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REPORT

U. E. Siebeck · N. J. Marshall · A. Klüter
Ove Hoegh-Guldberg

Monitoring coral bleaching using a colour reference card

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Abstract Assessment of the extent of coral bleaching has become an important part of studies that aim to understand the condition of coral reefs. In this study a reference card that uses differences in coral colour was developed as an inexpensive, rapid and non-invasive method for the assessment of bleaching. The card uses a 6 point brightness/saturation scale within four colour hues to record changes in bleaching state. Changes on the scale of 2 units or more reflect a change in symbiont density and chlorophyll *a* content, and therefore the bleaching state of the coral. When used by non-specialist observers in the field (here on an intertidal reef flat), there was an inter-observer error of ± 1 colour score. This technique improves on existing subjective assessment of bleaching state by visual observation and offers the potential for rapid, wide-area assessment of changing coral condition.

Keywords Coral bleaching · Coral colour · Coral condition assessment · Reef condition · Global climate change · Monitoring

Introduction

Coral bleaching is characterised by the loss of dinoflagellate symbionts (genus *Symbiodinium*) and/or symbiont pigmentation (Brown 1997). Since 1979, large scale events (affecting tens to thousands of km^2) have affected coral reefs with increasing frequency and severity (Hoegh-Guldberg 1999). Recent bleaching events (e.g. 1997–1998 and 2002) have damaged corals across large areas of the world's tropical oceans, with rates of mortality in some regions at some times exceeding 50% (e.g. Western Indian Ocean, Wilkinson et al. 1999). Coral bleaching is triggered by a number of stressful events including warmer than normal temperatures (Coles and Jokiel 1977; Hoegh-Guldberg and Smith 1989; Glynn and D'Croz 1990; Goreau and Hayes 1994; Brown 1997; Hoegh-Guldberg 1999). This association with elevated sea temperatures together with the fact that mass coral bleaching only appears in the scientific literature after 1979, suggest that these events are a response to the current warming of the world's oceans resulting from anthropogenic climate change. Projections of future change in sea temperature indicate that mass coral bleaching is likely to rise rapidly over the next 30–50 years until it becomes an annual event (Hoegh-Guldberg 1999). Under even modest predictive scenarios, changes in the stress on coral reefs look likely to cause the decline of coral communities worldwide.

Assessing current and future rates of change in reef condition is important to understanding how future scenarios will affect coral reefs. Different methods have been used to assess coral bleaching at varying scales. Remote sensing techniques have proved useful since they enable monitoring of large areas simultaneously (Dustan et al. 2000; Mumby et al. 2001; Hedley and Mumby 2002). However, satellite or low altitude aerial images can be expensive, and are only really suitable in circumstances where the advantages of large spatial resolution outweigh the large errors associated with the technique (Andréfouët et al. 2002; Hedley and Mumby 2002). Visual and video transects undertaken by swimming or during manta tows are probably the most widely used methods to assess the condition of individual reefs (Miller and Müller 1999). However, these methods are labour, equipment and time intensive, and

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U. E. Siebeck (✉) · N. J. Marshall
Vision Touch and Hearing Research Centre,
School of Biomedical Sciences, The University of Queensland,
St Lucia 4072 QLD, Australia
E-mail: u.siebeck@uq.edu.au
Tel.: +61-7-33654070
Fax: +61-7-33654522

A. Klüter
Australian Institute of Marine Science, Townsville, Australia

O. Hoegh-Guldberg
Centre for Marine Studies, University of Queensland,
St Lucia, Australia

require trained field personnel. Other more detailed investigations have involved measurement of photosynthetic processes and related physiological parameters (e.g. Jones et al. 1998; Fitt et al. 2001). These methods are often used in combination with measures of symbiotic dinoflagellate density and chlorophyll *a* content of the coral (e.g. Hoegh-Guldberg and Smith 1989). Although this technique allows the physiological condition of individual coral colonies to be monitored during stress, the need for specialist equipment and the time involved largely restricts this technique to the scale of individual coral colonies.

Observer based methods which rely on a subjective assessment of coral colour are, by comparison, rapid and inexpensive but suffer from bias and differing interpretation. For example, pale corals may be classified as "bleached" under some schemes while being accepted as "normal" under others. Methods based on the simple categories "normal", "partially bleached", "bleached" and "dead" (e.g. Hoegh-Guldberg and Salvat 1995) may miss important information due to the limited number of categories.

