, wave exposure and bedrock lithological and structural features. Within each Locality, three Sites 10s of meters apart were randomly selected, as homogeneous as possible regarding exposure and features of bedrock and biota cover. At each site, we randomly identified ten replicate 10x10 cm quadrats (plots), located in the middle portion of the vertical range of distribution of barnacle populations, with a percentage cover of barnacles not lower than 50% (verified through the point intercept method; Meese and Tomich, 1992). At each site, plots were randomly and evenly assigned to each of 2 treatments (factor Barnacle, fixed). In particular, at the beginning of the experiment 5 plots were manipulated by removing all barnacle individuals by gently scraping them off from the rock surface with a spatula (Treatment). Scraping was gently enough as not to damage even most surficial rock, as suggested by the visible imprint of organic glue secretions from the basal, soft chitinouse membrane (Fig. 1). The remaining 5 plots were left untouched (Control). The experiment was set up at mid-February at Calafuria, while at mid-March at Baratti-Populonia, due to time constrains and bad weather conditions. After about 4 months (at the beginning and the end of June at Calafuria and Baratti-Populonia, respectively), barnacles were removed also from Control plots (and any glue secretion gently removed through the use of a soft and wet cloth) and rock hardness immediately tested in both Treatment and Control quadrats (see section 2.2 for details on rock hardness testing).

2.3 Instrumental approach

Geological methods have been extensively employed to assess processes operating on rocky coasts (Naylor et al., 2012; Moses, 2014). Efficiency of both subaerial and marine processes in shaping rocky coasts have been related to relative reduction of rock hardness/strength of coastal rocks surfaces. Rock hardness was measured in the replicate plots using first the Equotip and then the Schmidt hammer.

The Schmidt hammer was originally designed for testing concrete hardness in situ, but has been extensively used in geomorphological research (Day and Goudie, 1977; Augustinus, 1992; Aydin and Basu, 2005). The instrument is formed by a piston that is released onto a plunger when it is pressed against the rock surface. The distance travelled by the piston as it is released onto the plunger is proportional to the energy that is not dissipated in the impact due to the penetration of the plunger into the rock. Thus, the harder the rock is, the longer the distance travelled by the plunger, which is expressed as a dimensionless index (R) directly proportional to rock hardness. This, in turn, is inversely correlated to the degree of weathering of the rock surface. Different models of the instrument are available and different operational techniques have been employed by different Authors (Basu and Aydin, 2004; Matsukura e Aoki, 2004; Goktan and Gunes, 2005; Aydin, 2009; Moses, 2014). At the moment there is not a standard test procedure recommended by an international organization that should be applied for evaluating the degree of weathering of a rock surface. In this work a L-type Schmidt hammer was employed, because its impact energy, 0.35 Nm, is intermediate and thus suitable for the type of rock tested. The methodology suggested by Day and Goudie (1977) was adopted for the selection of the sampling point and for operating the hammer. Based on previous experience in the tertiary sedimentary rocks along the coast of north-western Italy (Chelli et al., 2010) measurements were taken with the single impact method taking 10 readings (Niedzieldshi et al., 2009) on different spots within a 10x10 quadrat (plot, see section 2.1). Each value was corrected for impact direction using the method of Basu and Aydin (2004) and the 10 readings were averaged obtaining a value representative of the rebound index for that single plot.

The Equotip is a type of durometer originally used for testing steel (Kompatscher, 2004) and, due to its moderate impact energy (11 N mm), used in Heritage Science primarily to test stone degradation in historical buildings (Aoki and Matsukura, 2007). More recently, it has been employed in research on coastal rocks weathering (Coombes et al., 2013b), where it is preferred to Schmidt hammer because of its higher resolution power. Mechanically, the two instruments are very similar, but in the Equotip the plunger is replaced by a ball-shaped indenter and rock hardness is expressed as a dimensionless index (L) that is related to the rebound velocity of the piston. In this work a specific model of the device was used (Equotip Piccolo), that enables to record electronically the readings and automatically corrects for impact direction. Surface moisture conditions were kept, as much as possible, similar in all plots and variance due to change of operator was minimized. As regards the sample size, i.e. the number of readings that should be taken to get a statistically sound measure of the of the rock hardness, three measurements were taken within each plot, each of which was obtained by averaging the values obtained from 15 repetitions of the impact on the same spot (repeated impact method); the three resulting values were then averaged to obtain the L index of each plot. The number of repetitions of a single impact (15) was obtained using the statistical methodology proposed by Viles et al. (2011, p. 324).

We suggest that a difference between the two tools can be envisaged in the different capability of penetration of the plunger tip. In fact, the depth of penetration is negatively correlated to the rock hardness, but in the same rock type the Schmidt hammer penetrates up to one order of magnitude deeper than the Equotip. This implies that the first yields an index (R) that can be related to the hardness of the weathered portion of the rock at the sub-surficial scale, whereas the second is able to test only the hardness (and so the degree of weathering) of the most surface layer (L index).

