 Mar. Freshwater Res., 1997, **48**, 517–22

Effects of cyanide on corals in relation to cyanide fishing on reefs

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Abstract. Small fragments of the zooxanthellate corals *Pocillopora damicornis* and *Porites lichen* were subjected to a range of cyanide concentrations for various times (i.e. to various cyanide doses). Doses encompassed those likely to be experienced by corals as a result of various cyanide fishing practices. Following the highest doses, corals died; after medium doses, they lost their zooxanthellae (symbiotic algae) resulting in a discolouration or 'bleaching'; and after the lowest doses they lost zooxanthellae but not in sufficient numbers to cause noticeable discolouration. Respiratory rates of *P. damicornis* were inhibited by 10–90% following exposure to cyanide but recovered to pre-exposure levels within 1–2 h after transfer to clean sea water.

Extra keywords: bleaching, zooxanthellae.

Introduction

Cyanide has been used as an asphyxiant in the collection of aquarium fish in the Philippines since the early 1960s (Rubec 1986); up to 90% of aquarium fish exported from the Philippines have been collected by using cyanide (Hingco and Rivera 1992). Recently, Johannes and Riepen (1995) have reported increasing and largely uncontrolled use of cyanide on reefs in South-East Asia to supply a restaurant-based demand for live fish. The Asian live-fish market is expected to expand, with much of the increased demand coming from China. This will increase the practice of cyanide fishing, which has already spread from the Philippines to Sri Lanka (Couchman and Beumer 1992), Indonesia and Taiwan (Pajaro 1992).

There are several cyanide fishing techniques. In the simplest, sodium cyanide (NaCN) tablets are placed in small plastic bottles (e.g. used shampoo bottles) filled with sea water. The milky fluid produced in the bottles is squirted in the direction of a fish, which may be hiding in a coral colony, coral thickets or holes in the reef matrix. Divers then collect the asphyxiated fish (Johannes and Riepen 1995). In other techniques, cyanide is placed inside portions of bait which are thrown overboard, or it is made into a paste, combined with finely minced fish and then thrown overboard. Fish eat poisoned baits and rise to the surface, stunned and vomiting. Regurgitated, cyanide-laden baits may then be ingested by other fish and the cycle repeated, or baits may sink to the coral substratum, slowly releasing cyanide (Johannes and Riepen 1995). In other cases, 55-gallon drums of cyanide have been dumped into a shallow reef environment, or cyanide has been pumped from 5-gallon containers onto the reef (J. McManus personal communication 1995). Regardless of the technique used, reef corals come into contact with cyanide.

Cyanide fishing has been banned in many South-East Asian countries. However, widespread illegal cyanide fishing continues, and anecdotal reports from fishermen and tour-boat operators suggest that it damages corals. Only two studies on the effects of cyanide on corals have been published, both associated with determining the mechanisms of coral calcification. Photosynthesis and calcification of the staghorn corals *Acropora cervicornis* and *A. formosa* were inhibited at concentrations greater than 1×10^{-5} M cyanide (Chalker and Taylor 1975; Barnes 1985). Respiration in intact branch tips of *A. formosa* was not completely inhibited at the highest concentration tested, $\sim 1 \times 10^{-4}$ M NaCN, suggesting the existence of cyanide-resistant respiration in either the zooxanthellae or the host (Barnes 1985). Cyanide-resistant respiration has been observed in the symbiotic anemone, *Aiptasia pulchella* (Pickles 1992); cyanide resistance did not occur in either zooxanthellae-free tissue suspensions or aposymbiotic *A. pulchella* (lacking zooxanthellae), but it did occur in host-free zooxanthellae suspensions, and the cyanide-resistant respiration in the intact symbiosis therefore appears to be attributable to the zooxanthellae (Pickles 1992).

The present paper describes the physiological responses of the common reef corals *Pocillopora damicornis* and *Porites lichen* to various doses of cyanide and the effects of cyanide on respiratory rates in *P. damicornis*.

Materials and methods

All experiments were conducted in November 1995 at One-Tree Island, a mid-shelf lagoonal reef towards the southern limit of the Great Barrier Reef, Australia (Fig. 1).

