INTRODUCTION

The black sea urchin *Diadema antillarum* (Philippi, 1845) has been characterised as a keystone species in shallow subtidal ecosystems because of its effectiveness in reducing algal biomass and diversity (Bak et al., 1984; Carpenter, 1990; Larsen et al., 1996). However, grazing by *D. antillarum* is well-documented only for the Western Atlantic, where sea bottoms are dominated by coral reef communi-
ties (Sammarco et al., 1974; Sammarco, 1980, 1982a, b; Carpenter, 1981). Although this species has been less studied in the east Atlantic, where sea bottoms are dominated by rocky substrate communities, studies in the Canary Islands (Larsen et al., 1996; Casañas et al., 1998; Garrido-Sanahuja and Haroun, 1998) and off the Madeira Islands (Augier, 1985; Bianchi et al., 1998; Alves et al., 2001) have suggested a similar voracity of *D. antillarum* feeding on macroalgae. These studies also reported that *D. antillarum* may be responsible for nearly denuded substrata, which may have important consequences on the structure of benthic communities by leaving less food available for other herbivores and reducing the dissolved organic matter available for detritivores (McGlathery, 1995; Valentine et al., 1997). This study aimed to analyse the grazing activity by *D. antillarum* upon the algal communities on rocky substrates, and to evaluate its possible impact on the subtidal communities off Madeira.

**MATERIAL AND METHODS**

**Study site**

Madeira Island is located in the north-east Atlantic Ocean, at approximately 32°38’N and 16°54’W (Biscoito and Abreu, 1998). It has a reduced continental shelf, and forms part of the important Macaronesian biogeographic region (Beyhl et al., 1995; Stock, 1995). This island, of volcanic origin, is the largest of the archipelago bearing the same name, which includes Porto Santo and the smaller Desertas and Selvagens islands. Madeira Island itself extends W-NW to E-SE along 58 km, and its 153 km of coastline are predominantly rocky with boulders. The surface seawater temperatures usually range between 17.0 and 22.5°C (Abreu and Biscoito, 1998).

**Preliminary survey**

Preliminary prospective Scuba dives were made along the whole coast of Madeira Island to determine a rocky substrate area that would best fit the experiment requirements in terms of *D. antillarum* abundance and feasibility for divers to perform and monitor the experiment. The selected area was on the south coast, at Lido bay (see Alves et al., 2001), despite the considerable homogeneity of the benthic communities observed along almost the wholesubtidal rocky shore of the south and south-east coast of Madeira, featuring high densities of this species and nearly bare substrata. The natural density of *D. antillarum* and the percentage algal cover in the experiment area were determined by 27 random quadrats, using a square metre for *D. antillarum* abundance, and a 0.5 m x 0.5 m quadrat divided into a hundred 5 x 5 cm squares for algal cover.

Two Kolmogorov-Smirnov tests were performed to assess the normal distribution of *D. antillarum* abundance and algal cover. Both tests revealed that the data conformed to the normal distribution (p > 0.05), thus showing that all treatments were in the same initial conditions.

**Cage design**

The cages measured 0.5 0.5 m wide and 0.2 m high with a 0.2 m overhanging edge made of 2 cm mesh wire. They were built of 8 mm steel and attached to the bottom with iron nails and wire. The top was open to ensure that free-swimming herbivores could enter the cage. The cage design tried to minimise any disturbance of natural conditions on the algal colonisation and growth, such as current and light intensity. Two different cage designs were used: laterally closed cages (Fig. 1A) and open cages (controls), with the sides partly closed (Fig. 1B). The closed cages were previously tested in the experiment area for their ability to exclude sea urchins. The open cages were also tested for their ability to allow sea urchins in. This experiment was performed for two weeks, and both cage designs performed as expected.

**In situ cage experiment**

To estimate *D. antillarum* grazing upon the algal cover, an exclusion experiment was performed between May and September 1998. Three experimental treatments were used: (1) closed cages which excluded sea urchins; (2) open cages (controls), to control any eventual side effects of the cage structures themselves; and (3) uncaged controls (small iron cross markers).

Nine replicates of each treatment were set randomly on the bottom at depths of 11–13 m in the pre-determined area (approximately 200 m²). During the four months of the experiment, the cages were monitored weekly by Scuba divers to observe the integrity of the experiment. In September 1998, at the end of the experiment, the percentage algal
cover was quantified in all replicates of all treatments, using a 0.5 m x 0.5 m quadrat divided into 100 squares (5 cm x 5 cm): the number of squares with algae was counted and the percentage cover of the total area was calculated.

