

# INTERACTIVE EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON SEDIMENT-DWELLING MARINE CALCIFIERS

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### **CERTIFICATE OF AUTHORSHIP / ORIGINALITY**

I certify that the work presented in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Sutinee Sinutok

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Chapter 7:

**Sinutok S**, Hill R, Doblin MA, Madin J, Berkahn M, Bishop D, Ralph PJ. Ocean acidification and warming will increase vulnerability of *Halimeda* sp. to breakage and removal. Submitted to *Global Change Biology*.

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Table 5.1: Parameters of the carbonate system; total alkalinity (TA), CO<sub>2</sub> partial pressure ( $p\text{CO}_2$ ), dissolved inorganic carbon species (DIC; CO<sub>2</sub>, CO<sub>3</sub><sup>-2</sup>, HCO<sub>3</sub><sup>-</sup>), total DIC, and saturation state of seawater with respect to aragonite ( $\Omega_a$ ) from each pH (8.1, 7.7) and temperature (28°C, 32°C) treatment used in this study. Data represent means ( $n = 3$ ,  $\pm$  S.E.).

Table 5.2: Calcification rate (% increase day<sup>-1</sup>) and chlorophyll (Chl)  $a$  and  $b$  concentration ( $\mu\text{g g}^{-1}$  fw) of *Halimeda macroloba* and *Halimeda cylindracea* after 5 weeks in each pH and temperature treatment. Data represent means ( $n = 4$ , mean  $\pm$  S.E.). \* signifies  $P < 0.05$ .

Table 6.1: Parameters of the carbonate system; total alkalinity (TA), CO<sub>2</sub> partial pressure ( $p\text{CO}_2$ ), dissolve inorganic carbon (DIC; CO<sub>2</sub>, CO<sub>3</sub><sup>-2</sup>, HCO<sub>3</sub><sup>-</sup>), and saturation state of seawater with respect to calcite ( $\Omega_c$ ) from each pH (8.1, 7.7) and temperature (28°C, 32°C) treatment. Mean  $\pm$  SE ( $n = 3$ ).

Table 6.2: Calcification rate (% increase day<sup>-1</sup>) and chlorophyll (Chl)  $a$  and  $c_2$  concentration ( $\mu\text{g g}^{-1}$  fw) of *Marginopora vertebralis* after 5 weeks in each pH and temperature treatment. Data represent means ( $n = 4$ , mean  $\pm$  S.E.). \* signifies  $P < 0.05$ .

Table 7.1: Parameters of the carbonate system; total alkalinity (TA), CO<sub>2</sub> partial pressure ( $p\text{CO}_2$ ), dissolve inorganic carbon (DIC; CO<sub>2</sub>, CO<sub>3</sub><sup>-2</sup>, HCO<sub>3</sub><sup>-</sup>), and saturation state of seawater with respect to calcite ( $\Omega_c$ ) and aragonite ( $\Omega_a$ ) from each pH (8.1, 7.7)

and temperature (28°C, 32°C) treatment used in experiments. Data represent mean  $\pm$  S.E.  
( $n = 3$ )

## ABSTRACT

The increase in human activities, such as the burning of fossil fuels, has elevated the concentration of atmospheric carbon dioxide and warmed the planet through the greenhouse effect. In addition, approximately 30% of the CO<sub>2</sub> produced by human activities has dissolved into the oceans, lowering pH and reducing the abundance, and hence the availability, of carbonate ions (CO<sub>3</sub><sup>2-</sup>), which are essential for calcium carbonate deposition. Of great concern is the impact to photosynthetic marine calcifiers, elevated CO<sub>2</sub> and temperature is expected to have a negative impact on the health and survivorship of calcifying marine organisms.

This thesis explores the effects of elevated CO<sub>2</sub> and temperature on the microenvironment, photosynthetic efficiency, calcification and biomechanical properties in important sediment producers on coral reefs. The reef-building and sediment-dwelling organisms, *Halimeda* and symbiont-bearing foraminifera are prominent, co-existing taxa in shallow coral reefs and play a vital role in tropical and subtropical ecosystems as producers of sediment and habitats and food sources for other marine organisms. However, there is limited evidence of the effects of ocean warming and acidification in these two keystone species. Irradiance alone was not found to influence photosynthetic efficiency, photoprotective mechanisms and calcification in *Halimeda macroloba*, *Halimeda cylindracea* and *Halimeda opuntia* (**Chapter 2**). There is also limited knowledge of foraminiferal biology on coral reefs, especially the symbiotic relationship between the protist host and algal symbionts. *Marginopora vertebralis*, the dominant tropical foraminifera, shows phototactic behavior, which is a unique mechanism for ensuring symbionts experience an ideal light environment. The diurnal photosynthetic responses of *in hospite* symbiont photosynthesis was linked to host movement and aided in preventing photoinhibition and bleaching by moving away from over-saturating irradiance, to more optimal light fields (**Chapter 3**).