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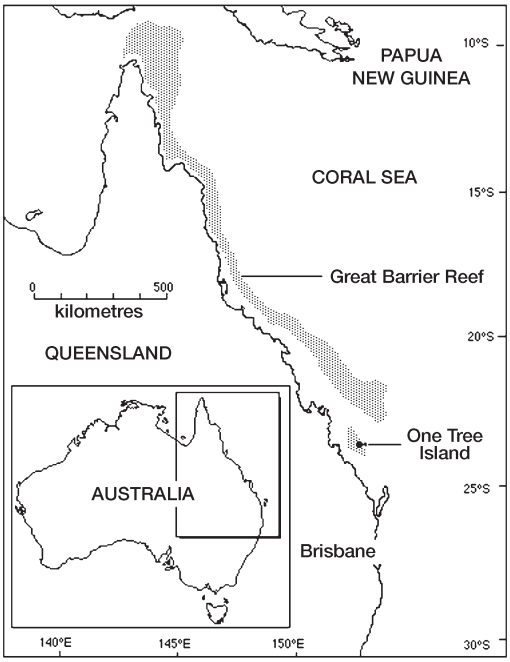

Fig. 1. Location of One-Tree Island on the Great Barrier Reef, Australia.

Toxicity tests

Fifteen colonies of *Pocillopora damicornis* (brown ecomorphs, see Takabayashi and Hoegh-Guldberg 1995) were collected from 1–2 m depth in the lagoon. Approximately 100 small coral fragments 40 mm long were cut from the colonies (5–10 fragments per colony) and their bases inserted into small acrylic tubes to provide support (prepared fragments are referred to as 'explants' hereinafter). Small (50 × 50 mm) colonies of *Porites lichen*, a small 'boulder' coral, were collected from the tops of the microatolls in the lagoon. Encrusting epiflora and epifauna were trimmed from the bases of these colonies. All corals were placed in running sea water under reduced lighting (<40 μmol photon m^{-2} s^{-1}) for 3–4 h prior to the experiments.

Specimens of *P. damicornis* and *P. lichen* were exposed to 2×10^{-1} M, 2×10^{-2} M, 2×10^{-3} M, or 2×10^{-4} M cyanide (nominal concentrations), for 1, 5, 10, 20 or 30 min. Incubation media using freshly collected unfiltered sea water were prepared immediately before each experiment. Media were stirred with a magnetically coupled stir bar before and during experiments. In each experiment, five replicate specimens of each coral species were randomly selected from the pool of prepared corals and placed in a 2-L plastic container holding 1 L of incubation medium. After incubation, corals were transferred to an aquarium receiving a supply of running sea water for 15–20 min, then secured to an acrylic tray at 1–2 m depth on the reef. Two controls were used for each species. For the first control set, called the 'Parent Colony' (PC), five corals were randomly selected from the pool of prepared corals and frozen prior to the incubations. A second set of five corals, 'Handling Controls' (HC), were exposed to an ambient sea-water solution alone for 30 min during the exposure experiments. Experimental and control corals were examined for mortality, general health and appearance for up to 12 days following incubations. Corals were frozen after the observation period.

Respirometry

The effect of cyanide on coral respiration was measured in a 4-chamber coral respirometer (see Klumpp *et al.* 1987 for details). All experiments used large fragments (60 mm) of *P. damicornis* colonies (brown ecomorphs) cut from 12 colonies (1–2 m depth) in the lagoon. Respiratory rates were determined during a series of 10–20 min incubations for ≈1–2 h before and after exposure to sea water with cyanide (1×10^{-1} M, 2×10^{-2} M or 2×10^{-3} M cyanide) for 7·5, 5 or 2·5 min, or to sea water without cyanide (control) for 7·5 min. Corals were exposed to cyanide outside the respirometry chambers to avoid contamination of the oxygen electrodes. During incubations, a black cloth was draped over the chambers to reduce light levels to <1 μmol photon m^{-2} s^{-1}. Water temperature during each of the incubations was 26°C ± 1°C.

