

# The effects of clove oil on coral: An experimental evaluation using *Pocillopora damicornis* (Linnaeus)

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## Abstract

Clove oil solution (10% clove oil, 90% ethanol) is an anaesthetic that is widely used to catch demersal fish on coral reefs. This study assessed the effects of clove oil solution on colonies of *Pocillopora damicornis*, a cosmopolitan reef coral. In the laboratory, low concentrations (0.5 ppt) of clove oil solution had no effect on coral colour or photosynthetic efficiency, irrespective of exposure time (1–60 min). Corals treated with high concentrations (50 ppt) of clove oil solution died immediately, including those that were exposed briefly (1 min). Intermediate concentrations (5 ppt) of clove oil solution produced variable results: a 1 min exposure had no effect, a 10 min exposure caused bleaching and reduced photosynthetic efficiency, and a 60 min exposure caused total mortality. To validate these observations, clove oil solution was applied to corals *in situ*. Sixty-three days after application, corals treated with 10 ml of clove oil solution appeared to be unaffected. It was concluded that (1) limited amounts of clove oil solution are unlikely to harm this coral, and (2) clove oil solution may represent an ‘eco-friendly’ alternative to cyanide for use in the live reef-fish trade. © 2007 Elsevier B.V. All rights reserved.

**Keywords:** Anaesthetic; Clove oil; Coral; Eugenol; Live reef-fish trade; *Pocillopora damicornis*

## 1. Introduction

Many of the world’s coral reefs are found in developing nations where reef fisheries are heavily relied upon as a source of food and income (McManus, 1997; Wilkinson, 2004). Over recent decades however, stocks of many reef fishes have become severely depleted, such that traditional fishing methods are no longer effective or profitable (Jackson et al., 2001; Wilkinson, 2004). Faced with few alternatives, many fishers resort to destructive

fishing practices (Pauly, 1994). This is particularly evident in the South–East Asian live reef-fish trade, where the depletion of fish stocks across vast areas has led to the broadscale misuse of cyanide (Johannes and Riepen, 1995; McManus, 1997).

Cyanide fishing began in the Philippines in the early 1960s, and has since spread to at least 15 other countries (Rubec, 1986; McManus, 1997). The technique itself involves the dissolution of sodium cyanide tablets in water (30–120 g l<sup>-1</sup>), which is subsequently ‘squirted’ across benthic coral communities using small plastic bottles (Johannes and Riepen, 1995; Pet, 1997). Fish that are exposed to the milky solution are rapidly asphyxiated,

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and can be easily captured as they sluggishly emerge from their coral shelters. Even when transferred to clean seawater, captured fish suffer a suite of physiological disruptions, and as many as 80% die as a consequence (Rubec et al., 2001). By far the most serious aspect of cyanide fishing, however, is its effects on corals, the principal reef builders.

The administration of  $5.2 \text{ g l}^{-1}$  of cyanide for 10 min killed corals within 7 d (Jones and Steven, 1997). Lower concentrations resulted in the loss of zooxanthellae and impaired photosynthetic capacity, which may cause corals to die over a longer period of time (Jones and Steven, 1997; Jones and Hoegh-Guldberg, 1999; Jones et al., 1999; Cervino et al., 2003). By all accounts, cyanide exposure reduces the quality and quantity of reef habitat (Rubec, 1986; Johannes and Riepen, 1995; McManus et al., 1997; Barber and Pratt, 1998). For this reason, cyanide fishing is regarded as one of the greatest direct threats to the sustainability of coral reefs (McManus, 1997; Wilkinson, 2004).

As an alternative to cyanide, Erdmann (1999) suggested the use of clove oil. This is a heterogeneous distillate made from the crushed buds of the terrestrial plant *Eugenia aromatica* (Soto and Burhanuddin, 1995). It has been manufactured in Indonesia for centuries, where it is commonly used as a topical anaesthetic for minor ailments such as tooth-ache (Soto and Burhanuddin, 1995). Clove oil is also an extremely efficacious fish anaesthetic, known to cause rapid and calm immobilization (Munday and Wilson, 1997; Keene et al., 1998). For this reason, clove oil is used to sedate fish during transport or surgery (Taylor and Roberts, 1999; Cooke et al., 2004), and to capture coral-dwelling reef fish, both for research and the aquarium trade (Erdmann, 1999; Ackerman and Bellwood, 2002). In the latter case, clove oil is applied to coral colonies in much the same way as cyanide, except that it is mixed with ethanol (1:9) instead of water. The active ingredient of clove oil is thought to be eugenol (4-allyl-2-methoxyphenol), which comprises 70–95% of the commercially available product (Erdmann, 1999; Harper, 2003). The remaining 5–30% is comprised of eugenol acetate and kariofilen-5 (Soto and Burhanuddin, 1995).

