An experimental investigation of the ability of adult crown-of-thorns starfish to survive physical damage.

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Abstract

On three occasions, adult Acanthaster planci were collected from a high density population and subjected to various levels of physical damage including bi- and tri-section. They were then held in cages for approximately 15 days to monitor survival. Results were variable: in one instance, where even bisection did not affect survival over the experimental period. On the other occasions damaged individuals showed poorer survival. Starving the animals for six weeks prior to the experiment did not reduce survival compared with that of newly collected individuals. Varying the density of animals in cages found lower survival at lower densities implying that the transmission of pathogens was not artificially high in cages. Given the variable results of this and other studies, and the frequency of damaged but healed or regenerating starfish in natural populations, predation is only conclusively lethal if the whole starfish is removed.

Introduction

Attention has been focussed on potential predators of the crown-of-thorns starfish, *Acanthaster planci,* because several authors have suggested that human impacts on populations of predators have increased the frequency of outbreaks (Endean 1976, Endean and Cameron 1990, Ormond *et al.* 1990). An adult *A. planci* represents a large prey item for all but the largest fishes and gastropods and it is well documented that *A. planci* of all sizes frequently have damaged and regenerating arms (refs. in Moran

1986, McCallum *et al.* 1989, Yokochi and Ogura 1987, Zann *et al.* 1987), which suggests that a proportion of predatory encounters are not fatal. Observations of predation are rare, but there are instances both of one fish killing a starfish (Ormond and Campbell 1974, Randall *et al.* 1978, *Marine Biologic* 1991) and of a fish's guts containing only part of a starfish (Birdsey 1988).

It is also of interest to know the extent of damage that is likely to be fatal to starfish for the purposes of control. Physical cutting of starfish seems to have been avoided as a control method for fear that the animals will regenerate damaged parts and survive and even multiply (Birkeland and Lucas 1990). Other control measures may be more reliable but they are either more laborious, such as removing the starfish and drying them on the shore, or involve injection of toxic substances, requiring equipment of varying sophistication, careful handling and involving risks to other reef organisms as well as the operators themselves. In this study we set out to investigate the extent of damage that would be fatal to adult starfish.

Materials and Methods

All fieldwork was carried out at Davies Reef (18^{o} 50'S, 147^{o} 38'E), a mid-shelf reef near Townsville, North Queensland, Australia. The crown-of-thorns starfish population on Davies Reef was declared an outbreak in summer 1986-87 when a large cohort reached maturity (age 3+). Further cohorts matured in the following two years (R. Stump, *pers comm.*). There were three experiments: winter 1991, summer 1991 and winter 1992. In all experiments adult crown-of-thorns starfish were collected by snorkellers and held in a 1000 l tank with running seawater on the deck of the research vessel for up to 24 hours before processing.

The winter 1991 experiment ran from 1-15 May. One hundred starfish were collected. Groups of five individuals were selected haphazardly and each individual was randomly allocated to one of five treatment groups. The treatment groups were: controls, two-, four-, eight-arms cut off and bisected starfish. Controls were collected and transferred to the holding tank, then lifted out of the tank placed on a flat surface, and then placed in another tank for transportation to the experimental cage. Three other groups were treated similarly except that when they were placed on the flat surface, two, four or eight adjacent arms were cut off at the point where the arm joined the oral disc with a diving knife. A final group was treated similarly except that starfish were cut in half across the oral disc and one half was discarded. *Figure 1* shows the frequency of arm damage in starfish in outbreak populations from two reefs in the central area of the Great Barrier Reef in the late 1980s. While 63% of individuals had damage to one or more arms, most had lost parts of one or two arms only and individuals with damage to more than six arms were very rare. Assuming that more extensive damage is fatal, the experimental treatments range from non-lethal to lethal.

The 20 members of each treatment group were then placed in a pen of 12 mm square mesh which was approximately oval and with a circumference of 12 m. The walls were 1.1 m high. Initially, the pen did not have a roof but the walls had an overhang that curved inwards for about 0.6 m. Dead rubble was put in the pen to provide cover. After seven days, the starfish were counted and the top of the pen was sealed with mesh. The starfish were counted again after 14 days and released.