The present study first developed, and then evaluated the usefulness of an observer based reference card consisting of four colour hues and a 6 point brightness/saturation scale to record visible differences in coral colour, and thus, bleaching. The accuracy of the technique was assessed using conventional methods of chlorophyll *a* analysis and symbiont density in a field evaluation and also under controlled laboratory bleaching. This was followed by a user trial to determine the extent of observer bias and error.

Materials and methods

Colour reference card development

In order to develop a colour reference card which could be used across a wide range of coral species in different symbiont/chlorophyll pigmentation states, a two-stage approach was adopted. Firstly, a controlled laboratory bleaching was conducted to establish the relationship between colour and symbiont/chlorophyll content, using five species of branching corals. Changes in pigmentation were recorded photographically and symbiont and chlorophyll were measured using conventional methods. Secondly, a photographic field survey of 200 corals was undertaken during a period of bleaching in order to identify the most common colours associated with normally pigmented and bleached corals from a broad range of species.

Controlled laboratory bleaching

Ten replicate branches from each of five different coral species were mounted on plasticine stubs and placed in a thermostatically controlled aquarium (±1°C). The temperature was increased from ambient (28°C) to 32°C over 4 days (1°C per day) and maintained there for a further day for four species (*Pocillopora damicornis*, *Montipora digitata*, *Stylophora pistillata* and *Platygyra daedalea*) and for 3 more days for *Acropora aspera*. The experimental set-up was similar to that used previously to simulate "natural" bleaching events (e.g. Hoegh-Guldberg and Smith 1989; Jones et al. 1998). Each day, all corals within the experiment were photographed together with a colour standard, which consisted of five coloured areas (black, white, red, green and blue). One sample per species was removed daily for measurement of symbiont density and chlorophyll *a* content.

Each sample was photographed at three different exposures (+1, 0, −1) under identical illumination with an Olympus 4040 digital camera. The camera was set to manual so that the gain and white balance settings remained constant. Photographs were analysed in Adobe Photoshop V6 using the histogram function to determine the hue (reflected colour), saturation (proportion of grey in the hue), and brightness (relative lightness and darkness) of the lightest part of five coral branches from each species at a constant distance from the tip (1–2 cm). An image from one of the three exposures was judged suitable for use when the white colour standard was not saturated (RGB values between 250 and 255), the RGB values of the black standard were close to 0 and the RGB values for the red green and blue standards were similar (± 5 units). The purpose of the photographic method was to provide reliable correlations between colour in standardised photographs and the colour of coral fragments at various stages of bleaching and recovery, not absolute changes in real hue, saturation and brightness (Endler 1990).

For the analysis of symbiont density and chlorophyll *a* content, tissue was removed from the coral skeleton using a jet (WaterPik^{TM}) of recirculated filtered seawater (0.45 μm, Whatman Glass Microfibre filters GF/C). The slurry was then homogenized in a hand-held blender (ProMix duo, Krups Electronic Silver) for 45 s and the volume of the homogenate (between 50 and 100 ml) recorded. Four aliquots of 10 ml were taken from the homogenate. One 10 ml aliquot was used immediately to count the number of dinoflagellates using a Neubauer Improved Haemocytometer with eight replicate counts for each aliquot. The total number of symbiotic dinoflagellates per area was calculated using the volume of the homogenate and the coral surface area. Coral surface area was measured using the paraffin wax method of Stimson and Kinzie (1991). The other three (10 ml) aliquots were frozen at −20°C for later chlorophyll *a* analysis using the methodology of Jeffrey and Humphrey (1975). Aliquots (10 ml) were centrifuged at 3,500*g* for 15 min at 4°C, the supernatant discarded, and the pellet re-suspended in 5–10 ml of 100% acetone. Chlorophyll *a* was extracted for 24 h in the dark at 4°C. Samples were then centrifuged at 3,500*g* for 10 min at 4°C and the optical density of the supernatant was measured at 630 and 663 nm on a Perkin Elmer

spectrophotometer MBA 2000. Chlorophyll content was also standardized to surface area of the coral.