2.4 Data processing

Data from the two areas were analyzed separately, due to the temporal shift of about 1 month in the run of the experiments. For each Area mean R and L values obtained from each plot were analyzed by means of multifactorial analysis of variance (ANOVA), with factors Locality (random, 2 levels, nested within Area) and Site (random, 3 levels, nested within Locality) crossed with factor Barnacle (fixed, 2 levels: Treatment and Control). Analyses were run using the GAD package in R (v 2.15.3, R Development Core team 2013). Heterogeneity of variances was tested by Cochran’s C test.

3. Results

3.1 Summary statistics

In the Calafuria Area the value of the R index (Fig. 2 and3A) ranges between a maximum value of 42 and a minimum value of 29, covering a range of 13 points. In Baratti-Populonia Area (Fig. 3B and 4) R ranges between 49 and 31(range 18). In Baratti-Populonia, though, R index values are less scattered than in Calafuria, as Site 1 of Locality 1 in Baratti-Populonia represents an outlier. On the whole, the two study Areas can be considered comparable as regards surface rock hardness assessed with Schmidt hammer. Within each Locality, the difference in R among sites may be as great as 10 points (up to 13 points in Site 1 of Locality 1 in Baratti-Populonia Area). This testifies that there is a remarkable variability between sites, as revealed by previous research on rock hardness tested with Schmidt hammer carried out in this area (Pappalardo et al., 2016). Within each site, instead, the difference in R index between Treatment and Control is very small, within the range 0-3 points, with a single exception of 4The two study Areas can be considered comparable as regards surface rock hardness assessed with the Equotip. In the Calafuria Area the value of the L index is rather constrained (Fig. 5A), ranging between a maximum value of 576 and a minimum value of 450, covering a range of 126 points. In Baratti-Populonia (Fig. 5B), excluding the outlier value of Site 1 at Locality 1, L ranges between 557 and 459 (range 98). In addition, the L index testifies a minor scattering of the hardness tested in Baratti-Populonia than in Calafuria, if we exclude the outlier. Also in this case the index displays a difference between Treatment and Control as great as a 10-20 points, whereas between sites the difference grows up to 50-100 points, highlighting a remarkable variability between sites. Locality 1displays more scattered values and wider standard errors, confirming its peculiarity within the sampled sites.

3.2 Analysis of variance

3.2.1 R index (Schmidt hammer)

Analyses of variance showed a significant positive main effect of the presence of barnacles on R values in both Areas (factor Barnacles: Calafuria, $p<0.05$, Table 1; Baratti-Populonia, $p<0.01$, Table 2), with larger values of rock hardness at the sub-surficial level in Control plots than in quadrats where *Chthamalus* has been removed 4 months before (Fig. 2). In addition, a significant variability among sites within localities was observed in both areas (factor Site(Locality): Calafuria, $p<0.01$, Table 1; Baratti-Populonia, $p<0.001$, Table 2).

3.2.2 L index (Equotip)

ANOVAs on L values showed a variable effect of the presence of barnacles at different localities, but only at Calafuria (factor Locality x Barnacles: $p<0.01$; Table 3). In particular, at 2 out of 3 localities rock hardness at the surface level was higher when barnacles were removed (Treatment) than in Control plots (Fig. 5A). As observed for the R index, a significant variability among sites was observed in both Areas (factor Site(Locality): Calafuria, $p<0.001$, Table 3; Baratti-Populonia, $p<0.001$, Table 4).

Discussion

Results of Schmidt hammer testing showed that the R index from control plots significantly exceeded that from plots where barnacles have been removed for 4 months. The exposed surface, thus, being less hard, was weathered more than the covered one. This emphasizes the bio-protective role (both active and passive) of *Chthamalus* cover at the sub-surficial level on coastal rocks. Weathering of exposed littoral rocks is caused by those elementary processes normally occurring in the subaerial environment, such as thermal stress and repeated wetting and drying, but is fostered by the occurrence of aerosol spray, tides and wave action. This is the reason why a number of Authors (pioneered by Stephenson and Kirk, 2000a) stressed the importance of weathering as a process responsible for shaping coastal landforms. The results of our hardness testing with Schmidt hammer revealed that, at the sub-surficial level, weathering acting for 4 months on the exposed rock surface was weathered more than the one protected by barnacles coating.

According to Coombes et al. (2012, 2017), barnacles may play a bioprotective role not only physically sheltering the rock surface, but also reducing sub-surface temperature and repeated wetting and drying of the rock, thus providing what is called ‘passive bioprotection’ (Carter and Viles, 2005). Temperature and humidity shift below the rock surface is prevented due to the physiology of barnacles, that retain seawater inside their shells in order to capture nutrients for their subsistence. This water maintains the rock surface permanently wet. The rate of thermal stress inside the rock at sub-surficial level is strongly dependent on the rock type. Coombes et al. (2012) highlighted that in granular rocks (granite in their case study) the gradient of temperature decrease from the surface to the sub-surficial layer is twice the gradient in limestone or in manmade material such as concrete. Interestingly, though, the lithological effect is up to one order of magnitude less relevant than the presence of barnacle cover in influencing temperature reduction with depth.

