Interactive Effects of Ocean Acidification and Warming on Sediment-Dwelling Marine Calcifiers

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B.Sc. (First Class Honours) & M.Sc. (Ecology)

January 2013

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Science

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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

ACKNOWLEDGEMENTS

First, I would like to thank to my supervisors Professor Peter Ralph, Dr Ross Hill and Dr Martina Doblin for their guidance, advice and support and all the opportunities they have provided during my candidature. I would like to thank Dr Ross Hill for inspiring me and assisting me throughout my PhD.

I would like to thank Professor Michael Kühl for teaching me the microsensor technique. Professor Anthony Larkum, Dr Justin Seymour, Dr Lucy Buxton, Dr Isabel Jimenez, Dr Nikolaus Császár, Dr Milan Szabo, Dr Katharina Petrou, Dr Daniel Neilson and Dr Raymond Ritchie are also thanked for their guidance during the completion of this research.

Thanks are also extended to Professor Louise Evans and Linda Xiao, Mark Berkahn, Dr Richard Wuhrer, David Bishop and Dr Michael Johnson for assistance with autotitration, X-ray diffraction, environmental scanning electron microscopy, ICP-MS, and Confocal microscopy, respectively. Thank you Professor Robert DeWreede, Dr. Joshua Madin and Dr. Yusuke Onoda for your assistance on the biomechanical work. Thank you Dr. Klairung Samart for her guidance on statistical analyses.

Thank you to all laboratory, technical and administrative staff at UTS and Heron Island Research Station. Special thanks to Dr Vinod Kumar, Marlene Fretz (Zbinden) and John Moore for their assistance.

Thank you to all members of the Aquatic Processes Group (APG) and special thanks to Verena Schrameyer, Ying Hong and Olivia Sackett, for their support and friendship. I have thoroughly enjoyed working with you all.

I would like to thank my lovely husband Ponlachart Chotikarn for his support and inspiration. I would like to also thank my family and friends for their support.

Thank you to Professor Tony Moon for his kind support and special thanks to Dr Auppatham Nakaruk, Bhanupong Dhechanunt, Pojwaree Lertsutthichawan, Weenaththa

Likitkom, Supitcha Supansomboon and Sirinut Sawatdeenarunat for their friendship and support.

I have received financial support from a number of sources. These include the Faculty of Science, School of the Environment, Plant Functional Biology and Climate Change Cluster at UTS, the Australian Government, the Australian Coral Reef Society, and the Phycological Society of America. Without these financial contributions, this research would not have been possible. In addition, I would like to thanks the Australian Coral Reef Society and the Australasian Society for Phycology and Aquatic Botany for travel funding to attend international and domestic conferences.

I would also like to acknowledge the Great Barrier Reef Marine Park Authority for approving the research permit (G09/30853.1 and G11/34063.1).

PUBLICATIONS

Peer reviewed journal articles arising directly from this thesis:

Chapter 2:

Sinutok S, Hill R, Doblin MA, Ralph PJ. The effect of irradiance on photosynthetic efficiency and calcification in three *Halimeda* species

Chapter 3:

Sinutok S, Hill R, Doblin MA, Ralph PJ. Diurnal photosynthetic response of the symbiotic benthic foraminiferan *Marginopora vertebralis*. *Marine Ecology Progress Series.* In press.

Chapter 4:

Sinutok S, Hill R, Doblin MA, Wuhrer R, Ralph PJ (2011) Warmer more acidic conditions cause decreased productivity and calcification in subtropical coral reef sediment-dwelling calcifiers. *Limnology and Oceanography* 56(4): 1200-1212.

See Appendix 1

Chapter 5:

Sinutok S, Hill R, Doblin MA, Kühl M, Ralph PJ (2012) Microenvironmental changes support evidence of photosynthesis and calcification inhibition in *Halimeda* under ocean acidification and warming. *Coral Reefs* 31:1201-1213.

See Appendix 2

Chapter 6:

Sinutok S, Hill R, Doblin MA, Kühl M, Ralph PJ. Ocean acidification and warming alter microscale photosynthesis and calcification of the symbiont-bearing foraminifera *Marginopora vertebralis*. Submitted to *Marine Biology*.

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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and temperature (28ºC, 32ºC) treatment used in experiments. Data represent mean ± 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_2 produced by human activities has dissolved into the oceans, lowering pH and reducing the abundance, and hence the availability, of carbonate ions (CO_3^{2-}), which are essential for calcium carbonate deposition. Of great concern is the impact to photosynthetic marine calcifiers, elevated CO_2 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_2 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 protest 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 pCO_2 levels (380, 600, 1000, 2000 µatm; 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 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 CO_2 levels, all species died. The elevated CO_2 and temperature greatly affect the $CaCO_3$ 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 pCO_2 concentration of 1000 µatm are the upper limit for survival of these species art our site of collection (Heron Island on the Great Barrier Reef, Australia).

Microsensors enabled the detection of O_2 surrounding specimens at high spatial and temporal resolutions and revealed a 70-80% in decrease in O_2 production under elevated CO_2 and temperature (1200 µatm 32°C) in *Halimeda* **(Chapter 5)** and foraminifera **(Chapter 6)**. The results from O_2 microprofiles support the photosynthetic pigment and chlorophyll fluorescence data, showing decreasing 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 32ºC and 1000 µatm, 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_2 conditions. Significant changes in Mg:Ca and Sr:Ca ratios under elevated CO_2 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.