The use of clove oil on coral reefs began in the mid-1990s (Munday and Wilson, 1997). It is now used in many parts of the world (e.g. Erdmann, 1999; Whiteman and Cote, 2004; Arvedlund et al., 2006), including Australia's Great Barrier Reef (GBR). In fact, the Great Barrier Reef Marine Park Authority (GBRMPA) currently administers 40 research permits which allow for the use of clove oil on the GBR. Given that some of these permits are issued to whole institutions (e.g. universities), there may be hundreds to thousands of clove oil

users in Australia alone. Surprisingly, however, the effects of clove oil on coral have never been investigated.

Previous work indicates that corals exposed to toxic substances exhibit a variety of responses. In the most severe cases, colonies may experience total or partial mortality, depending on the proportion of polyps that die (Loya and Rinkevich, 1980; Pastorok and Bilyard, 1985). Sub-lethal effects typically include bleaching (loss of zooxanthellae and [or] their pigments) or reduced photosynthetic efficiency, both of which may reduce growth, reproductive output and long-term survival (Szmant and Gassman, 1990; Jones et al., 1999; Cervino et al., 2003; Siebeck et al., 2006). In order to regulate the future use of clove oil, and to promote its use as an 'eco-friendly' alternative to cyanide (Erdmann, 1999), management agencies need to be sure that clove oil has no (or minimal) effects on corals. The aim of this study, therefore, was to assess the effects of clove oil on a common and cosmopolitan reef coral, *Pocillopora damicornis* (Linnaeus). This species forms an integral part of coral reef ecosystems in the Indo-Pacific region (Done, 1982; Veron, 1986), and is known to provide essential habitat for a range of fishes and invertebrates (Austin et al., 1980; Pratchett, 2001).

To investigate both short- and long-term effects, experimental trials were conducted in a controlled laboratory environment as well as in the field. Since the dose and exposure time of clove oil to which corals are exposed during fishing activities is highly variable (due to differences in water currents, turbulence and susceptibility of target fish species), clove oil was applied in three different concentrations for three different periods of time. In each case, an attempt was made to simulate typical fish-catching operations, and the choice of minimum and maximum doses (0.5 and 50 ppt, respectively) was based on the amount of clove oil required to induce slow *versus* immediate anaesthetisation in a range of fish species (Soto and Burhanuddin, 1995; Munday and Wilson, 1997; Keene et al., 1998; Taylor and Roberts, 1999). After clove oil application, the health and photosynthetic efficiency of treated corals was assessed by measuring tissue colour (degree of bleaching) (Siebeck et al., 2006), chlorophyll *a* fluorescence (Schreiber, 2004), and the extent of mortality.

## 2. Materials and methods

### 2.1. Aquarium experiment

Twelve colonies of *P. damicornis* were collected from the fringing reef (depth 2–4 m) at Orpheus Island (18° 30' S, 146° 29' E) on 8th April, 2006 and transported

to the James Cook University Aquarium Facility in Townsville, Australia. Colonies were divided into fragments (70–90 mm in length; 10–20 fragments per colony) using a hammer and chisel, after which 189 fragments were randomly chosen (from the pool of prepared fragments) and placed onto perforated trays in a single 1000 l outdoor tank. This tank was covered with 90% Solarweave (VP Structures, Yatala, Australia) and was supplied with recirculating seawater at a rate of  $22 \text{ l min}^{-1}$  (salinity 35 ppt; temperature  $27 \pm 1 \text{ }^\circ\text{C}$  [mean  $\pm$  range]). After a 4 d acclimation period, groups of nine fragments (replicates) were temporarily removed and placed into one of seven plastic boxes (50 l each) containing either (a) 0.5, 5 or 50 ppt clove oil–ethanol solution (1:9) in seawater, (b) 0.5, 5 or 50 ppt ethanol in seawater, or (c) seawater only (controls). Each group of fragments was incubated for either 1, 10 or 60 min (*i.e.*, 21 treatment combinations). To ensure that the incubation media were homogenous, and to maintain water flow across the fragments, a submersible pump with a capacity of  $15 \text{ l min}^{-1}$  was placed in each plastic box. After incubation, all fragments were rinsed in clean seawater for approximately 10 s and then returned to the recirculating system. All treatments were performed within 1 h of each other during the early morning, when the ambient underwater light intensity was  $\sim 80 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$  (light intensity was measured with a quantum irradiance meter; Li-Cor, Lincoln, U.S.A.). Throughout the experiment, the ambient underwater light intensity at noon ranged from  $100\text{--}350 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ , and this did not vary among positions within the tank (*i.e.*, each fragment was exposed to the same light regime). All fragments were monitored daily for the next 7 d.