The role of *Chthamalus* cover in protecting rock from salt weathering is suggested by La Marca et al (2014). According to these authors, barnacles create a physical barrier capable of reducing salt penetration inside the rock and thus protect rock from the mechanical stress that salt exerts on rock joints on fracture walls, when it precipitates below the rock surfaces due to water drying (Fairbridge, 2005). Salt weathering is relevant especially in granular rock types such as the ones outcropping in our study areas. Morphological evidence generally referred to salt weathering (i.e. honeycombs) is present, although not continuously, in both study areas and have been investigated especially in Calafuria (Mc Bride and Picard, 2004). According to La Marca et al (2014), the bioprotective effect of barnacles is proportional to their percentage cover: the protective effect is greater where the cover is more abundant and continuous, like in the plots selected for this work, in which percentage cover was very high and in any case exceeding 50%. This type of bioprotection can be defined “active”, according to the conceptual model of Carter and Viles (2005).

Ecological studies have shown that barnacles may exert positive effects by directly or indirectly facilitating other organisms. Kawai and Tokeshi (2004) showed that the presence of extended patches of the goose barnacle *Capitulum mitella* facilitates the persistence of the mussel *Septifer virgatus* in the upper intertidal in south Japan, by reducing thermal and physical stress. Similarly, *Tetraclita japonica* provides a suitable habitat for the littorinids *Echinolittorina malaccana* and *E. vidua* on rocky shores in Hong Kong (Cartwright and Williams, 2012). Along Mediterranean coasts, a recent study highlighted the positive role of high densities of *Chthamalus* for the development of microphythobenthos, likely due to the provision of a favorable secondary habitat, as well as the amelioration of abiotic conditions to nearby rock (Maggi et al. 2015). Our study confirms that the positive role of barnacles is not only confined to that of an ecological foundation species. In fact, their bio-protective effect at the sub-surficial level of sandstone rocks was shown to be more important than any variability in topography of the bedrock or exposure to wave-action, present at scales up to tens of kilometers in the western Mediterranean.Moreover the experimental evidence obtained through Shmidt hammer testing confirms what previously stated by other Authors. Carter and Viles (2005) suggest that "bioconstruction, bioprotection and bioerosion are not mutually exclusive and … their interrelationships are varied, complex and dynamic" (p. 279).

Our results fit into this statement. In fact, despite the clear cut results from the Schmidt hammer measurements, evidence obtained through Equotip testing at our study areas highlights that the presence of barnacle cover can also promote rock deterioration, but at surface level. In fact testing hardness of naturally exposed rock at a less deep degree of penetration proves that its surface is harder than below the armored coating of barnacles, This evidence represents the innovative result of our work, highlighting not only the bioerosive effect of *Chtamalus* at surface level, but also provides experimental evidence to the above mentioned statement of Carter and Viles (2005). Detecting how the measured difference in hardness arises is beyond the scope of this work. Nevertheless we provide a working hypothesis for the cause of pattern we observed.

Not all barnacles glue the base of their bodies to rock surfaces using the same mechanisms of adhesion (Power et al., 2010). Some genus of barnacles are recognized to be bioeroders because they etch the bedrock, attaching their shells directly to it, in particular cementing the shell to the carbonate substrate (Bromly and Heinberg, 2006). The tropical barnacle *Lithotrya dorsalis*, for example, produces holes up to 4 cm deep in which carbonaceous plates that are secreted by the peduncle are allocated, and serve as a holdfast (Donn and Boardmann, 1988). Barnacles belonging to the *Chthamalus* genus, instead, do not etch the rock surface, as their style of attachment to the substrate is based on organic glue secretions from the basal, soft chitinouse membrane. Nonetheless, our results highlight for the first time that also not-boring barnacles are able to erode the most surface level of rocks, suggesting the need for further investigations.

From the geological point of view, in both study areas local varieties of the turbiditic sandstone called Macigno Fm, typical of the Italian Northern Apennines (Falorni, 2007), outcrop. Although quite heterogeneous in its different occurrences, this formation displays a predominant siliciclastic composition, a granular texture and a minor component of carbonatic cement, generally not exceeding 10% of the total amount (Gandolfi and Pagannelli, 1992). This carbonatic cement is though essential for keeping the mineral grains together. Barnacles, and specifically C. *montagui*, are considered important producers of carbon dioxide in the littoral environment (Golléty et al., 2008; Clavier et al., 2009). Part of this carbon dioxide is produced through their amphibious respiration, but the greatest part of it is released when they secrete their calcareous skeleton (especially during the Spring-Summer season). The increase in carbon dioxide in the seawater trapped inside the shell, in presence of soluble calcium carbonate from the rock, can cause the dissolution of the rock cement. Moreover, the dissolution power of bicarbonate water is favored by high concentrations of ions such as $Na+$, Cl^{-} and $K+$ (Ford and Williams, 2007), such as inside barnacles shell, due to partial water evaporation under prolonged desiccation conditions. Formal tests of these hypotheses are needed to clarify the mechanisms by which *Chthamalus stellatus* can act as a bioeroder of the surface layer of rocks.