With this greater understanding of *Halimeda* and foraminiferan biology and

photosynthesis, the impacts of ocean warming and acidification on photosynthesis and calcification were then tested (**Chapter 4, 5 and 6**). Impacts of ocean acidification and warming were investigated through exposure to a combination of four temperature (28, 30, 32, 34°C) and four  $p\text{CO}_2$  levels (380, 600, 1000, 2000  $\mu\text{atm}$ ; equivalent to future climate change scenarios for the current and the years 2065, 2100 and 2200 and simulating the IPCC A1F1 predictions) (**Chapter 4**). Elevated  $\text{CO}_2$  and temperature caused a decline in photosynthetic efficiency ( $F_v/F_m$ ), calcification and growth in all species. After five weeks at 34°C under all  $\text{CO}_2$  levels, all species died. The elevated  $\text{CO}_2$  and temperature greatly affect the  $\text{CaCO}_3$  crystal formation with reductions in density and width. *M. vertebralis* experienced the greatest inhibition to crystal formation, suggesting that this high Mg-calcite depositing species is more sensitive to lower pH and higher temperature than aragonite-forming *Halimeda* species. Exposure to elevated temperature alone or reduced pH alone decreased photosynthesis and calcification in these species. However, there was a strong synergistic effect of elevated temperature and reduced pH, with dramatic reductions in photosynthesis and calcification in all three species. This study suggested that the elevated temperature of 32°C and the  $p\text{CO}_2$  concentration of 1000  $\mu\text{atm}$  are the upper limit for survival of these species at our site of collection (Heron Island on the Great Barrier Reef, Australia).

Microsensors enabled the detection of  $\text{O}_2$  surrounding specimens at high spatial and temporal resolutions and revealed a 70-80% decrease in  $\text{O}_2$  production under elevated  $\text{CO}_2$  and temperature (1200  $\mu\text{atm}$  32°C) in *Halimeda* (**Chapter 5**) and foraminifera (**Chapter 6**). The results from  $\text{O}_2$  microprofiles support the photosynthetic pigment and chlorophyll fluorescence data, showing decreasing  $\text{O}_2$  production with declining chlorophyll *a* and *b* concentrations and a decrease in photosynthetic efficiency under ocean acidification and/or temperature stress. This revealed that photosynthesis and calcification are closely coupled with reductions in photosynthetic efficiency leading to reductions in calcification.

Reductions in carbonate availability reduced calcification and that can lead to weakened calcified structures. Elevations in water temperature is expected to augment this

weakening, resulting in decreased mechanical integrity and increased susceptibility to storm- and herbivory-induced mortality in *Halimeda* sp. The morphological and biomechanical properties in *H. macroloba* and *H. cylindracea* at different wave exposures were then investigated in their natural reef habitats (**Chapter 7**). The results showed that both species have morphological (e.g. blade surface area, holdfast volume) and biomechanical (e.g. force required to uproot, force required to break thalli) adaptations to different levels of hydrodynamic exposure. The mechanical integrity and skeletal mineralogy of *Halimeda* was then investigated in response to future climate change scenarios (**Chapter 7**). The biomechanical properties (shear strength and punch strength) significantly declined in the more heavily calcified *H. cylindracea* at 32°C and 1000  $\mu\text{atm}$ , whereas were variable in less heavily calcified *H. macroloba*, indicating different responses between *Halimeda* species. An increase in less-soluble low Mg-calcite was observed under elevated CO<sub>2</sub> conditions. Significant changes in Mg:Ca and Sr:Ca ratios under elevated CO<sub>2</sub> and temperature conditions suggested that calcification was affected at the ionic level. It is concluded that *Halimeda* is biomechanically sensitive to elevated temperature and more acidic oceans and may lead to increasing susceptibility to herbivory and higher risk of thallus breakage or removal from the substrate.

Experimental results throughout the thesis revealed that ocean acidification and warming have negative impacts on photosynthetic efficiency, productivity, calcification and mechanical integrity, which is likely to lead to increased mortality in these species under a changing climate. A loss of these calcifying keystone species will have a dramatic impact on carbonate accumulation, sediment turnover, and coral reef community and habitat structure.