Data analysis

The mean and the standard error of the percentage algal cover of each treatment were calculated. A one-way ANOVA was used to test the null hypothesis that there were no significant differences in the percentage algal cover between the three treatments. Because more than two comparisons were made, this analysis was followed by a post-hoc comparison using the Tukey honest significant differences (HSD) test. Concerning the ANOVA test assumptions, the data conformed to the normal distribution (Kolmogorov-Smirnov test, p > 0.05) and to homogeneity of variance (Levene’s test, p > 0.05). The significance level assumed for all tests was 95% (p < 0.05). All statistical tests were performed with the Statistica V.5 software package.

RESULTS

The preliminary survey showed that the natural density of *D. antillarum* at Lido bay was 5.11 ± 1.56 individuals/m² (mean ± standard deviation). It was also observed that *D. antillarum* was the most abundant sea urchin and predominated as the main herbivore in the experimental area.

At the end of the experiment, the mean algal cover (± standard error) was 4.4 ± 1.2% in the uncaged controls, 5.8 ± 1.5% in the open cage controls, but as high as 14.6 ± 2.7% in the closed cages (where sea urchins were excluded) (Fig. 2). One-way ANOVA showed that algal cover differed significantly between treatments (Table 1). However, the Tukey (HSD) test revealed that significant differences only occurred between closed cages with either of the controls. The mean percentage algal cover was not significantly different between uncaged controls and open cage controls (Table 1). The percentage algal cover observed in the closed cages, compared with the uncaged and open cage controls, allows us to conclude that, in the area where *D. antillarum* was excluded (closed cages), the algal abundance increased by about 10% in the four-month period.

During the experimental period, it was registered that adult *D. antillarum* individuals (measuring approximately 10 cm in test diameter) were com-

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monly observed invading the control replicates (both uncaged and open cage controls).

DISCUSSION

Studies in the Caribbean have also used cages to exclude *Diadema antillarum* (Sammarco, 1980, 1982a; Carpenter, 1981), as well as to eliminate an entire *D. antillarum* population efficiently (Sammarco et al., 1974; Sammarco, 1982b). Also, our attempts to maintain *D. antillarum* exclusion from the closed cages, and at natural densities inside controls (both uncaged and open cage controls), were successful, demonstrating that the cage design was efficient because it excluded predators and did not significantly influence algal growth. Because of the low annual seasonal variations in weather conditions and seawater temperature off Madeira (Instituto Hidrográfico, 1979; Abreu and Biscoito, 1998; Carita, 1998), we consider that the present results will only be slightly and non-significantly affected by seasonal variations.

The present study documented an increase in algal cover in the areas where *D. antillarum* were excluded (closed cages). Similar results were described in Caribbean waters by Sammarco (1980, 1982a, b) and Carpenter (1981).

Liddell and Ohlhorst (1986) studied algal recovery in Discovery Bay (Jamaica) immediately after a mass urchin cull on coral reefs, and described an increase in algal cover of about 40% over a four-month period. In our study we observed a 10% increase in algal abundance. Differences in water temperature between sites may justify the different results obtained from the present study, together with the negative relation observed by Alves et al. (2001) between percentage algal cover and densities of *D. antillarum* in Madeira, suggest that *D. antillarum* grazing pressures control algal abundance on rocky substrates (such as Madeira, Canary and Cape Verde – East Atlantic archipelagos) and not just in coral reef communities (West Atlantic). The impact of *D. antillarum* on the structure of rocky shore benthic communities may have important consequences for the ecosystem. Thus, benthic communities will probably undergo significant changes if *D. antillarum* abundance significantly increases or decreases.

If a similar event to the one that happened in the Western Atlantic, where entire populations of *D. antillarum* suffered the most extensive and severe mass mortality ever recorded for a marine animal (Levitan, 1988; Lessios, 1995), occurred in the Madeira Archipelago, an increase in the total algal abundance could probably be expected. If this happened, the present study would be significant, as it would be possible to compare *D. antillarum* densities, algal abundances and increase rates. For the above reasons, we consider that the management of sea urchin abundance (such as *Diadema antillarum*) on rocky substrates (such as Madeira Island) is important in order to prevent unfavourable ecosystem changes.

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