Tissue colour was recorded on a scale of 1 (near-white) to 6 (dark brown) using the ‘coral health chart’ developed by Siebeck et al. (2006). This method involves matching the colour of coral tissues with that on a textured plastic chart. Importantly, changes in colour can be used as a proxy for changes in zooxanthellae density in host tissues when differences of at least two scores are present (Siebeck et al., 2006). To estimate colour score, the plastic chart was held alongside the fragment, approximately 30 mm beneath the tip. A single colour score (estimated to the nearest 0.5) was then recorded daily for each fragment.

Photosynthetic efficiency of zooxanthellae was assessed using pulse-amplitude-modulated (PAM) fluorometry (*e.g.* Jones et al., 1999; Schreiber, 2004; Ulstrup et al., 2006). To do this, we used a Diving-PAM (Heinz Walz GmbH, Effeltrich, Germany) which emits short (3  $\mu\text{s}$ ) pulses of weak red light (wavelength=650 nm, intensity= $0.15 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ) followed by a

saturation pulse (0.8 s) of white light (wavelength=710 nm, intensity= $4500 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ). The flexible probe attached to the Diving-PAM was held  $\sim 10 \text{ mm}$  from the tip of each fragment, and dark-acclimated maximum quantum yield (Fv/Fm; an indicator of zooxanthellar photosynthetic efficiency) was measured daily at 2000 h ( $\sim 2 \text{ h}$  after sunset). The first measurement took place during the evening after incubation, and each series of measurements was performed within a 30 min period. Hill and Ralph (2005) monitored the diurnal fluctuation of zooxanthellar photosystem II (PSII) quantum yield and found that 2 h of darkness was sufficient to fully reduce PSII, which is required to measure Fv/Fm (for a detailed description of Fv/Fm and its relationship to PSII, see Jones et al., 1999).

The occurrence of mortality among coral fragments was based on the combined observations of tissue sloughing and exposure of bare skeleton. Towards the end of the 7 d monitoring period, a small number of fragments ( $\leq 3$  per treatment combination) became infected with *Helicostoma nonatum*, a disease which is particularly common among captive corals (Willis et al.,

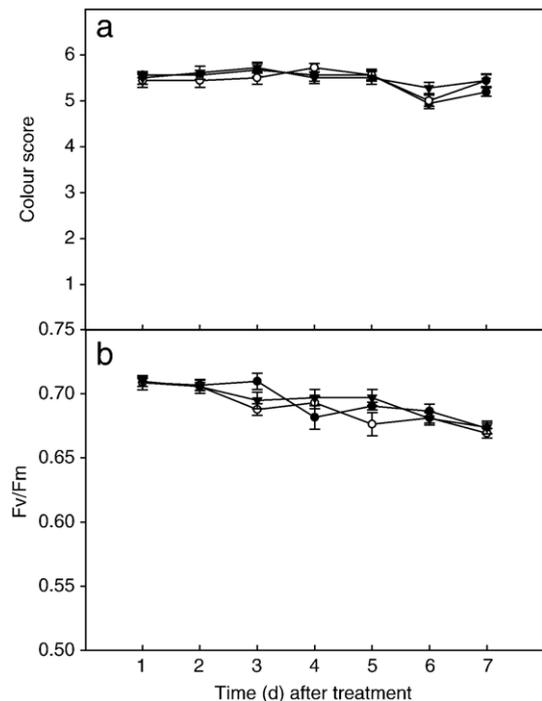


Fig. 1. (a) Tissue colour score, and (b) photosynthetic efficiency (Fv/Fm) of aquarium-acclimated fragments of *Pocillopora damicornis* after a 60 min exposure to 0.5 ppt clove oil solution (●), 0.5 ppt ethanol (○), or seawater (▼). Differences between groups (within each day) are not statistically significant.