It is worth noting that our study did not detect a consistent bio-erosive effect of barnacles at all the spatial scales analyzed. In particular, the effect was significant only at 2 out of 3 localities in Calafuria. This spatial variability does not rule out the importance of our findings; rather, it highlights the possible interaction between barnacles cover and other biotic or abiotic factors. From a geological perspective, variability in the percentage of carbonatic cement or in the texture of the sandstone between areas tens of kilometers apart as well as between localities tens of meters apart could have influenced the magnitude of the erosive effect exerted by barnacles through the calcification process. As a non-mutually exclusive alternative, lack of differences between values of the L-index from Control and Treatment plots at some localities could be due to ecological reasons. For example, higher densities of littorinid gastropods, naturally occurring at some localities, might have reduced the difference between Control and Treatment plots. In fact, the development of a microbial assemblage were barnacles were removed for 4 months, as well as the amelioration of biotic conditions due to surrounding barnacles, might have fostered the grazing activity of littorinids within Treatment plots. Where gastropods were naturally more abundant, their bio-eroding effect of the surface layer could have equaled that exerted by barnacles, resulting in no significant differences from Control plots.

Conclusions

It is widely recognized that landforms evolve under the influence of biological communities over a wide range of time scales, but also that ecological dynamics control landscape evolution at different spatial scales (Reinardt et al., 2010; Corenblit et al., 2011). Geomorphological research may benefit from integrating concepts and experimental methodologies specific to ecological research. In this work, an experimental design was specifically set based on those practices typical of studies on the ecology of benthic biota. This approach not only enabled us to highlight causality between the occurrence of barnacles and coastal landforms evolution, but also to identify plausible interactive factors in case of variability of effects at specific spatial scales. Our results are in accordance with past studies, but are characterized by the key aspect of having tested this hypothesis through a manipulative experiment in the field. In particular, the use of a hierarchical design enabled us to state, for the first time, that the bio-protective role at the sub-surficial level was generalizable to spatial scales ranging from a few centimeters up to tens of kilometers. Moreover, by testing rock hardness *in situ* by means of two different geotechnical tools (namely Schmidt hammer and Equotip), we revealed a complex role of the benthic crustacean *Chthamalus* as bio-remodeler of coastal rock surfaces. In our study area, located in a Mediterranean, moderately energetic and microtidal sandstone rocky shore, *Chthamalus* play a bio-protective role in the midlittoral at sub-surficial level (and consistently at all the spatial scales analyzed), as previously shown along other coastal shorelines around the world. Interestingly, at surface level they can act as bioeroders, likely causing corrosion of the rock surface by fostering dissolution of the sandstone carbonate matrix. This could be the result of an aggressive water trapped within barnacles' shells, particularly rich in carbon dioxide (coming from their amphibious respiration as well as from the construction of their calcareous skeleton) and ions concentration due to water partial evaporation. This effect might be particularly intense in a system such as the Mediterranean Sea, were the limited amplitude of tides makes rocky coasts an extremely variable environment, where abrupt fluctuations in thermal and desiccation conditions are frequent all year round (Benedetti-Cecchi et al. 2006).

Further research is needed to quantify, more in detail than previously established by Clavier et al. (2009), the amount of carbon dioxide actually emitted by barnacles and their role in the geochemical equilibrium with seawater and inorganic carbonate. At the same time, the spatial variability in the bioerosive effect of barnacles suggest an interactive role with abiotic and/or abiotic factors, which deserves further experimentation.

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Figure captions

Fig. 1 Sketch map showing the location of the two study areas (Calafuria and Baratti-Populonia) along the NW coast of Italy, and of the three Localities identified within each area. In the frame, the experimental design applied within each Locality is shown, including three random Sites within each locality, in each of which five Treatment plots and five Control plots were included.

Fig. 2 Mean R values (+1SE, n=90) in control plots (Control) and plots where *Chthamalus* has been removed 4 months before (Treatment), at Baratti-Populonia and Calafuria. Analyses of variance showed a significant positive main effect of the presence of barnacles on R values in both areas (Table 1 and 2), with larger values of rock hardness at the sub-surficial level in Control than Treatment plots.

Fig. 3 Mean R values (+1SE, n=10) at each site within each locality at Calafuria (A) and Baratti-Populonia (B). At Calafuria, individual R values ranged between 42 and 29 (covering a range of 13 points), while at Baratti-Populonia R ranges between 49 and 31 (a range of 18 points).

Fig. 4 Mean L values (+1SE, n=15) in control plots (Control) and plots where *Chthamalus* has been removed 4 months before (Treatment) at each locality in Calafuria. ANOVA showed that rock hardness at the surface level was higher in Treatment than Control quadrats at 2 out of 3 localities.

Fig. 5 Mean L values (+1SE, n=10) at each site within each locality at Calafuria (A) and Baratti-Populonia (B). At Calafuria, individual L values ranged between a maximum of 576 and a minimum of 450 (covering a range of 126 points), while at Baratti-Populonia, L ranged between 557 and 459 (98 points).