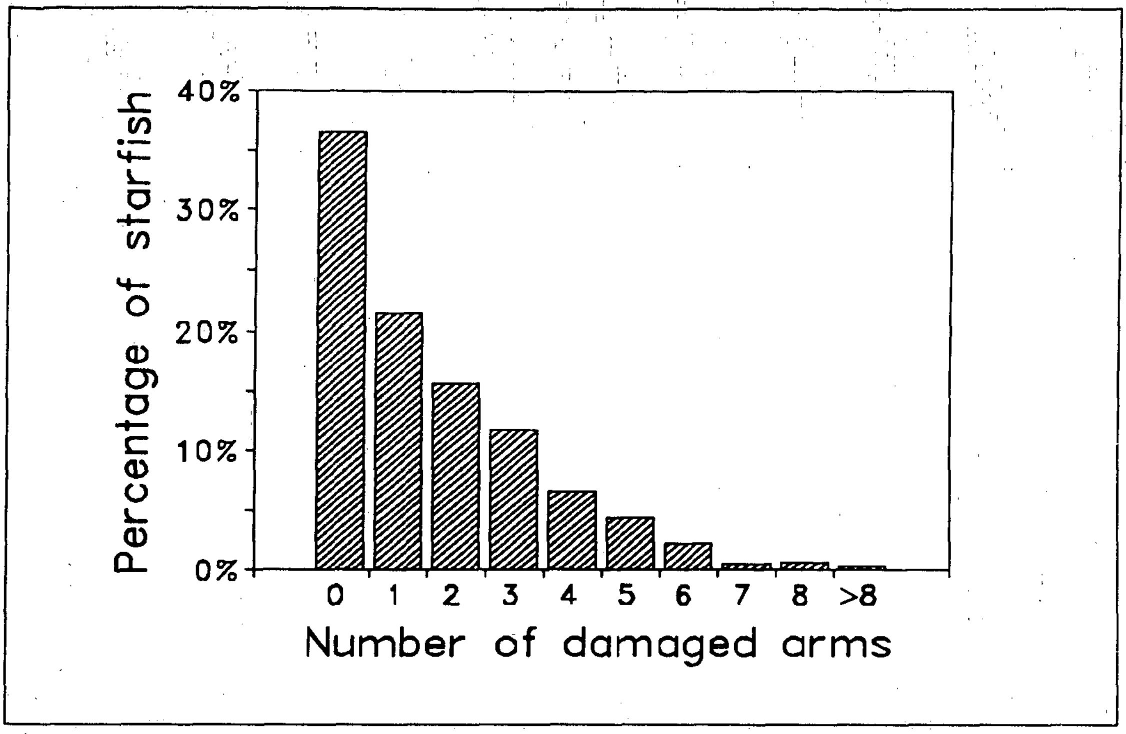

Figure 1: Proportion of 638 *A. planci* from natural populations with damaged arms. Samples from outbreaks at Keeper and Helix Reefs 1985-87 (Kettle, *unpublished*).

In the first experiment (winter 1991), very few starfish died in the two week period following damage. There have been elevated densities of starfish at Davies Reef for some years, but the population does not appear to have formed local concentrations that decimate all the coral and lead to malnutrition. For this reason, we decided to include animals that were less healthy due to starvation in future experiments to simulate a situation where high densities of starfish eat the coral to extinction. Kettle (1991) took *A. planci* from an area with abundant coral and kept them in aquaria without food for 22 weeks by which time more than half had died. He followed their decline in condition by measuring the percentage of the total calorific value of the animal represented by the pyloric caeca. Pyloric caeca are storage organs, so this may represent loss of reserves. He found that about half the total decline occurred in six weeks. In mid-October 1991, six weeks prior to the summer 1991 experiment, 108 starfish were collected and kept in cages without any live coral. Ninety-seven animals survived after six weeks.

The summer 1991 experiment was set up 6 - 14 December. There were two other differences to the winter 1991 experiment beside the inclusion of a starvation treatment. The damage treatments were also changed by omission of the loss of two arms and addition of a treatment where two thirds of the starfish, based on number of arms, was removed. By the end of the experiment, animals that were cut in half could not be distinguished reliably from those that had two thirds of their arms removed, so the two categories were combined for analysis. The design of cages was also different: rather than having a single pen, we used rectangular cages 3.5 x 1.5 x 0.45 m made of the same 12 mm square mesh. Each cage was divided into two compartments so that the starved and unstarved animals were kept separated but subjected to the same

conditions. Twenty-five animals were put in each compartment. When the cages were full, they were wrapped on three sides with black polythene sheet to give the starfish cover. Animals in the first two cages to be filled suffered high mortality in the first week. Before the covers were put on, these cages were holed by large puffer fish, *Arothron stellatus*, that attacked some captive *A. planci* and possibly allowed others to escape. The remaining animals were all put into one cage and later omitted from analyses. To compensate, twenty-five more unstarved starfish were placed in the other cage on 14 December. Cages were checked on 21 December (7 - 15 days) and the experiment finished 3 January 1992 (20 - 27 days).