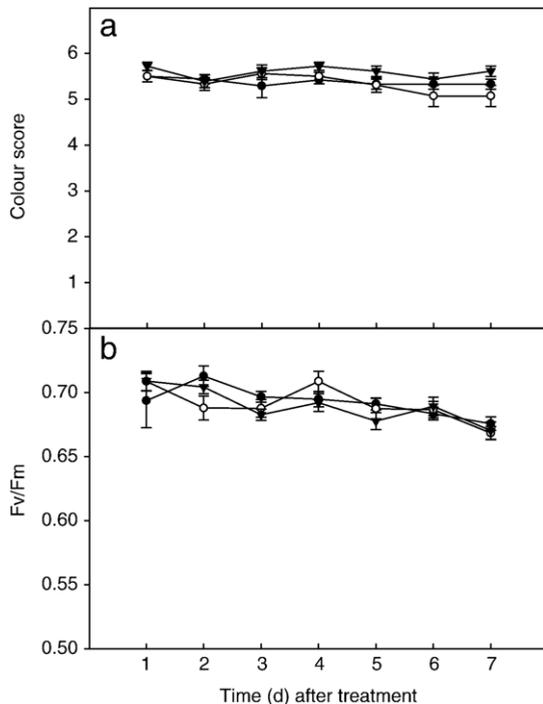


Fig. 2. (a) Tissue colour score, and (b) photosynthetic efficiency (Fv/Fm) of aquarium-acclimated fragments of *Pocillopora damicornis* after a 1 min exposure to 5 ppt clove oil solution (●), 5 ppt ethanol (○), or seawater (▼). Differences between groups (within each day) are not statistically significant.

2004). To prevent spread of the disease, infected fragments were immediately removed from the experiment (and excluded from subsequent analyses).

Because pre-treatment data were not collected, the effects of clove oil solution and (or) ethanol on corals were inferred by comparing the condition (*i.e.*, tissue colour and photosynthetic efficiency) of treated fragments with control fragments (within each day). This was considered to be satisfactory, given that all fragments were randomly allocated to treatment groups, and that they were maintained in the same tank (*i.e.*, it was unlikely that any differences between treatment groups were caused by anything other than the treatment itself).

## 2.2. Field experiment

To validate the laboratory observations, clove oil solution was applied to corals *in situ* using 'typical' fishing techniques. Forty-two colonies of *P. damicornis* (10–20 cm diameter), which were spread across ~500 m of fringing reef at Orpheus Island, were labeled with a unique identification tag (plastic cattle tag). Seven replicate colonies were chosen at random and treated with either 10 or 100 ml of clove oil–ethanol solution

(1:9) using a hand-held spray bottle with a metered dose (1 ml per stroke). The clove oil solution was applied to each coral over a period of 60 s with the nozzle of the spray bottle pointed downwards, directly above (*i.e.*, within 3 cm of) the centre of the colony. Two other groups of seven corals were treated in the same way using equivalent volumes of ethanol or seawater. All treatments were administered on 29th April, 2006 when wave height and water current were estimated to be 0.5 m and  $0.25 \text{ m s}^{-1}$ , respectively. Percentage partial mortality was visually estimated to the nearest 5%, and tissue colour (see above) was evaluated in the centre of each colony, approximately 30 mm beneath the branch tips. Both parameters were assessed immediately before and 2, 9 and 63 d after treatment application. In addition, all colonies were photographed during each census using a digital camera (DSC-P9, Sony, Tokyo, Japan).

## 2.3. Statistical analyses

Tissue colour scores and Fv/Fm were analysed by repeated measures analysis of variance (ANOVA) followed by *post hoc* comparisons of group means using Tukey's test (Zar, 1999). In cases where sphericity was

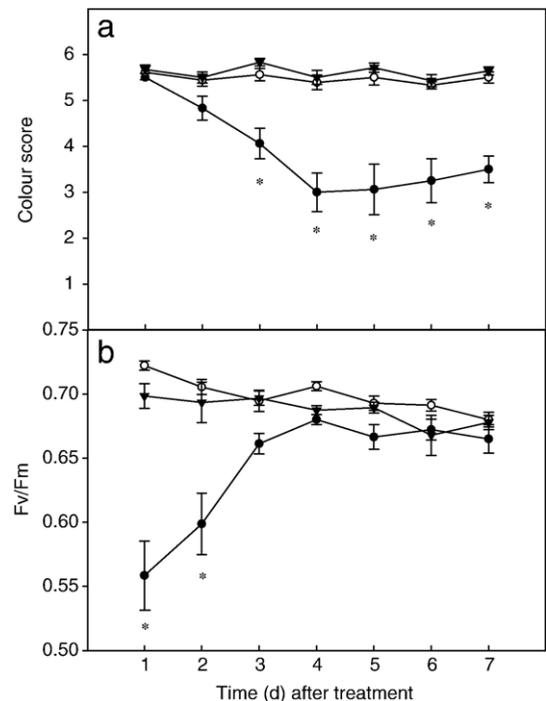


Fig. 3. (a) Tissue colour score, and (b) photosynthetic efficiency (Fv/Fm) of aquarium-acclimated fragments of *Pocillopora damicornis* after a 10 min exposure to 5 ppt clove oil solution (●), 5 ppt ethanol (○), or seawater (▼). Groups that are significantly different ( $p < 0.05$ ) from controls are denoted by asterisks (\*).