Field measurements of coral colour

During a period of widespread bleaching, 200 corals were photographed on the reef flat of Heron Island (Great Barrier Reef) together with a colour standard. Corals were chosen to maximise the number of different colours as well as the number of brightness levels. For each coral, the brightest and darkest areas were selected in the photograph and the average hue, brightness and saturation were determined within a 25 × 25 pixel square as previously described. The resulting 400 colour values were sorted according to hue and grouped into 4 colour categories (Photoshop hue levels: 8, 21, 31, and 50) to represent the range of hues found (hue 4–56). Blue and purple colours were excluded since they are a result of host pocilloporins rather than symbiotic dinoflagellates (Dove et al. 1995, 2001), and tend to remain for some time after the loss of the symbiotic dinoflagellates.

Combination of results to create colour reference card

The thermal stress experiment showed that in bleached corals, as symbiont density and chlorophyll *a* content decreased, there was an accompanying increase in the brightness of the corals, a decrease in saturation, but almost no change in hue (Fig. 1). In the two species (*Platygyra daedalea*, *Montipora digitata*) where changes in symbionts density or chlorophyll *a* were noticeably less, the hue, saturation and brightness did not change. Because of the lack of replicate samples these changes were not compared statistically, but rather only assessed qualitatively in the development of the card. Within each of the four chosen colour categories (based on hue) from the field measurements, it was therefore possible to allocate a scale of decreasing brightness and increasing saturation which represented an increase in symbiont density and chlorophyll *a* content. The final selection of this scale was based on the requirement for each colour to be visually distinct. The resulting colour card had four colour hues with six gradations for each colour (Fig. 2).

Each colour square on the card is identified by a letter indicating hue (b, c, d, e) and a number coding for brightness and saturation (1–6). Identical numbers therefore label colours with identical brightness and saturation levels. The card is used by finding the closest match between one of the card colours and the coral. Since the principal change in coral colour observed during the laboratory bleaching experiment was a result of changes in brightness/saturation, the number scale indicates the bleaching condition of the coral. However, slight hue changes can also occur when the coral skeleton or tissue contains green pigmentation (e.g. endolithic algae) which is exposed as the symbionts are lost during bleaching (Fine et al. 2004).

Validation of the colour reference card

Accuracy of the technique to record symbiont density and chlorophyll a content

Because the purpose of the card is to record the progression of corals from a healthy to a bleached state, and thus as a proxy for symbiont density and/or chlorophyll