The winter 1992 experiment was set up 25 - 29 May and was similar to the preceeding experiment and involved the same damage levels for newly collected starfish. Once again, animals that were cut in half were combined with those that had two thirds of their arms removed for analysis. One hundred and twelve *A. planci* were collected six weeks before, but all except 30 died during the period of starvation, and five of those had obvious necrosis.

The remaining 25 starved animals were put in one cage and allocated to only two treatments: undamaged controls and loss of eight adjacent arms. An additional, low density treatment was added to test the possibility that the high experimental densities exaggerated mortality by enhancing conditions for transmission of pathogens. Four cages were set up, each containing five unstarved starfish in each of two treatment groups: controls and -8 arms. All cages were made of heavier mesh to resist puffer fish. Each cage consisted of a single compartment measuring 1.2 x 2.0 x 0.4 m. The experiment finished 12 June (14 - 17 days).

In all experiments, the counts of survivors after approximately 15 days were used. At the end of each experiment, the starfish were inspected individually before release to determine which treatment group they belonged to. This was not always obvious because the body wall may contract to seal wounds causing the animal to assume contorted shapes. Also, necrotic tissue may also form along the edge of wounds so it may become hard, for example, to distinguish animals cut in half from those that lost eight arms. In the experiment in summer 1991, the animals were censused at 7 - 15 days by looking at them through the cage, though they were handled and inspected individually at the end of the experiment. For analysis we used counts from the 7 - 15 day census but adjusted them where these contradicted the final census.

Results

Effects of damage

When freshly collected and apparently healthy animals are considered, the effects of increasing arm loss varied among the experiments (*Fig. 2a - 2c*, significant interaction in *Table 1*). Because of this the experiments will be considered separately. In the experiment in May 1991, there was no significant difference in survival among the groups of damaged animals (*Fig. 2a*). This was true whether the five levels of damage were considered separately (logistic regression, slope not significantly different from zero, $x^2 1 = 0.0$) or all damaged starfish were grouped together and compared with the undamaged control group ($x^2 1 = 0.06$). By contrast in the experiment in December 1991, survival tended to decrease with increasing arm damage for unstarved *A. planci*

(*Fig.* 2*b*, logistic regression, slope greater than zero, $x^2 1 = 18.88$, $p < 0.001$). In the experiment in May - June 1992, survival was less among damaged individuals than among controls, but it did not decrease linearly with increasing extent of the damage (*Fig. 2c, Table 2*).

Table 1: Effect of damage on survival of freshly collected *A. planci*. Analysis of deviance table for May 1991 (-2 arms omitted), December 1991 and May 1992 (- $^1/_2$ and - $^2/_3$ combined). I = intercept, D = damage, E = experiment.

Model	Deviance	df	Difference	δdf	component	p
I+E	103.5	10	$d_{I+D+E} - d_{I+E} = 53.31$	1	D	0.000
I+D	115.0	10	$d_{I+D+E} - d_{I+D} = 64.81$	1	E	0.000
I+D+E	53.90	9	$d_{I+D+E+DxE} - d_{I+D+E} = 46.19$	6	DxE	0.000
I+D+E+DxE	7.71	3				0.052

Table 2: Effect of damage on survival of freshly collected *A. planci*. Analysis of deviance tables for experiment in May 1992 (- $^1/_2$ and - $^2/_3$ combined).
I = intercept, D = damage.

Model	Deviance	df	Difference	δdf	component	p
Linear scale of increasing damage.						
I	50.60	3	$d_{I+D} - d_I = 43.66$	1	D	0.000
I+D	6.94	2				0.031
Controls vs all damaged animals combined.						
I	50.60	3	$d_{I+D} - d_I = 47.50$	1	D	0.000
I+D	3.10	2				0.212