Table 1  
Survival of aquarium-acclimated *Pocillopora damicornis* fragments ( $5 \leq n \leq 9$ ) that were treated with clove oil solution, ethanol or seawater

Treatment	Concentration (ppt)	Exposure time (min)		
		1	10	60
Clove oil solution	0.5	○	○	○
	5	○	○	×
	50	×	×	×
Ethanol	0.5	○	○	○
	5	○	○	○
	50	○	○	○
Seawater	–	○	○	○

Groups of fragments that remained alive after 7 d are represented by circles (○), while groups of fragments that died within 1–2 d are represented by crosses (×).

violated (as determined by Mauchly’s test), the Greenhouse–Geisser adjustment was employed (Geisser and Greenhouse, 1958). All analyses were performed using SPSS software (Chicago, U.S.A) and a significant difference was considered to exist if  $p < 0.05$ . All data given in the text and figures are the arithmetic mean  $\pm$  standard error (SE).

### 3. Results

#### 3.1. Aquarium experiment

Low concentrations (0.5 ppt) of clove oil solution did not affect tissue colour or photosynthetic efficiency (Fv/Fm). This result was consistent for each of the three different exposure times (1, 10 or 60 min). For brevity, only the results from the 60 min treatment are illustrated (Fig. 1).

Intermediate concentrations (5 ppt) of clove oil solution produced variable results, depending upon exposure time. Firstly, a 1 min exposure had no effect on tissue colour or Fv/Fm (Fig. 2). Secondly, a 10 min exposure

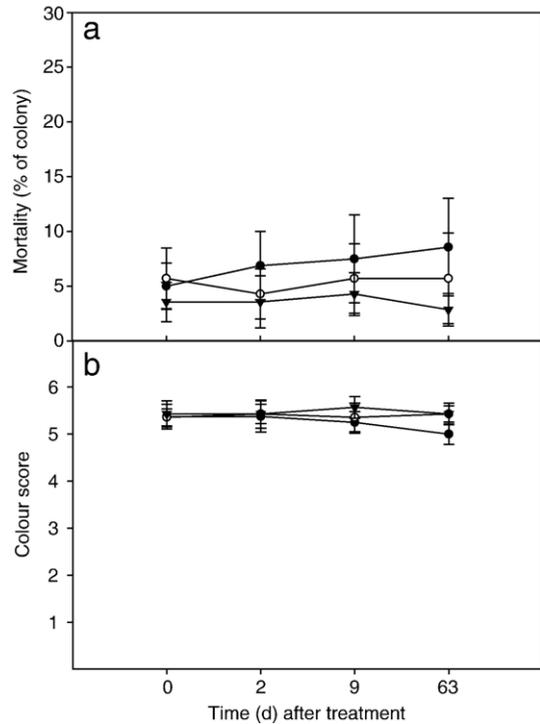


Fig. 5. (a) Partial mortality and (b) tissue colour score of *Pocillopora damicornis* colonies ( $n=7$ ) after treatment *in situ* with 10 ml of clove oil solution (●), 10 ml of ethanol (○), or 10 ml of seawater (▼). Differences between groups (within each day) are not statistically significant.

caused bleaching (whitening) and a temporary reduction in Fv/Fm: after 3 d, mean colour scores in fragments treated with clove oil solution ( $4.4 \pm 0.3$ ) and seawater ( $5.8 \pm 0.1$ ) were significantly different ( $F_{2,17} = 18.6$ ,  $p < 0.001$ ) (Fig. 3a), while mean Fv/Fm in the same two groups of fragments was significantly different for the first 2 d after exposure ( $F_{2,19} = 18.7$ ,  $p < 0.001$ ) but not thereafter (Fig. 3b). Thirdly, a 60 min exposure caused a  $90 \pm 4\%$  decline in Fv/Fm in relation to controls

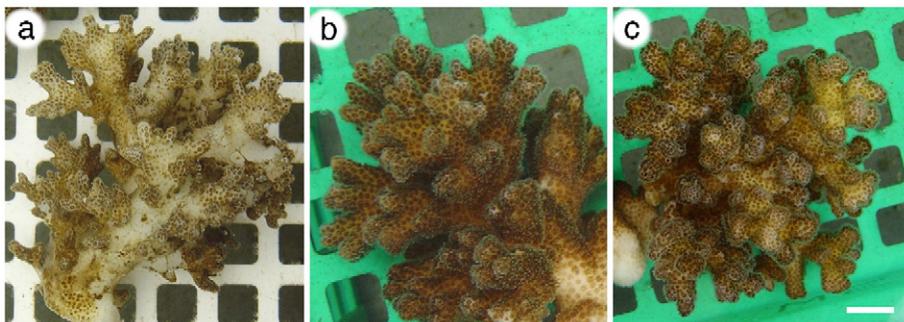


Fig. 4. Photographs showing aquarium-acclimated fragments of *Pocillopora damicornis* that were treated for 10 min with (a) 50 ppt clove oil solution, (b) 50 ppt ethanol, or (c) seawater. All photographs were taken 1 d after treatment. Scale bar=10 mm.

after 1 d (data not shown) and total mortality within 2 d (Table 1).