Respirometry experiments were conducted over 3 days and used four different pieces of coral each day. During incubation, oxygen concentrations were logged every 20 s, and every 10–20 min the chambers were flushed with fresh sea water for 2 min to prevent oxygen concentrations from falling below 75% saturation. After pre-exposure incubation, each piece of coral was removed from the respirometer chamber and placed in 1 L of sea water containing cyanide (prepared as above) or in sea water without cyanide (control). Following this exposure, corals were transferred to running sea water for 10–15 min to flush any residual cyanide from the coral, then returned to the respirometer chambers for determination of respiratory rates for 1–2 h. Respiratory rates for each colony were expressed relative to the mean respiratory rate of the coral in the pre-exposure incubation period. At the end of each experiment, corals were transferred back to the reef, secured at 1–2 m depth and examined daily for 1 week.

Processing of corals

The tissues of *P. damicornis* corals involved in the toxicity tests were removed from the skeletons with a jet of re-circulated sea water (WaterPik, Johannes and Wiebe 1970). Zooxanthellae densities and algal chlorophyll-*a* (chl-*a*) concentrations were determined according to the techniques outlined in Jones (1997). The population density of zooxanthellae and the concentration of chl-*a* in the *P. lichen* colonies were not determined because the tissues could not be adequately stripped from the coral with the WaterPik, probably because of deeper penetration of the tissues within the skeletal matrix. For *P. damicornis*, bone-white skeletons were produced after use of the WaterPik, and microscopy showed that no algae or host tissues remained on the skeleton.

Data are presented as mean ± 95% confidence intervals. To test the null hypothesis that the concentration of cyanide or duration of exposure had no effect on zooxanthellar density or chl-*a* concentration, data were analysed ($\alpha = 0{\cdot}05$) by Type I ANOVA (Anon. 1994). Dunnett's test of significance was used to compare the nature of significant differences by comparing the means for treatment with control (HC) means. Prior to all analysis, assumptions of normality (Shapiro–Wilks' test) and homogeneity of variance (Welch's test) were tested.

Results

Toxicity tests

P. damicornis explants exposed to 2×10^{-1} M cyanide for 10, 20 and 30 min discoloured from a normal brown to almost bone-white within 12 h and died within 24 h. Eventually the pale tissue began sloughing off the skeletons and small fish (banded humbugs, *Dascyllus aruanus*) were observed grazing on the disintegrating coral tissues. After 5–6 days, a thin layer of green algae covered the bare skeletons. *P. damicornis* explants exposed to 2×10^{-1} M cyanide for 5 min discoloured from brown to a light tan within 24 h. Similarly, colonies exposed to 2×10^{-2} M cyanide for 10, 20 and 30 min discoloured to a light tan, almost white, colouration. No discolouration or mortality was observed in corals exposed to 2×10^{-3} M or 2×10^{-4} M cyanide or ambient sea-water controls.

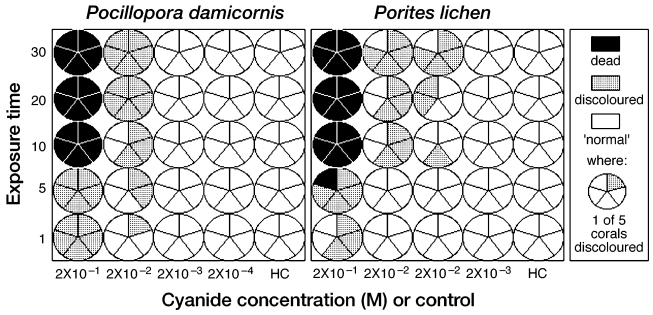

Fig. 2. Mortality and visual assessment of discolouration in five explants of *Pocillopora damicornis* and *Porites lichen* 6 days after exposure to a cyanide solution. (Only *P. damicornis* for the 2×10^{-4} M cyanide solution. *Porites lichen*, replicate experiments at 2×10^{-2} M). *P. damicornis* classified as discoloured if light brown, light tan/yellow or white. *P. lichen* classified as discoloured if bright green–yellow. HC, handling control.