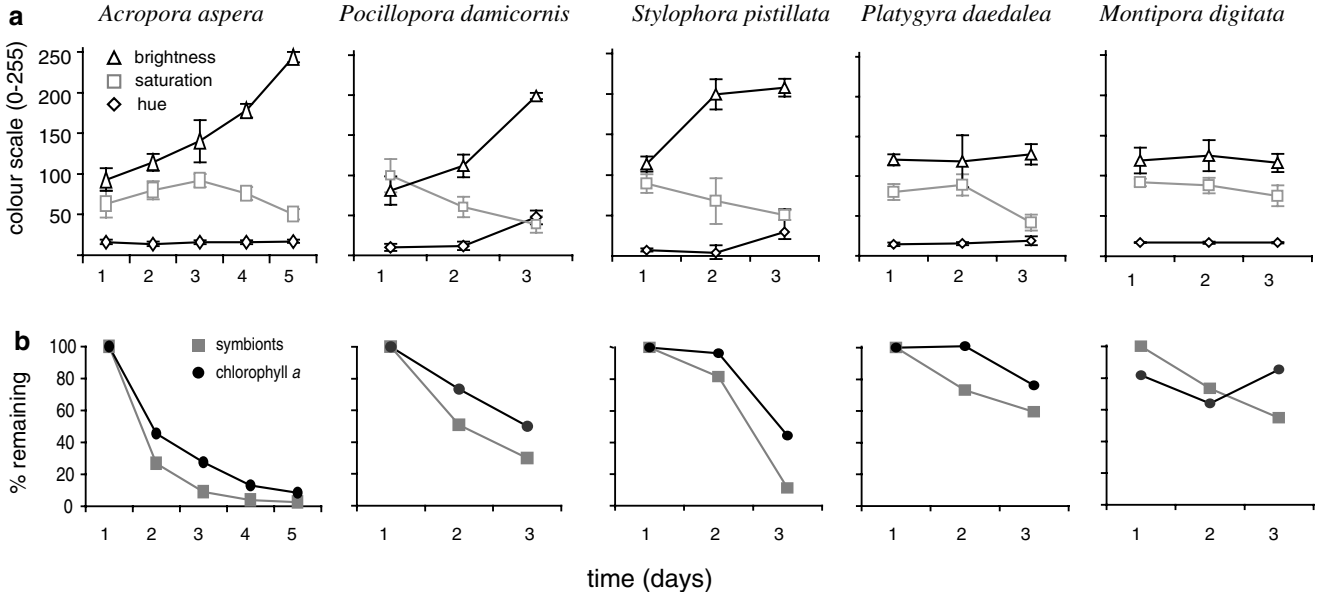

Fig. 1 Laboratory bleaching experiment; **a** changes in brightness, saturation, and hue values derived from photographic analysis. The scale vale of 255 is equivalent to 100% saturation or brightness, and for hue 360° on the standard colour wheel. **b** Changes in symbiont density and chlorophyll *a* content

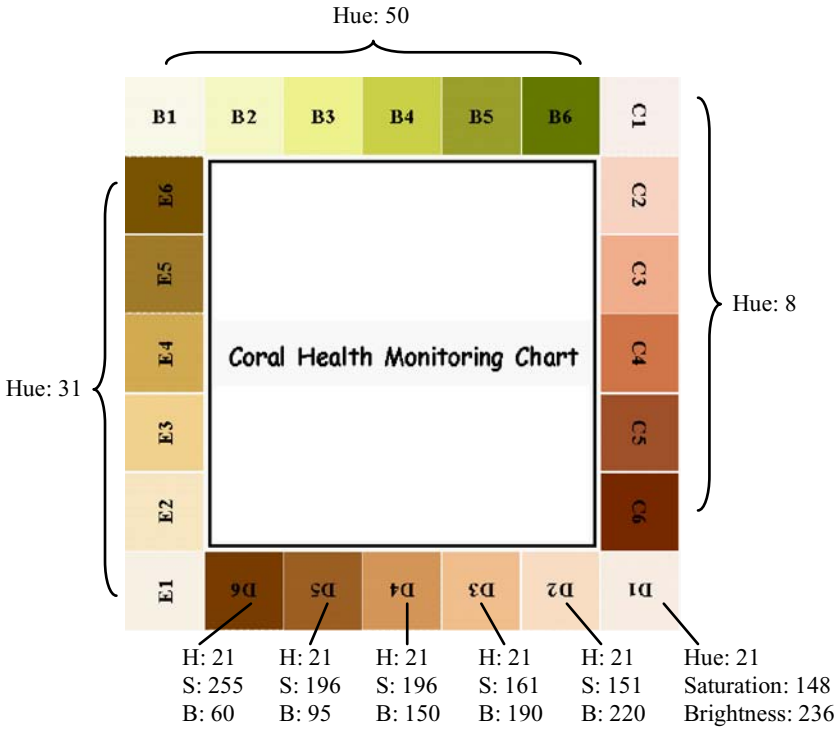

Fig. 2 The Coral Colour Reference Card developed for standardizing changes in coral colour. The hues are given for the four *different colour* categories arranged in groups around the sides of the chart. *Brightness and saturation values* are given for one hue only since they are identical for the same numerical colour score for each of the other hues

a content, it was necessary to determine the accuracy of the technique. The first stage involved a field study under similar conditions to those intended during use of the card.

In March 2002, at a time when corals were bleaching on the Heron Island reef flat, 15 randomly selected colonies of branching *Acropora* spp. were marked using numbered tags. Eight of the tagged colonies appeared very light in colour (colour score of 2 or less; "pale group") while the remaining seven showed no signs of bleaching at the time of selection ("dark group"). Tissue samples were taken in March 2002 during the bleaching event and again in May and June as the corals recovered their colour. On each occasion, a small branch (3–6 cm in length) was cut from each colony, and the colour recorded using the colour card prior to measurement of symbiont density and chlorophyll *a* content.

The second stag of the validation involved a repeat of the earlier laboratory bleaching experiment using only a single species (*Acropora aspera*). Symbiont density and the colour card value were measured immediately following collection and during the experiment when the corals were judged exactly to match one of the colour scores (1–6). Three replicate branches were analysed for each score value.