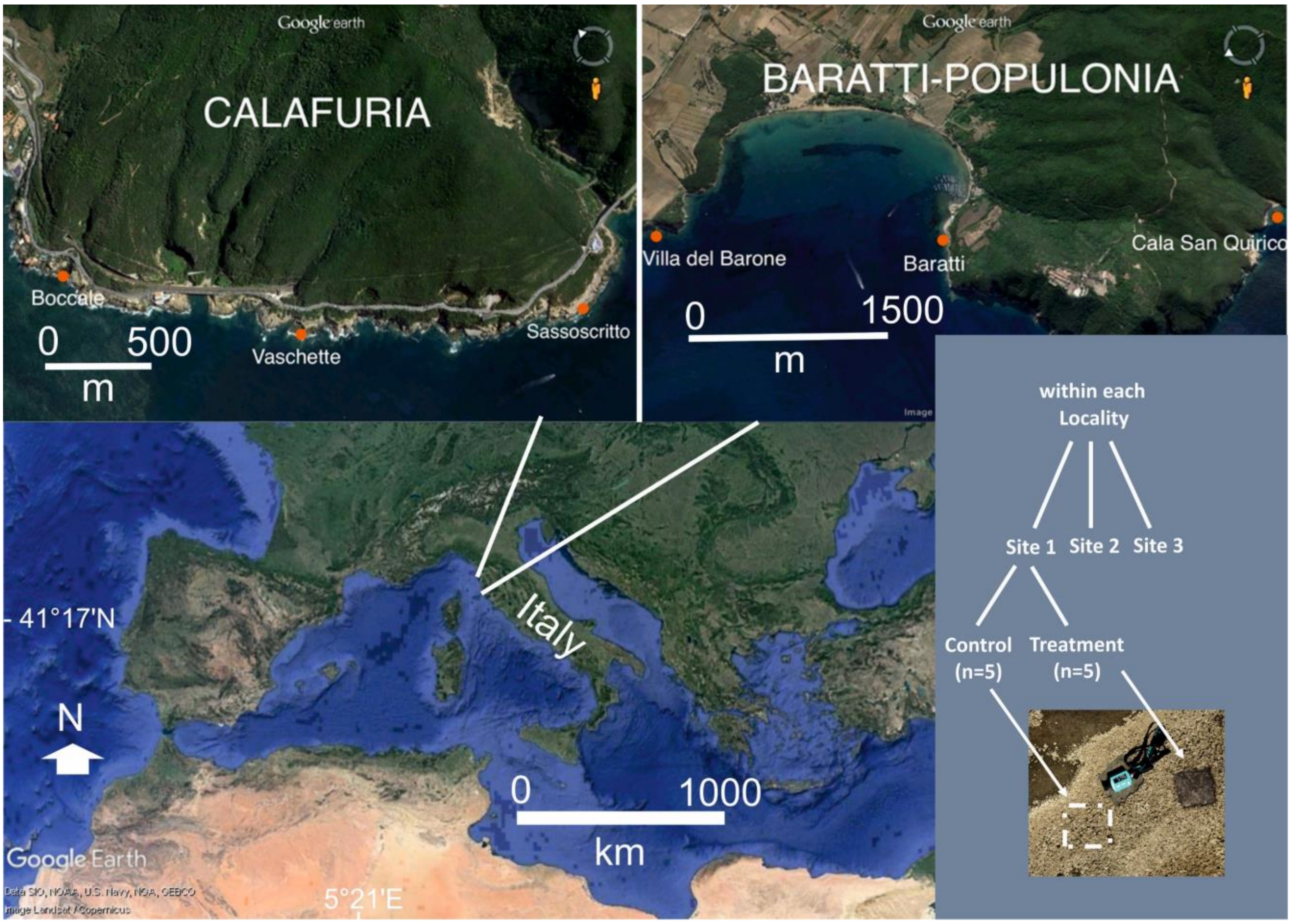
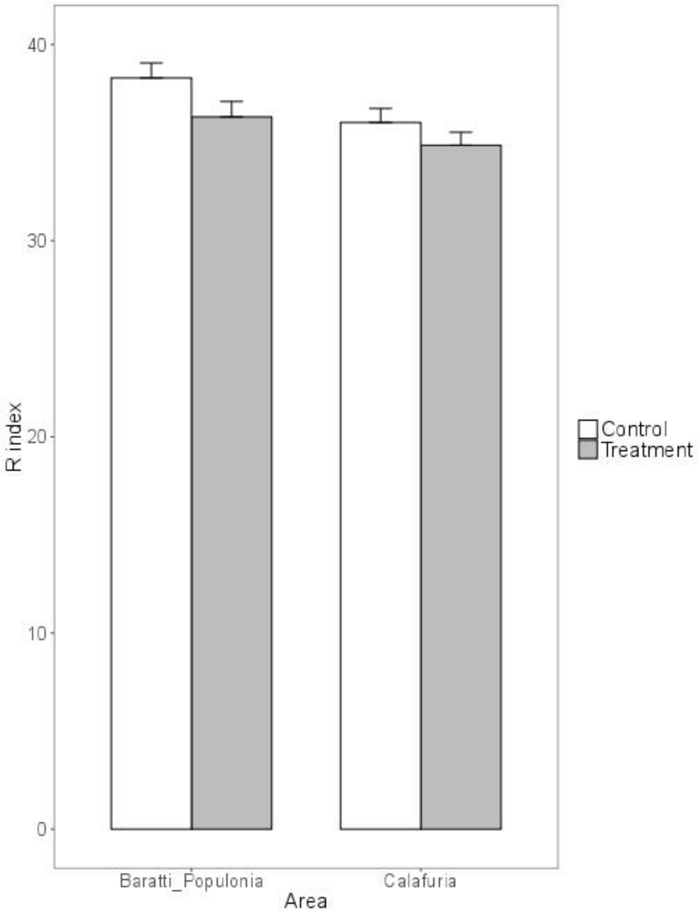