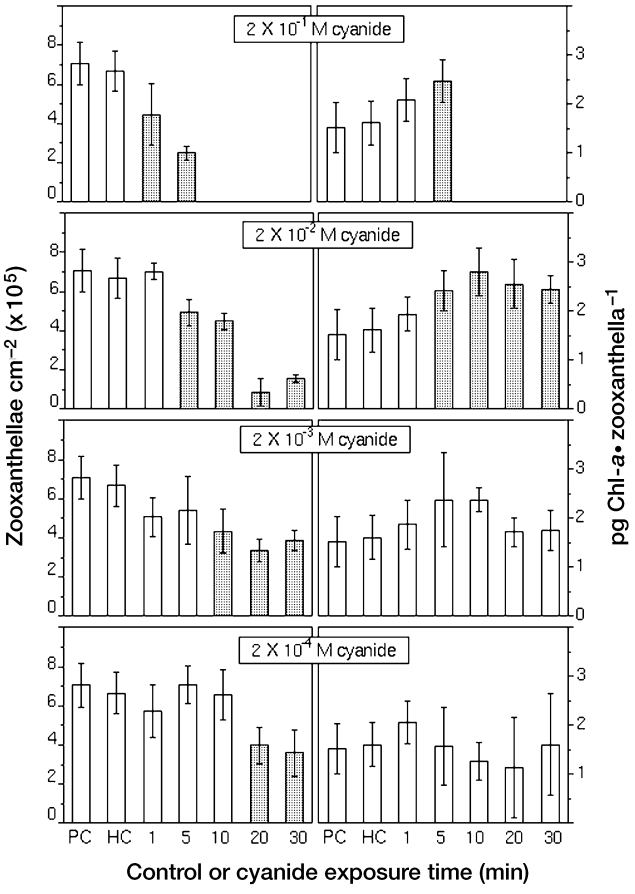

Fig. 3. Zooxanthellae density (hundred thousands of zooxanthellae per cm^2) and algal pigment concentration (pg chl-*a* per zooxanthella) in *P. damicornis* 12 days after exposure to cyanide. PC, parent colony control; HC, handling control. Significant differences in algal densities or algal pigment concentration (ANOVA, $P < 0{\cdot}05$) between experimental and control colonies (HC) are indicated by shading.

All *P. lichen* colonies exposed to 2×10^{-1} M cyanide for 10, 20 or 30 min died. It was difficult to determine the exact time of death because the colonies became covered in a thick dark-grey 'mucus-like' tunic within 12–24 h. After 7 days the tunics began to lift off, revealing a grey skeleton devoid of tissues. The skeletons then became progressively fouled with algae. No change in coral colouration was observed before the tunics were formed. No colonies that produced tunics survived.

Some of the *P. lichen* colonies exposed to 2×10^{-1} M cyanide for 5 min discoloured from a normal dark green–yellow to a bright green–yellow (Fig 2). A similar discolouration was observed in some of the colonies exposed to 2×10^{-2} M cyanide for 10, 20 or 30 min (Fig. 2). No discolouration or mortality was observed in corals exposed to 2×10^{-3} M cyanide or to ambient sea water.

The number of corals that discoloured and the intensity of discolouration reached a maximum 6 days after exposure to cyanide for each coral species. By the end of the 12-day observation period, many of the corals appeared to have regained some of their colouration. This effect was subtle, and no coral previously classified as discoloured was re-classified as normally coloured.

Discoloured *P. damicornis* explants contained fewer zooxanthellae than the normal brown control colonies at the end of the 12-day recovery period (Fig. 3). After exposure to 2×10^{-1} M or 2×10^{-2} M cyanide solution, the algal density in the coral tissues was inversely proportional to the duration of exposure (Fig. 3). The algal densities in explants exposed to the 2×10^{-3} M cyanide solution for 10, 20 or 30 min or to 2×10^{-4} M cyanide solution for 20 or 30 min ($3{\cdot}4–4{\cdot}5 \times 10^5$ zooxanthellae per cm^2) were significantly different than those in control corals (HC = $6{\cdot}6 \times 10^5 \pm 1.0$ zooxanthellae per cm^2, ANOVA $P < 0{\cdot}05$), although experimental corals were the same colour as control corals (Fig. 2). Discoloured *P. damicornis* had higher algal chl-*a* concentrations than control colonies (Fig. 3). When no significant loss of zooxanthellae was measured, the algal chl-*a* concentrations were similar to control values ($1{\cdot}6 \pm 0{\cdot}4$ pg chl-*a* per zooxanthella).