Observer validation

Since the colour card is intended to be used by multiple untrained observers in differing field conditions, it was also necessary to evaluate the degree of variability between observers in realistic conditions, each measuring the same coral. In the first trial, 33 students used the colour card to assess 6 branches of *A. aspera* which had been collected from the Heron Island reef flat. The assessments were made outside the laboratory in natural sunlight with the corals presented in individual white containers filled with fresh seawater. In every case, each student independently determined the colour of the coral branches 3 cm from the tip. The second trial was conducted under field conditions at low tide on the exposed reef flat, when 20 students recorded the colours of 6 marked colonies (3 branching and 3 massive).

Results

Validation of the colour reference card

Accuracy of technique to record symbiont density and chlorophyll a content

In March 2002 the pale group of corals had significantly fewer symbionts and lower chlorophyll *a* content than the dark corals (Mann Whitney: symbionts $P = 0.0003$, chlorophyll *a* $P = 0.0059$) (Fig. 3a). This was reflected in a low colour score of 1.9 ± 0.14 (mean $\pm$ SE) for the pale group compared to 4.9 ± 0.13 for the dark group (Mann Whitney $P < 0.0003$). By May and June the pale corals regained colouration and there were no longer any differences in any of the parameters. Analysing the same data, there was a clear positive relationship between colour score and symbiont density (coefficient of determination $r^2 = 0.63$, $P < 0.0001$) (Fig. 3b), but this relationship was much weaker for chlorophyll *a*