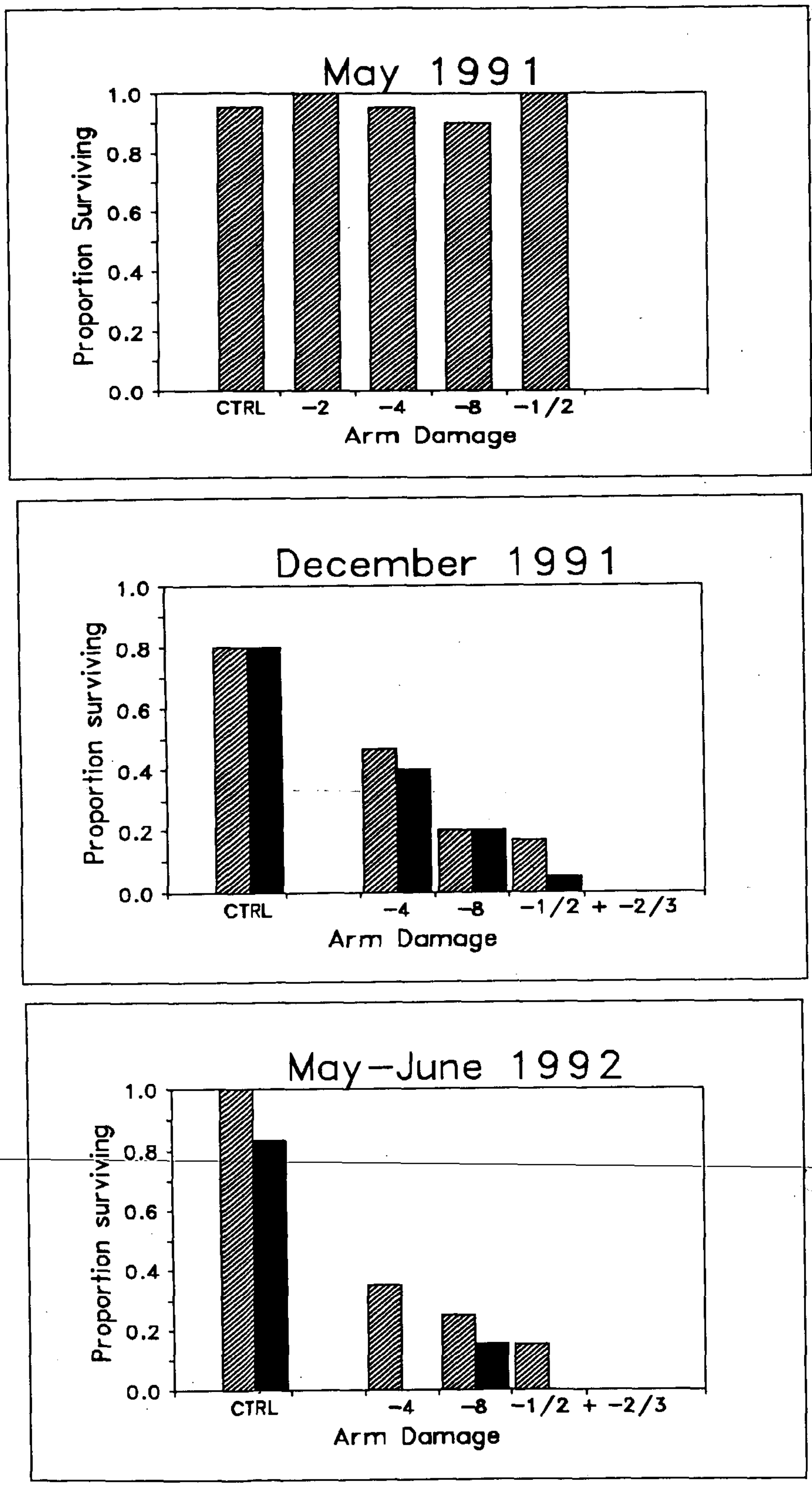

Figure 2: Proportions of *A. planci* subject to different levels of arm damage surviving in the three experiments. Hatched bars represent newly collected animals, filled bars represent starved animals.

Effect of starvation and damage

The low survival of starfish over the six week starvation period prior to the experiment in May 1992 meant that the effect of starvation could only be examined at two levels of damage (controls and -8 arms). Considering these levels of damage in the December 1991 and May 1992 experiments, there was no evidence that starvation had a significant effect (*Table* 3). The intensity of the effect of damage differed between experiments (*Table* 3), but in each experiment damaged starved starfish showed poorer survival than starved control animals (*Fig. 2b, 2c*).

Table 3: Effect of starvation on survival of damaged *A. planci*. Analysis of deviance table for experiments in December 1991 and May 1992. Data from two damage treatments (Control and -8 arms) subjected to logistic regression.
I = intercept, D = damage, E = experiment and S = starvation.