Fragments treated with high concentrations (50 ppt) of clove oil solution experienced total mortality within 1–2 d, irrespective of exposure time (Table 1). A 1 min exposure caused a  $97 \pm 1\%$  decline in Fv/Fm after 1 d, with total mortality occurring within 2 d. Exposure to clove oil solution for 10 or 60 min caused total mortality within 1 d (Fig. 4).

Fragments treated with ethanol were not significantly different from control fragments (in terms of tissue colour or photosynthetic efficiency), regardless of exposure time or concentration (Figs. 1–3, Table 1).

### 3.2. Field experiment

*In situ* treatment with a small volume (10 ml) of clove oil solution had no significant effect on the percentage partial mortality or tissue colour score of *P. damicornis* within 63 d (Fig. 5). In contrast, treatment with a large volume (100 ml) of clove oil solution caused a significant increase in mean partial mortality ( $F_{2,21}=5.0$ ,  $p<0.05$ ) and a significant decline in mean colour score ( $F_{2,21}=4.1$ ,

$p<0.05$ ) (Fig. 6). This result was confirmed photographically (Fig. 7). Two days after treatment, localised bleaching occurred in the central region of each colony (*i.e.*, directly at the point where the clove oil solution was applied). After 9 d, some of the bleached tissues had died, allowing algae to colonise the exposed skeleton. However, the peripheral regions of treated colonies appeared unaffected and remained alive for at least 63 d.

Partial mortality and tissue colour in colonies treated with seawater (controls) were unchanged throughout the monitoring period (Figs. 5–7). Colonies treated with ethanol were not significantly different from the controls (in terms of partial mortality or tissue colour), regardless of treatment volume (10 or 100 ml) (Figs. 5–7).

### 4. Discussion

The effects of clove oil solution on *P. damicornis* were variable and dependent upon both dose and exposure time: low concentrations produced no response; high concentrations produced a lethal response; and intermediate concentrations produced (1) no response when exposure time was 1 min, (2) a sub-lethal response when exposure time was 10 min, and (3) a lethal response when exposure time was 60 min. The effects of ‘clove oil fishing’ on *P. damicornis* therefore depend on how clove oil solution is used during fish-catching operations.

The application of intermediate to high doses of clove oil solution caused (in the absence of mortality) a decline in dark-acclimated maximum quantum yield (Fv/Fm). Decreased Fv/Fm signifies a reduction in zooxanthellar photosynthetic efficiency (Jones et al., 1999; Ulstrup et al., 2006), which is thought to reduce the growth and reproductive output of host corals (Goreau and McFarlane, 1990; Szmant and Gassman, 1990; Jones et al., 1999). Subtle, sub-lethal effects such as reduced zooxanthellar function may therefore have delayed (but significant) physiological and ecological consequences.

In one group of corals (*i.e.*, those exposed to 5 ppt clove oil solution for 10 min), the decline in Fv/Fm was temporary (Fig. 3b). The colour score of these corals, however, was significantly lower after 3 d (compared to controls) and did not show signs of recovery (Fig. 3a). After studying the effects of cyanide on coral, Jones and Hoegh-Guldberg (1999) suggested that any post-disturbance recovery of Fv/Fm was associated with the selective loss of damaged zooxanthellae (*i.e.*, those with lower Fv/Fm). Since colour (an indicator of zooxanthellar density) and Fv/Fm were (more or less) inversely related during the 7 d monitoring period (Fig. 3), our data support the notion that damaged zooxanthellae are preferentially expelled after disturbance.