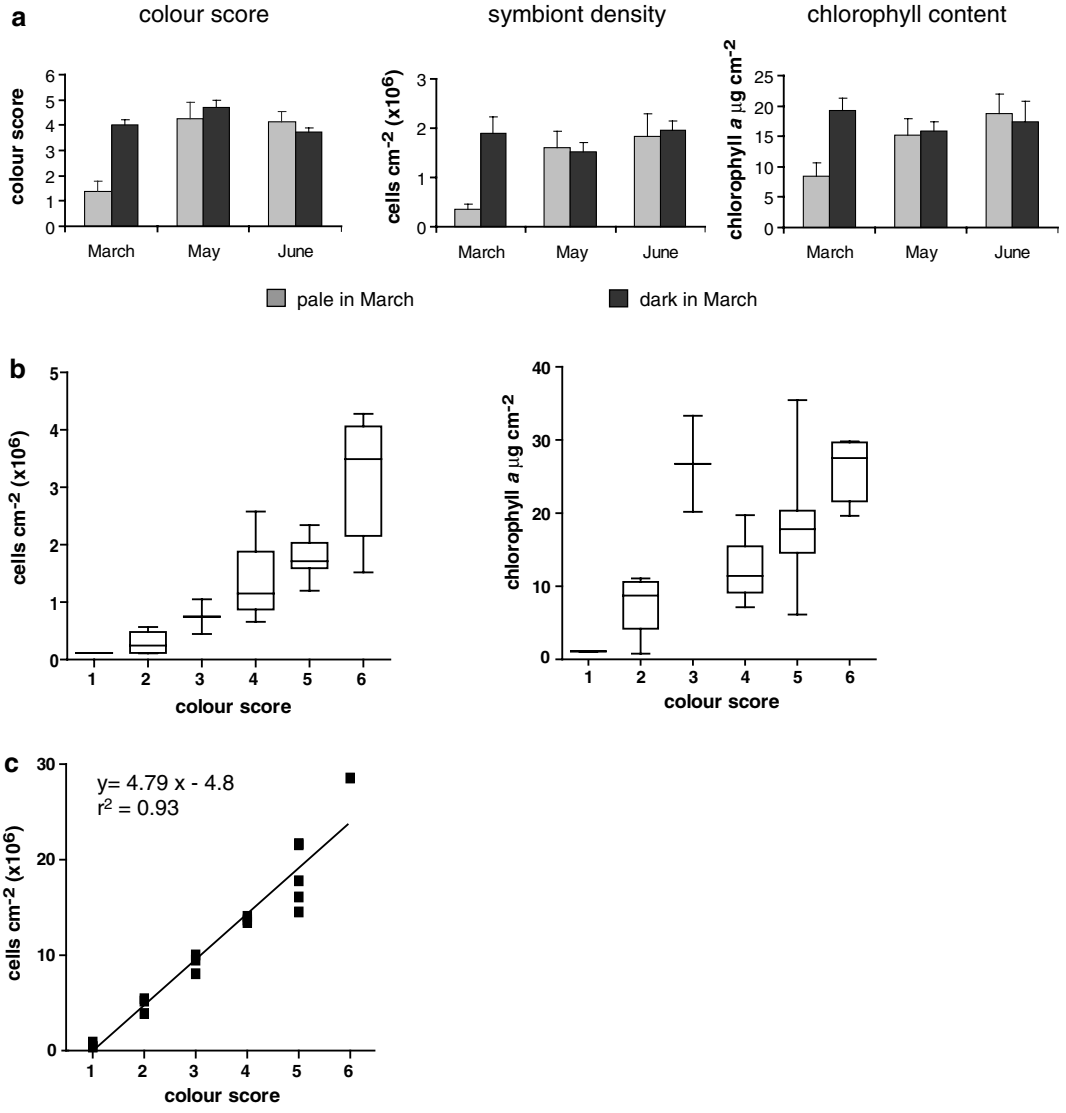

Fig. 3 **a** Colour measurements, symbiont density, and chlorophyll *a* content for 15 coral colonies sampled in March, May and June 2002 (mean ± SE). **b** Symbiont density and chlorophyll *a* content as a function of the colour score. Box plot center = mean, outer limit = 75% percentile, and range is shown by the whiskers. In each case data of 3 replicate measurements of the same 15 branching coral are shown. **c** Symbiont density and colour score in *Acropora aspera* during laboratory bleaching. Initial colour scores of the dark branches and three replicate measurements for each colour score during progressive bleaching are shown

($r^2 = 0.36$, $P < 0.0001$). For symbiont density an ANOVA revealed a significant difference between colour scores ($F_{4,39} = 20.3$, $P < 0.001$), but multiple post hoc tests (Tukey tests) showed that a colour score difference of at least 2 is consistently required to detect changes [between scores 2 and 4 ($P = 0.01$), 2 and 5 ($P < 0.01$), 2 and 6 ($P < 0.001$), 4 and 6 ($P < 0.001$), and 5 and 6 ($P < 0.001$)]. A similar relationship also existed for chlorophyll *a* ($F_{4,39} = 13.22$, $P < 0.001$) with differences between colour scores, 2 and 5 ($P < 0.01$), 2 and 6 ($P < 0.001$), 4 and 5 ($P < 0.05$), 4 and 6 ($P < 0.01$), and 5 and 6 ($P < 0.05$,). Since only two samples were found with a colour score of 3 and one with a colour score of 1, these scores had to be excluded from the analysis.

Results for the single species (*A. aspera*) laboratory bleaching experiment showed an improved correlation between symbiont density and colour score (coefficient of determination $r^2 = 0.93$, $P < 0.0001$) (Fig. 3c) and it is possible that an improvement in performance can be obtained by calibrating the reference card to each species. However, it is important to note that this experimental calibration artificially excluded intermediate colours which would be found in normal use.

Observer validation

The field and laboratory observer trials demonstrated a variability of up to 3 colour scores between different observers (Fig. 4a, b). In some cases this narrowed down to two scores, e.g. colour score 6 and 1 for the laboratory trial, and score 2 for the field trial. The pooled standard deviation for the best case scenario (single

coral species in the laboratory trial) was ± 0.5 scores, and in the worst case (field conditions, cloudy sky, rising tide, several species) ± 0.59.

Precision (standard error/mean) was then calculated for subsets of 3, 6, 10 and 15 observers to evaluate the change in variability with increased observer numbers. The subsets were determined by randomly sampling the data pool and the pooled standard deviation and standard error were then calculated for each subset. This process was repeated ten times for each subset. Precision was 0.1 for the field measurements using 3 observers, doubling when the number of observers was increased to 6 (Fig. 4c).