Fig. 1


R index
40
30
20
10
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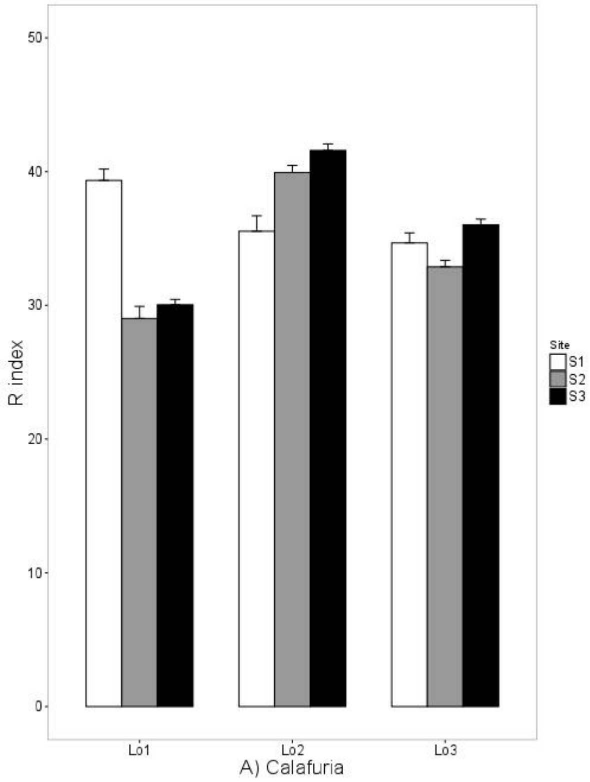
Control
Treatment
Baratti_Populonia
Calafuria
Area

Fig. 2


R index
50
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S1
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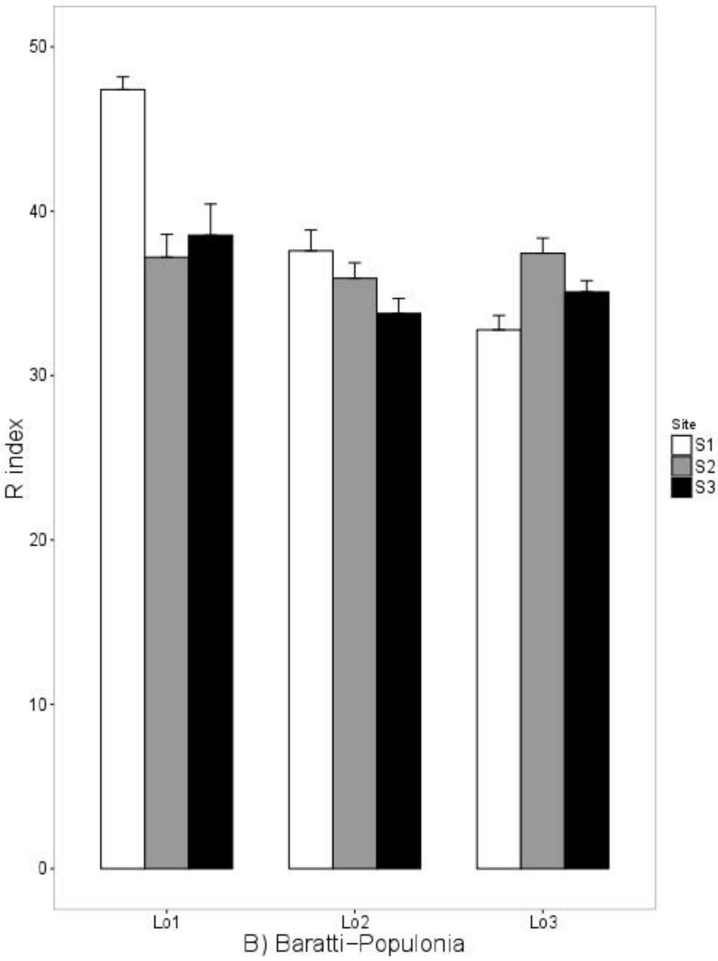
Lo1
Lo2
Lo3
A) Calafuria

Fig. 3 A

689



R index
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Site
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B) Baratti–Populonia