Respirometry

Corals exposed to 1×10^{-1} M cyanide for 2·5, 5 or 7·5 min discoloured to a light tan within 12 h. The next day, colonies had discoloured further to a pale yellow. Corals exposed to 2×10^{-2} M cyanide for 7·5 and 5 min were paler than the parent colonies after 24 h. No colour change was observed in corals exposed to 2×10^{-3} M cyanide or in control colonies.

Respiratory rates of control corals after transfer to an ambient sea-water solution for 7·5 min were the same as before the manipulation. However, for the controls used in the 2×10^{-2} M cyanide and 1×10^{-1} M cyanide experiments there was a slight increase in respiratory rate as the experiment progressed (Fig. 4).

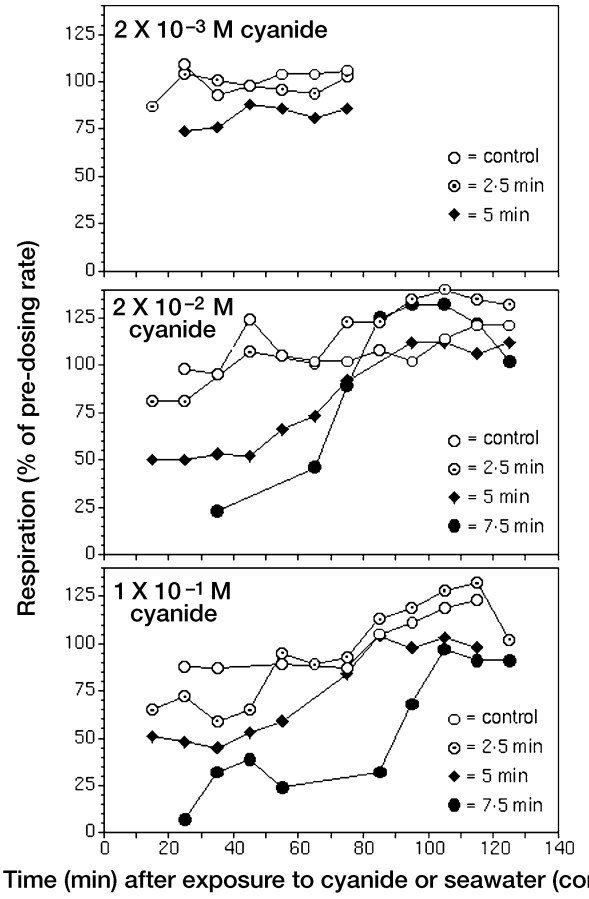

Fig. 4. Respiratory oxygen consumption in fragments of *P. damicornis* following exposure to ambient sea water for 7·5 min (controls), or to cyanide for 2·5, 5 or 7·5 min (1 coral for each line plot). Respiratory rates (over 10-min intervals) for each coral expressed relative to the mean respiratory rate determined over a ≈1–2 h period before cyanide exposure. Data for exposure to 1×10^{-4} M cyanide solution for 7·5 min not determined because of failure of the oxygen sensor.

In contrast, corals exposed to cyanide solutions showed markedly lower rates of oxygen consumption (Fig. 4). A >90% inhibition of respiration occurred in the coral exposed to 1×10^{-1} M cyanide for 7·5 min (the highest dose of cyanide tested during respirometry). At the lowest dose tested (i.e. 2×10^{-3} M for 2·5 min) the respiratory rate of the coral was inhibited by 10–20% of the 'normal' rate (Fig. 4). Respiratory rates of corals exposed to cyanide returned to pre-incubation levels within ~0·5–2.0 h (Fig. 4).

Discussion

The most obvious response of the corals *Pocillopora damicornis* and *Porites lichen* to sublethal doses of cyanide was a change in colouration, a 'bleaching'; the degree of discolouration was dependent on cyanide concentration and duration of exposure, i.e. on cyanide dose. Most corals are brown, gaining their colour from photosynthetic pigments of the zooxanthellae in their tissues. Bleaching describes the change in colouration as white skeleton becomes visible through the transparent animal tissues following a reduction in either the number of zooxanthellae (Yonge and Nicholls 1931) or the pigment concentration of the zooxanthellae (Hoegh-Guldberg and Smith 1989) or both. The fact that densities, but not chl-*a* concentrations, of zooxanthellae were lower after exposure of *P. damicornis* to cyanide suggests that discolouration was due to a decrease in zooxanthellae density.