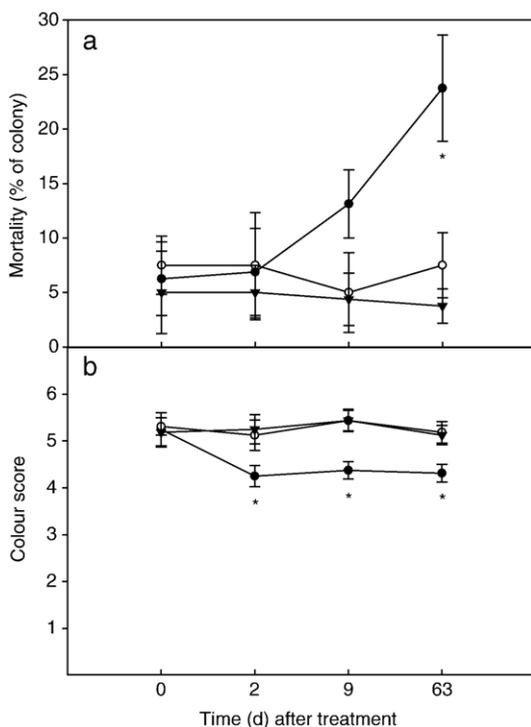


Fig. 6. (a) Partial mortality and (b) tissue colour score of *Pocillopora damicornis* colonies ( $n=7$ ) after treatment *in situ* with 100 ml of clove oil solution (●), 100 ml of ethanol (○), or 100 ml of seawater (▼). Groups that are significantly different ( $p<0.05$ ) from controls are denoted by asterisks (\*).

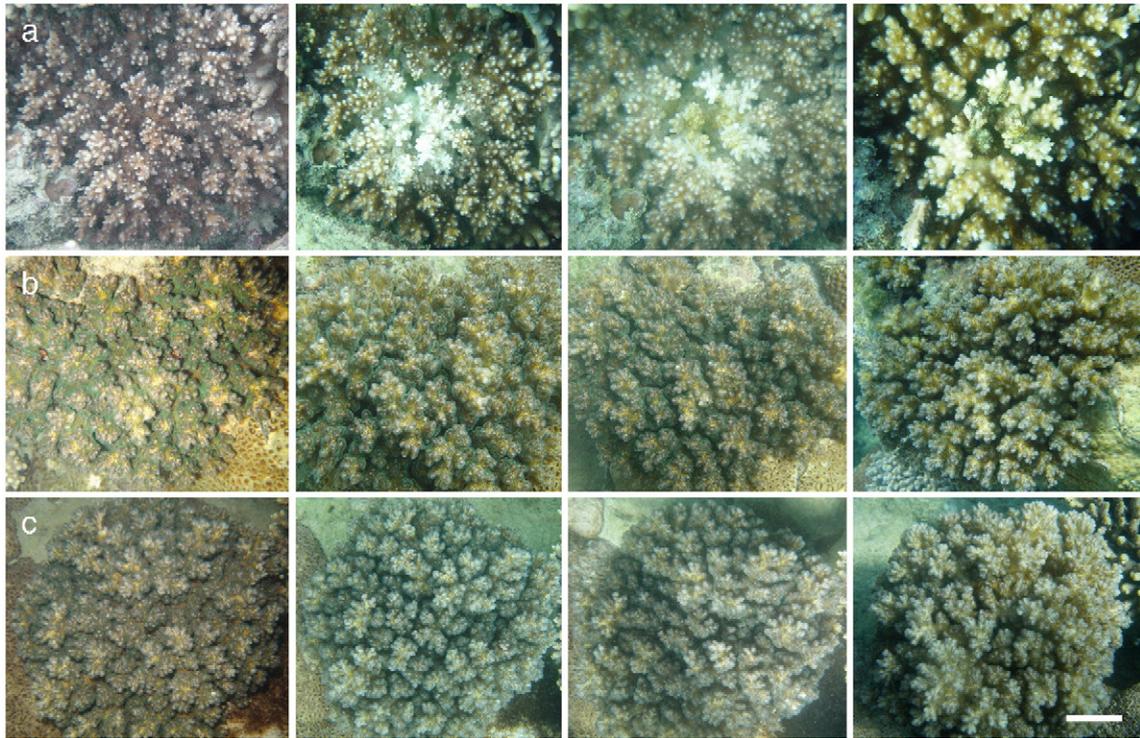


Fig. 7. Photographs showing *Pocillopora damicornis* colonies that were treated *in situ* with (a) 100 ml of clove oil solution, (b) 100 ml of ethanol, or (c) 100 ml of seawater. Each liquid was applied using a 500 ml spray bottle held directly above (*i.e.*, within 3 cm of) the centre of each colony. The photographs were taken at 0, 2, 9 and 63 d after treatment and are displayed chronologically from left to right. Scale bar=3 cm.

Although expulsion of zooxanthellae is a common response to stress in scleractinian corals (Hoegh-Gulberg, 1999; Siebeck et al., 2006), bleaching is not necessarily fatal. For example, thermally-stressed corals can restore their depleted zooxanthellae populations in 16–24 wk (Hayes and Bush, 1990; Jones and Yellowlees, 1997). Recovery from clove oil-induced bleaching is therefore expected to be slow (assuming that recovery is indeed possible). The observation that partially-bleached *P. damicornis* failed to restore their zooxanthellae populations within 63 d (Fig. 7) is consistent with this hypothesis.