Model	Deviance	df	Difference	δdf	component	p
I+E	65.33	6	$d_{I+D+E} - d_{I+E}$ = 55.84	1	D	0.000
I+D	20.37	6	$d_{I+D+E} - d_{I+D}$ = 10.88	1	E	0.001
I+D+E	9.49	5	$d_{I+D+E+DxE} - d_{I+D+E}$ = 3.87	1	DxE	0.049
I+D+E+DxE	5.62	4	$d_{I+D+E+S+DxE} - d_{I+D+E+DxE}$ = 1.75	1	S	ns
I+D+E+S+DxE	3.87	3	$d_{I+D+E+S+DxE+SxE} - d_{I+D+E+S+DxE}$ = 0.99	1	SxE	ns
I+D+E+S+DxE +SxE	2.88	2	$d_{I+D+E+S+DxE+DxS+SxE} - d_{I+D+E+S+DxE+SxE}$ = 1.86	1	DxS	ns
I+D+E+S+Dx+ DxS+SxE	1.02	1				

Table 4: Effect of starvation on survival of damaged *A. planci*. Analysis of deviance table for December 1991 with 4 levels of damage (- $^1/_2$ and - $^2/_3$ combined) subject to logistic regression. I = intercept, D = damage, S = starvation.

Model	Deviance	df	Difference	δdf	component	p
I+D	47.99	6	$d_{I+D+S} - d_{I+S}$ = 44.35	1	D	0.000
I+S	4.54	6	$d_{I+D+S} - d_{I+D}$ = 0.90	1	S	ns
I+D+S	3.64	5	$d_{I+D+S+DxS} - d_{I+D+S}$ = 0.30	1	DxS	ns
I+D+S+DxS	3.34	4				ns

There is no statistical evidence that starvation affected survival in the December 1991 experiment when freshly collected and starved animals were subjected to four levels of damage (*Fig. 2b*; *Table 4*) or in May 1992 (*Fig. 2c*, logistic regression, $x^2 1 = 2.41$, $p > 0.1$).

Effect of experimental density and damage

Comparison of the two damage levels (Control and -8 arms) that were present at the two densities in May 1992 showed evidence that the effect of damage depended on density (*Fig. 3, Table 5*) but the difference was a matter of degree rather than a qualitative difference. More importantly, survival was lower at the low density (*Fig. 3*). There was no evidence that the experimental density increased mortality by favouring pathogens.

Table 5: Effect of density on survival of damaged *A. planci*. Analysis of deviance table for May 1992. I = intercept, D = damage, LD = low density.

Model	Deviance	df	Difference	δdf	component	p
I+LD	41.03	2	$d_{I+D+LD} - d_{I+LD} = 31.50$	2	D	0.000
I+D	9.53	2	$d_{I+D+LD} - d_{I+D} = 4.20$	1	LD	0.040
I+D+LD	5.33	1	$d_{I+D+LD+DxLD} - d_{I+D+LD} = 5.33$	1	DxLD	0.021

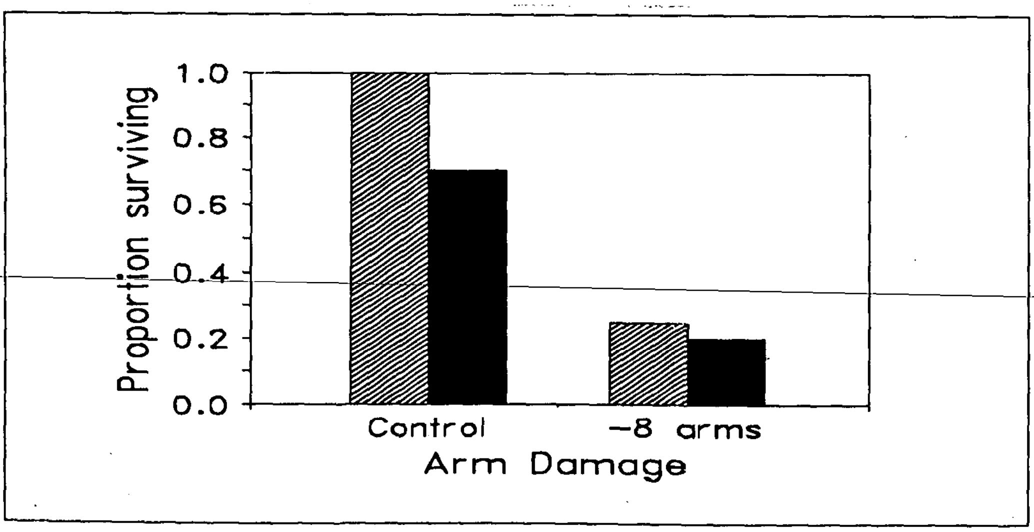

Figure 3: Comparison of survivorship of *A. planci* held at experimental density (hatched bars) and a lower density (filled bars), May - June 1992.