Discussion

Bleaching, or the loss of symbionts and/or their pigmentation, is symptomatic of stress in reef-building corals. Recent decades have seen an increase in both the

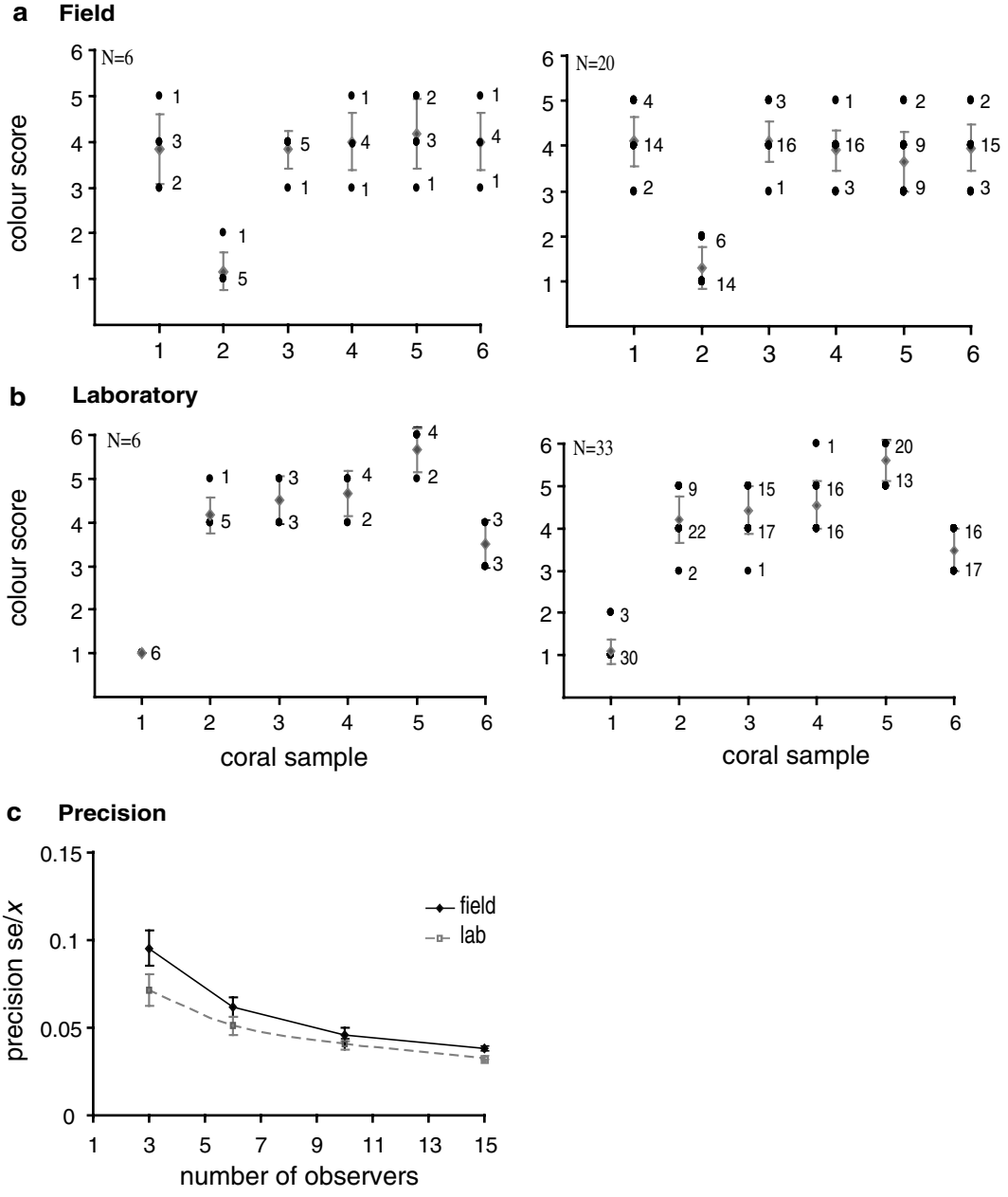

Fig. 4 Variability between untrained observers. **a** Colour measurements of six randomly selected coral colonies on the Heron Island reef flat. Single observer measurements and means (*grey*; ± SD) for a sub sample of 6 and all 20 observers. *Numbers* indicate selection frequency of colour scores. **b** Colour measurements of 6 *Acropora aspera* branches measured in the laboratory. Single observer measurements and means (*grey*; ± SD) for a sub sample of 6 and all 33 observers. **c** Change in precision (SE/mean) with increasing observer numbers for field and laboratory colour measurements. Precision calculations are made for 10 replicate sub samples of 3, 6, 10 and 15 observers

frequency and intensity of mass bleaching events. Rapid, inexpensive and easy-to-use technologies can assist in understanding changes in reef condition that are now occurring at global scales. The present study involved the development of one such tool, the colour reference card, for use in recording the bleaching status across a broad spectrum of different coral species.