Fig. 3B

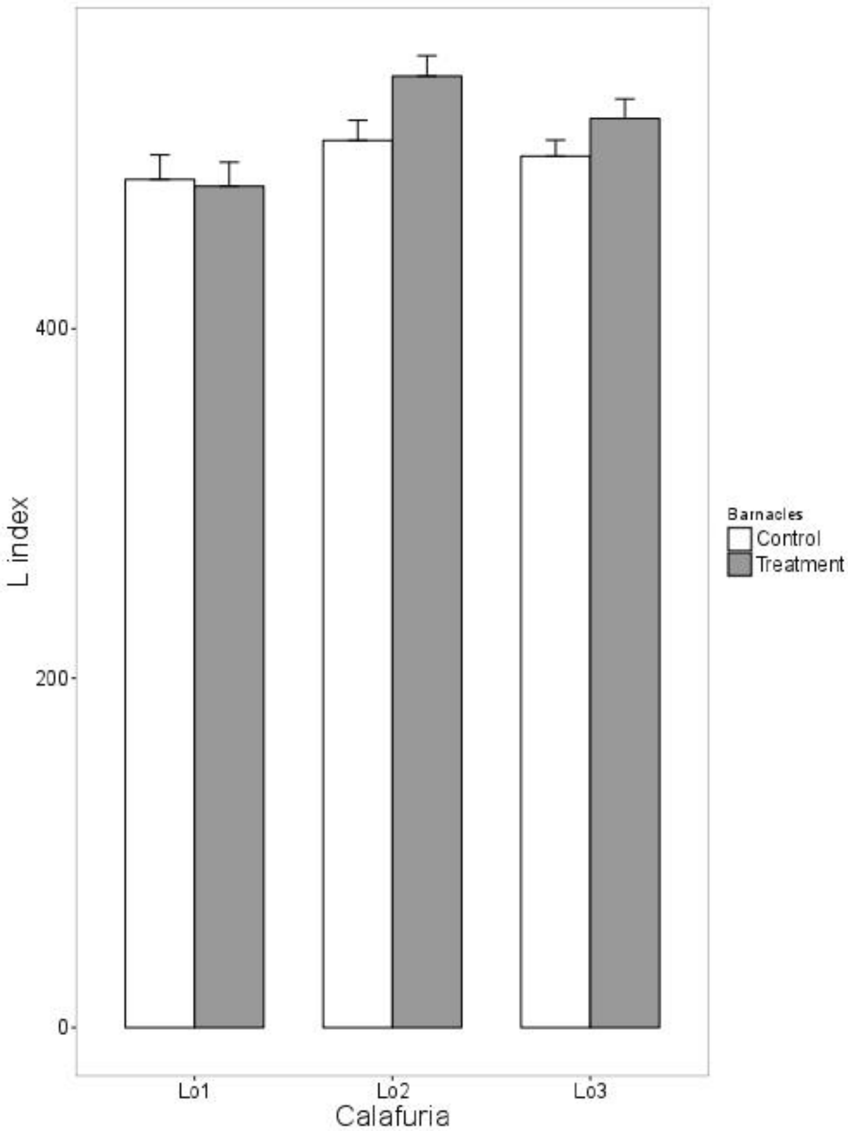
L index
400
200
0
Lo1
Lo2
Lo3
Calafuria
Barnacles
Control
Treatment