When clove oil solution is dispensed from a spray bottle, its concentration decreases exponentially with increasing distance from the nozzle, due to the diluting effect of seawater. Since most fish are calmly and rapidly anaesthetised at 0.2–0.6 ppt of clove oil solution (Soto and Burhanuddin, 1995; Munday and Wilson, 1997; Keene et al., 1998; Taylor and Roberts, 1999), this is the desired concentration of anaesthetic once it reaches the target area (n.b. using higher concentrations of clove oil does not usually improve its effectiveness, because a milky cloud is formed that fish tend to avoid; pers. obs.). Accordingly, if 0.2–0.6 ppt is the concentration of clove

oil to which corals are typically exposed, then ‘fishing’ with clove oil is unlikely to harm *P. damicornis* (n.b. 0.5 ppt of clove oil solution is equivalent to the ‘low concentration’ treatment used in our laboratory experiment). The same would be true if corals were exposed to ten times this concentration (*i.e.*, 5 ppt clove oil solution), provided of course that exposure time was short. In our experience, clove oil solution is rapidly dispersed by water currents and turbulence when it is used on coral reefs. Only in extreme situations (*e.g.* in stagnant micro-atolls at low tide) does clove oil linger for lengthy periods of time.

If however, clove oil solution is ‘sprayed’ directly onto a colony, to extract a coral-dwelling damselfish for example, the adjacent coral branches would be temporarily exposed to clove oil concentrations which are much higher than that required for anaesthetising fish. Based on the results of our laboratory study, one might expect the tissue on these branches to bleach or die. This is exactly what occurred in the field experiment, but only when 100 ml of clove oil solution was administered. Treatment with a smaller volume of clove oil solution (*i.e.*, 10 ml) had no visible effects, presumably because local clove oil concentrations did not reach the threshold

level required to cause bleaching or mortality. These results suggest that (1) if clove oil solution is used sparingly, it can be sprayed directly onto a coral without causing harm to it, and (2) even if copious amounts of clove oil solution are used, any detrimental effects such as bleaching and mortality are likely to be localised. Although it is difficult to quantify the full range of clove oil concentrations to which corals are exposed during fish-catching operations, we believe it to be rare that any more than 10 ml of clove oil solution would be administered to a single coral colony at any one time.

If clove oil is to be marketed as an ‘eco-friendly’ alternative to cyanide for use in the live fish trade (Erdmann, 1999), it must be shown to be effective, inexpensive, and harmless to corals. Previous research indicates that clove oil satisfies the first two of these criteria (Munday and Wilson, 1997; Erdmann, 1999), while this study has shown that clove oil is unlikely to harm *P. damicornis* when it is used in small amounts. Although this result is promising, it must be interpreted with care. Firstly, we used *P. damicornis* as the test organism due to its high abundance and cosmopolitan distribution. However, these attributes may indicate that this species is ‘hardy’ with respect to environmental tolerances. Whether our results are representative of other, perhaps more sensitive species of coral is not known, but this must be investigated before the use of clove oil is encouraged. Secondly, the validity of our results for predicting the effects of ‘clove oil fishing’ is highly dependent on how much clove oil is typically sprayed onto a coral, and how long the clove oil remains in contact with the coral. These parameters will vary with the objectives of the fish-collector, and with the local hydrodynamic conditions. Future research should therefore aim to establish the full range of clove oil concentrations (and residence times) to which corals are exposed during fish-catching operations.

It is interesting that ethanol had no detectable effect on *P. damicornis*, either in the laboratory or *in situ*, regardless of dose or exposure time. This result was unexpected because it was previously believed that ethanol was more detrimental to corals than clove oil (Erdmann, 1999; Great Barrier Reef Marine Park Authority, pers. comm.). This misconception may have arisen from the fact that coral tissues can be effectively preserved in ethanol, albeit at very high concentrations (e.g. Ulstrup and van Oppen, 2003). At concentrations up to 50 ppt, however, it is apparent that ethanol is probably harmless to *P. damicornis*.

In summary, this study has demonstrated that large amounts of clove oil have the potential to reduce the health or cause the death of *P. damicornis*, a common reef-building coral. However, when clove oil is used

sparingly (i.e., at the minimum dose required for anaesthetising fish) it is unlikely to harm this coral. Although other coral species may react differently, it seems that clove oil is considerably less destructive than cyanide, and thus may represent an ‘eco-friendly’ alternative to cyanide for use in the live reef-fish trade. At the same time, it seems that the use of clove oil as a tool for scientific research is probably justified, provided that it is used responsibly (i.e., in limited amounts). We therefore advocate the development of a best practice protocol for the future use of clove oil on coral reefs.

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