By analysing a large number of species in the field and conducting an experimental bleaching of five species, it has been demonstrated that bleaching (as defined by symbiont density and/or chlorophyll *a* content) principally involves change in colour brightness and saturation of a coral, but not a change in hue. Slight changes in hue, however, were also found in some coral species during bleaching, possibly due to differences in skeletal colour, particularly at low symbiont concentrations when corals with white skeletons will have a different overall colour compared to corals with green skeletons due to the presence of endolithic algae (Fine et al. 2004). It has been possible, therefore, to design a colour reference card using four hues to encompass colour differences between species, whilst within each of the hues, bleaching can be measured on a 6 point scale consequent upon changes in brightness and saturation.

It is important to define the accuracy of the technique when recording changes in coral colour using the 6 point scale in terms of changes in the bleaching state of the coral. The logical yardstick for this involves the conventional measures of symbiont density and chlorophyll *a* content. In multispecies use the changes in both symbiont density and chlorophyll content could be detected by a separation of two colour scores, but not between adjacent scores. There was some evidence that this might be improved by calibrating the card to each individual species but this would require further evaluation.

Two factors undoubtedly affect the accuracy of the method namely that corals taken from the field may not match a colour category perfectly and are therefore assigned to the nearest category, and secondly, the diverse mix of species adds variability due to differences in tissue thickness and skeletal structure. The relationship between symbiont density and colour chart score was also weakest in the darkest corals indicating that at high symbiont densities the colour response has become saturated. The correlation of colour chart score to chlorophyll *a* was also weaker compared to correlations of symbiont density. This difference may be a consequence of differences in the abundance of accessory pigments such as peridinin relative to chlorophyll *a*. That is, colour may change due to peridinin concentrations which respond to changes in light and nutrient levels while chlorophyll *a* may remain constant (Iglesias-Prieto and Trench 1997).

There are further caveats to the use of the technique. For example, different species of corals will often have different colour scores even when they are in a healthy condition. The colour card method is therefore more appropriate for measuring changes in bleaching state in the same species or colonies over time rather than as an absolute measure of bleaching between species or between locations. Additionally many species of coral are known to retract when subject to environmental stress, e.g. particularly on intertidal reef flats. In the more extreme cases such as *Coeloseris mayerii*, retraction during sub-aerial exposure can give rise to a marked 'blanching' of the coral surface which might be misinterpreted as bleaching (Brown et al. 1994). Also, when using the card on branching corals care needs to be taken to adopt a consistent sampling strategy. In this study colour measurements were taken at a distance of about 3 cm from the tip of branching corals to avoid the variations in colour that are frequently found in and around the axial polyp. Similar considerations may also apply to other coral morphologies where natural colour variation is an intrinsic feature.

Ensuring consistency of the method between different users is also an important requirement. Multiple non-specialist users obtained colour score values that fell within a maximum range of three colour scores and although field conditions affected this (the standard deviation increased from $\pm$ 0.5 to $\pm$ 0.59 moving from the laboratory to working on the reef flat at low tide) the accuracy remained at $\pm$ 1 score because of the resolution of the scale. Also although the precision of the technique can be improved by increasing the number of users, it is still not possible to improve the repeatability of observations beyond the $\pm$ 1 score value. It is possible that with a finer scale (more than the present 6 points) better results could be obtained but this would pose additional problems involving the ability to discern smaller colour differences and may not be practicable.

This study has demonstrated that simple and cheap techniques such as the colour reference card can improve the resolution of observer based measurements of coral bleaching compared to restricted categories such as "bleached", "partially bleached" and "healthy". The 6 point scale is also a direct indicator of coral symbiont density and chlorophyll *a* content, albeit care must be taken only to infer changes in bleaching state when colour differences are greater than 2 scale points. Although the technique cannot replace conventional measurements of bleaching, it has advantages of cheapness, speed, minimal training, and is non-invasive. Potential uses are in wide area or long-term monitoring, possibly in conjunction with transect or quadrate sampling. Although it has not been tested underwater, the technique has the potential for use whilst snorkelling or using SCUBA subject to further examination of observer error in these circumstances.

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