The vivid colouration of some scleractinian corals and hydrocorals is due to pigments in either the skeleton or the animal tissues (Dove *et al.* 1995). Such corals do not bleach (whiten) following loss of zooxanthellae, but change from dull colours (blues, mauve–pinks or greens) to 'brighter' variations of the same colour. This effect probably accounts for the changes in colour of *P. lichen* from a normal brown–yellow to a bright yellow–green following exposure to higher cyanide doses in the present study.

Loss of zooxanthellae is a typical stress response to abnormal environmental conditions (Brown and Howard 1985) and has been observed in corals exposed to a diverse range of natural and artificial stresses including terpenes (toxic secondary metabolites of soft corals, Aceret *et al.* 1995), heavy metals (Harland and Brown 1989; Jones 1997) and elevated water temperatures (Glynn 1993). Bleaching has been observed in corals following exposure to quinaldine, a chemical used in the collection of fish (Jaap and Wheaton 1975), to particulate peat (Dallmeyer *et al.* 1982) and to depressed water temperature (Kobluk and Lysenko 1994).

Bleaching results in a loss of photosynthetic potential (Porter *et al.* 1989), cessation or reduction of growth (Coles and Jokiel 1978; Porter *et al.* 1989; Goreau and McFarlane 1990) and a decrease in reproductive output (Szmant and Gassman 1990). Loss of zooxanthellae can, however, be a sublethal response. There are numerous reports of recovery of pigmentation by bleached corals (Yonge and Nicholls 1931; Hoegh-Guldberg and Smith 1989; Porter *et al.* 1989; Fitt *et al.* 1993). In colonies of *P. damicornis* and *Acropora formosa* that lost 40–99% of their zooxanthellae during a natural bleaching event on the Great Barrier Reef, zooxanthellae density recovered to a steady-state level in 16–24 weeks (Jones 1995; Jones and Yellowlees 1997). An additional stage in the recovery process involves the restoration of storage lipid to pre-bleaching levels (Fitt *et al.* 1993). The time taken for corals to fully recover from loss of zooxanthellae can take between 6 months and 1 year.

Colonies of *P. damicornis* that had lost significant quantities of zooxanthellae during the present toxicity tests had significantly higher algal chl-*a* concentrations than control corals. Studies conducted after natural bleaching events have also found that bleached corals, with lower than

normal algal densities, often have higher algal chl-*a* concentrations (Hoegh-Guldberg and Smith 1989; Fitt *et al.* 1993; Jones, in press; but see also Kleppel *et al.* 1988; Porter *et al.* 1989). The higher algal chl-*a* concentration may reflect increased nutrient availability for the remaining zooxanthellae as a result of decreased algal competition (Høegh-Guldberg and Smith 1989; Jones and Yellowlees 1997).

Visual estimates of the degree of discolouration in the *P. damicornis* explants after 6 days did not correlate with the measured decreases in zooxanthellae density after 12 days (Figs 2 and 3). Similarly, colonies of *A. formosa* that lost 40–50% of their zooxanthellae during a period of elevated sea-water temperature did not discolour (Jones, in press). Hence, corals may be suffering from stress-related loss of algal symbionts both in the field and in laboratory manipulations without any gross observable effect; this must be taken into account when interpreting results of reef surveys conducted after cyanide fishing or natural bleaching events.

Given the known properties of cyanide as a respiratory inhibitor, it is not surprising that oxygen consumption by corals was markedly lower after exposure to cyanide. However, all corals in the present study survived the exposure despite 80–90% inhibition of oxygen consumption. Pickles (1992) reported that respiratory rates of the symbiotic anemone *Aiptasia pulchella* measured 24 h after 4-h exposure to 6·5 ppm KCN were not significantly different from control rates. The time taken for the corals to return to pre-dosage respiratory rates varied from 0·5 h to ~2 h, depending on cyanide concentration and duration of exposure. The increase in respiratory rates of some of the control corals as the experiment progressed (Fig. 4) suggests a small 'stress-effect' of the experimental procedure and a requirement of >2 h for the corals to recover from the exposure to cyanide.