Fig. 4

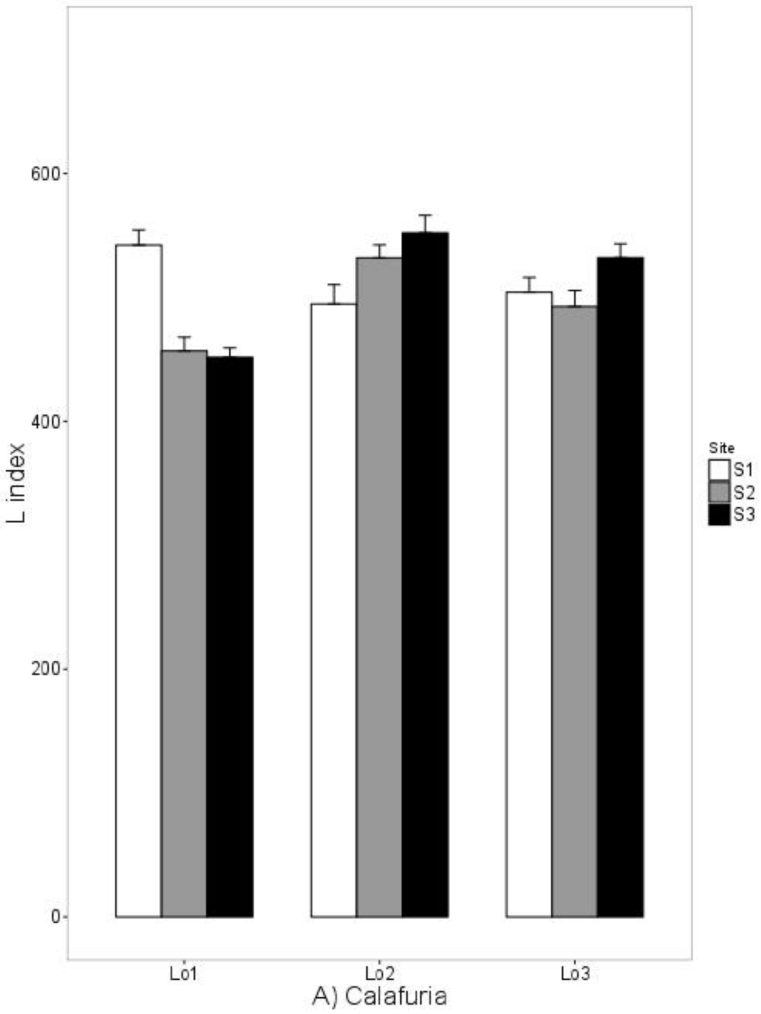

Fig. 5a

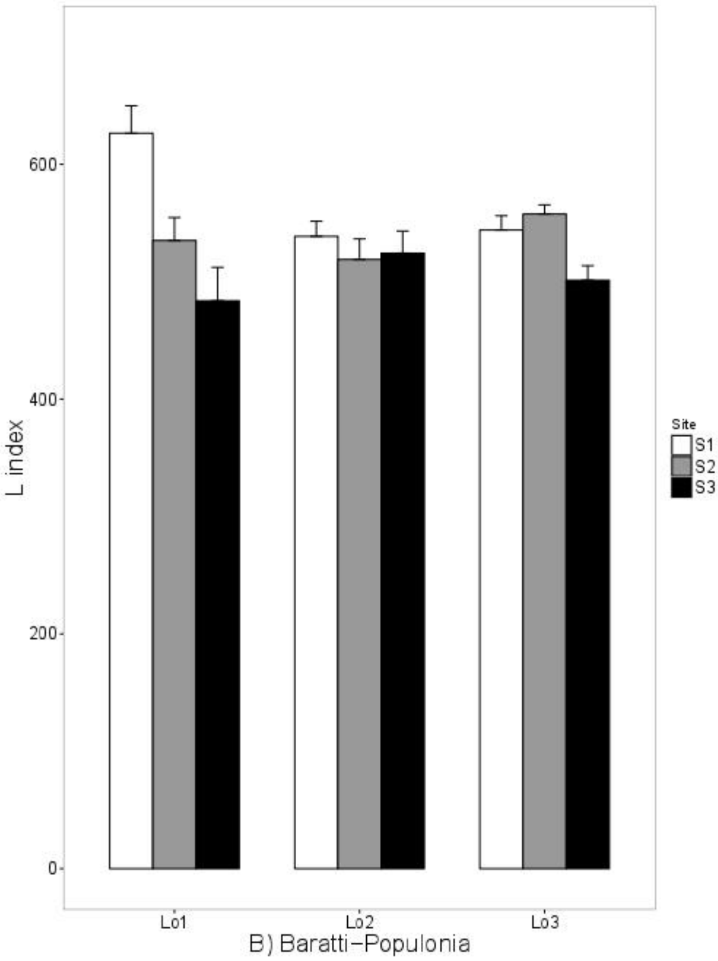

Fig. 5B

Table 1. Analysis of variance (ANOVA) on R values (Schmidt hammer) at Calafuria. *, $p < 0.05$, **, $p<0.01$

Sources of variability	**df**	**MS**	**F**
Locality = Lo	2	309.03	2.08
Barnacles = Barn	1	30.28	27.85*
Site(Locality) = Site	6	148.55	29.9**
Lo x Barn	2	1.09	0.36
Site x barn	6	3.02	0.61
Residual	72	4.97	
Cochran's C	0.18, ns		

<u>SNK</u> *Barnacles*: Control>Treatment

Site: Lo 1: S1>S3=S2
Lo 2: S3=S2>S1
Lo 3: S3>S2, S1 not ranked

Table 2. Analysis of variance (ANOVA) on R values (Schmidt hammer) at Baratti-Populonia. **, p<0.01, ***, p<0.001.

Sources of variability	**df**	**MS**	**F**
Locality = Lo	2	318.36	2.40
Barnacles = Barn	1	88.80	11.42[§]**
Site(Locality) = Site	6	132.66	10.74***
Lo x Barn[a]	2	5.66	0.67
Site x Barn[a]	6	8.48	0.69
Residual	72	12.35	
[a]pooled factors	8	7.78	0.63
Cochran's C	0.20, ns		

[§]tested on pooled factors (Underwood 1997)

SNK *Barn*: Control>Treatment

Site: Lo 1: S1>S3=S2
Lo 2: S1>S3, S2 not ranked
Lo 3: S2>S1, S3 not ranked

Table 3. Analysis of variance (ANOVA) on L values (Equotip) at Calafuria. **, p<0.01, ***, p<0.001. When interaction terms were significant, only SNK tests of interest were reported.

Sources of variability	**df**	**MS**	**F**
Locality = Lo	2	13878.4	1.08
Barnacles = Barn	1	7429.3	2.34
Site(Locality) = Site	6	12820.2	8.93***
Lo x Barn	2	3171.5	11.67**
Site x Barn	6	271.7	0.19
Residual	72	1435.9	
Cochran's C	0.12, ns		

SNK *Lo x Barn*: Lo 1: Control=Treatment
Lo 2: Treatment > Control
Lo 3: Treatment > Control

Site: Lo 1: S1>S3=S2
Lo 2: S3>S1=S2
Lo 3: S1=S2=S3

Table 4. Analysis of variance (ANOVA) on L values (Equotip) at Baratti-Populonia. ***, p<0.001.

Sources of variability	**df**	**MS**	**F**
Locality = Lo	2	2137.8	0.12
Barnacles = Barn	1	6992.5	4.87
Site(Locality) = Site	6	17458.0	5.68***
Lo x Barn	2	1436.1	0.51
Site x Barn	6	2836.2	0.92
Residual	72	3071.3	
Cochran’s C	0.21, ns		

SNK *Site*: Lo 1: S1>S2>S3
Lo 2: S1=S3=S2
Lo 3: S2=S3=S1