DISCUSSION

The aim of this project was to determine the degree of arm damage that is fatal to adult crown-of-thorns starfish. The results of the three experiments are inconsistent in this

regard, particularly because of the contrast between the May 1991 experiment, when there was practically no mortality over the experimental period for any of the levels of damage, and the other two experiments. There are two obvious sources of variation among experiments: seasonal changes in reproductive condition and progressive ageing of the main cohort of the population.

There was a decrease in survival of control starfish in the December 1991 experiment. Controls serve to show the effect of handling on the experimental animals. The experimental procedure meant that handling was a considerable source of stress, since the animals were lifted out of the water during collection and during experimental processing; at either instance the coelomic membrane could rupture. The experiment coincided with the main spawning period for 1991 at Davies Reef (R Babcock, *pers. comm.*). The bulk of the current population reached maturity in summer 1988-89 which would make them 6+ years old at the time of the experiment. We suggest that the low survivorship even among control animals in December 1991 was due to the experimentally induced stresses being added to the physiological stresses of gonad production. This would mean that adult *A. planci* are most susceptible to damage at the time when they have maximally developed gonads and so would presumably be most energetically rewarding as prey. The differences in survival rate over the two periods of starvation prior to the experiments in December 1991 (about 90%) and May-June 1992 (<25%) suggests that there may be a general ageing of the population. Prior to the last experiment, the starfish were held in four cages each containing 28 animals. The poor survival was general: all the starfish in one cage were dead after six weeks and no cage contained more than ten intact starfish.

However the differences among experiments came about, the finding of the experiment in May 1991, that even animals that were cut in half showed little mortality, makes it impossible to be sure that any level of damage up to loss of half of the animal is necessarily lethal. This conclusion is conservative because the population at Davies Reef was mainly composed of large adults (35 - 45 cm in diameter) and it is likely that larger animals will be more vulnerable to damage because of their lower skeletal content which makes it difficult to seal wounds (Birkeland and Lucas 1990). Predation is only certainly lethal if the whole starfish is taken, though this may be achieved by several predators acting together.

Our experiments were based on the assumption that any mortality would be rapid and that a 15 day period would be adequate. This seemed to be the case in the later experiments. Prolonging the experiments would mean that starvation in the experimental period would become more significant, which raises the logistical problem of having to provide quantities of coral. There are two pieces of anecdotal evidence that heavily damaged animals did not die after the end of the experiment in May 1991. In October 1991 a starfish that had been cut in half was found within 50m of the site of the pen. The wound had healed but no regeneration was apparent. In November 1991 an animal missing eight adjacent arms was seen near the site of the experiment. It too had healed but no regeneration was evident.

Other anecdotal reports of healing and regenerative abilities of *A. planci* suggest that animals usually survive the loss of a few arms, but consequences of more extensive damage are inconsistent. Pearson and Endean (1969) kept three individuals (16, 23 and 31 cm) alive for at least a month after cutting off one arm. Owens (1971) cut two arms

off six animals (size unspecified) and released them. He recovered one 50 days later and found the wound had healed but there was no regeneration. Pearson and Endean (1969) cut two large adult animals in half and found that they were dead the next day. Owens (1971) cut a 35 cm individual in half and found that the halves appeared to be rejoining seven days later. He separated them again and, a month later, the wounds of each half had healed and the two animals were feeding. Apart from the differences in size among animals, Owens' animals were kept in cages in the sea while Pearson and Endean used tanks. Birkeland and Lucas (1990) cite a report by G Walker that 92 *A. planci* were cut into quarters and released in Okinawa. An intensive search 28 days later found two quarter-starfish that had apparently healed. The fate of the other 366 quarters is unknown, but clearly *A. planci* can survive such treatment under some circumstances. In Guam, H Moore put 300 *A. planci* in a cage at high densities and found that animals that sustained any damage developed infections and died though undamaged individuals survived for "several months" without food, implying that they were in good condition at the start (Birkeland and Lucas 1990). In summary, the extent of physical damage that *A. planci* can survive seems very variable and, though size may be important, there are clearly other unknown factors involved.

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