Effects of cyanide fishing on corals

One approach to relate the results from laboratory studies to conditions occurring *in situ* is to calculate the dose of a pollutant encountered in both situations. This technique has primarily been used to estimate the effects of crude and chemically dispersed oil on marine organisms (Anderson *et al.* 1984; McAuliffe 1986, 1987). Thus, in the present toxicity tests with *P. damicornis*, cyanide concentration (M) multiplied by the exposure time (min) yields a cyanide dose as 'M-min' cyanide. Cyanide dose can then be related to mortality and algal density; all corals exposed to doses above 2 M-min cyanide died, below a dose of 2×10^{-3} M-min no significant algal loss occurred, and between these doses various degrees of algal loss occurred (Fig. 5).

During cyanide fishing on reefs, corals are likely to experience initially high (10^{-1} to 10^{-2} M) rapidly fluctuating concentrations of cyanide that ultimately fall to very low levels (10^{-5} to 10^{-6} M) in seconds to hours. The initial cyanide concentration, the proximity to target fish and the local hydrological conditions will determine the dose experienced by corals. Johannes and Riepen (1995) estimated the cyanide concentration in a typical squirt bottle to be $\approx 4{\cdot}1 \times 10^{-1}$ M, which gives the milky-white solution observed during cyanide fishing. In a situation where a coral thicket is exposed to cyanide directly from a squirt bottle and the cyanide concentration decreases logarithmically (i.e. decreasing to 4×10^{-6} M cyanide in ~8 min), a coral will be exposed to $\sim 4{\cdot}5 \times 10^{-1}$ M-min cyanide; according to the present results (Fig. 5), this would result in significant loss of zooxanthellae.

The technique outlined above must be interpreted with care, because the response of a coral to a very brief exposure to a high concentration may not be the same as the response to a long exposure to a very low concentration. A threshold dose to initiate loss of zooxanthellae is likely to be more time-dependent at lower cyanide concentrations.

Nevertheless, high concentrations of cyanide are used during cyanide fishing, loss of zooxanthellae can occur after very short (1-min) exposures to these concentrations, and inhibition of photosynthesis and calcification can occur after 30-min exposure to only $\sim 1 \times 10^{-5}$ M cyanide (Chalker and Taylor 1975; Barnes 1985), so cyanide fishing may have deleterious effects on corals in the immediate vicinity. Use of dyed water has revealed that water was trapped in a stagnant zone behind a 1-m-diameter coral head for 30 min (Wolanski and Jones 1980). Under such conditions, and also during the more destructive fishing techniques such as pumping cyanide from surface boats, coral mortality is likely to be extensive.

It was assumed in the present experiments that the corals that were not dead 12 days after exposure to cyanide

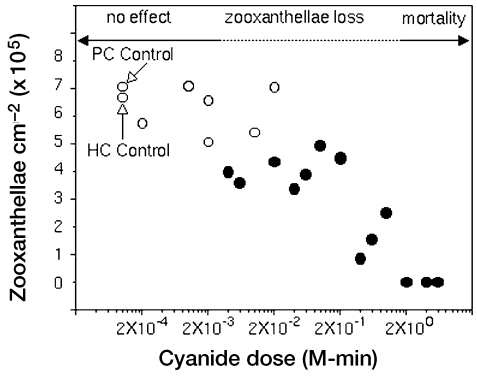

Fig. 5. Relationship between cyanide dose ('M-min', see text) and zooxanthellae density (hundred thousands of zooxanthellae per cm^2) in colonies of *P. damicornis* 12 days after exposure. Each point represents the mean of five corals (including the HC and PC controls). Filled symbols represent significant differences in algal densities relative to control (HC) explants (ANOVA, $P < 0{\cdot}05$, see Fig. 3).

would survive, but this has not been confirmed; further studies should investigate long-term survival of corals after cyanide exposure, the longer-term effects of exposure to low concentrations, and the effects of experimental doses in the field.

Acknowledgments

We thank Bob Johannes and John McManus for helpful discussion.

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Manuscript received 16 April 1997; revised and accepted 1 July 1997