Strategic Research Fund for the Marine Environment (SRFME)

Final report **December 2006**

volume **one**

Edited by John K. Keesing and John N. Heine **CSIRO** Marine and Atmospheric Research

Strategic Research Fund for the Marine Environment
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Private Bag 5 Wembley 6913 AUSTRALIA

National Library of Australia
Cataloguing-in-Publication data:

Strategic Research Fund for the Marine Environment (SRFME) :

final report. Vol. 1, The SRFME initiative and SRFME collaborative linkages program.

ISBN 1 921061 90 1

1. CSIRO - Appropriations and expenditures. 2. Marine

sciences - Research - Western Australia - Finance. 3.

Marine resources - Research - Western Australia - Finance.

I. Keesing, John K. II. Heine, John N. III. CSIRO.

354.5709941

Published by Strategic Research Fund for the Marine Environment, CSIRO, Australia

For bibliographic purposes, this report may be cited either as an entire volume, eg.:

Keesing J.K. and Heine, J.N. (2006). Strategic Research Fund for the Marine Environment Final Report. Volume 1: the SRFME initiative and collaborative linkages program 260p. Strategic Research Fund for the Marine Environment, CSIRO, Australia.

or where referring to specific sections we would encourage the following form of citation; eg.

Goldberg, N. (2006). Ecological and historical processes maintaining macroalgal diversity in the Recherche Archipelago, Western Australia. pp 22 - 28. In: Keesing J.K. and Heine, J.N. (Eds). Strategic Research Fund for the Marine Environment Final Report. Volume 1: the SRFME initiative and collaborative linkages program 260p. Strategic Research Fund for the Marine Environment, CSIRO, Australia.

Preface

The Strategic Research Fund for the Marine Environment (SRFME) was established as a joint venture by the Western Australian State Government and the CSIRO in 2001 with the aims of building capability and capacity in marine science in Western Australia through the reestablishment of CSIRO's marine research capability and the training of postgraduate students, facilitating strong collaboration among the Western Australian marine science community, and conducting strategic research that is of benefit to Western Australia.

These two volumes comprise the Final Report of SRFME. Volume 1 outlines the establishment of SRFME, the development of its research framework and research portfolio as well as its structure and governance in chapter 1 and details the SRFME Collaborative Linkages Program which was comprised of a set of PhD Scholarship Projects (chapter 2), SRFME Collaborative Projects (chapter 3) and SRFME State Linkage Projects (chapter 4). Volume 1 also introduces the SRFME Core Projects (chapter 5) and concludes with a list of publications arising from SRFME (chapter 6). Volume 2 of the SRFME Final Report comprises an overview summary (chapter 1), followed by detailed chapters on the scientific research conducted in the areas of physical oceanography (chapter 2), coastal and continental shelf pelagic community structure (chapter 3), coastal and continental shelf biogeochemistry and modelling (chapter 4), coastal benthic ecosystem structure and dynamics (chapters 5 and 6) and concludes with a description of the data archiving systems and the interactive data and model output visualisation software developed in SRFME (chapter 7).

A list of acknowledgements to the many people who have contributed to the success of SRFME is included elsewhere in this final report, but I would like to make special mention of a few in particular, whose support to me in my role as SRFME Research Director has been invaluable. I would like to thank Dr Nan Bray (CSIRO) and Dr Sue Meek (WA Government) who had the vision to develop and establish SRFME, and subsequent senior people in the WA State Government; Dr Bruce Hobbs, and CSIRO; Dr Greg Ayers, John Gunn, Dr Tony Haymet, Tim Moltmann, Dr John Parslow, Dr Ian Poiner and Craig Roy who all provided tremendous support. I would also like to thank other members of the SRFME Joint Venture Management Committee and Technical Advisory Committee, especially Dr Ray Masini, Peter Millington, Phillip Murray, Linda Penny and Dr Chris Simpson for their support and advice, CSIRO project Leaders; Dr Russ Babcock, Dr Peter Craig, and Dr Tony Koslow for their excellent science leadership, Lucy Kay for her tireless work for SRFME and John Heine for producing the final report.

Dr John Keesing

Research Director
Strategic Research Fund for the Marine Environment

31 December 2006

Foreword

Premier of Western Australia

FOREWORD BY THE PREMIER OF WESTERN AUSTRALIA
HON ALAN CARPENTER MLA

The $20 million Strategic Research Fund for the Marine Environment (SRFME) was established as a joint venture between the State Government of Western Australia and the CSIRO. Through this partnership, each invested $10 million to build capability and capacity in marine science in Western Australia, facilitate strong collaboration among the Western Australian marine science community, and conduct strategic research that is of benefit to Western Australia.

The outcomes described in these two volumes of the SRFME Final Report, even at over 500 pages, seek only to summarise the vast amount of work undertaken in SRFME by CSIRO and its collaborators in Western Australian universities, State agencies and Museum. From this report, it is apparent that the goals for SRFME have been impressively exceeded.

Encouraged by the track record of success in SRFME, the State Government has recently announced investment of a further $21 million to establish the Western Australian Marine Science Institution (WAMSI). In doing so, they have demonstrated the Government's commitment to ensuring the capability and capacity for marine science in Western Australia is maintained and grown. Through WAMSI, the strategic research needs of the State will continue to be addressed and the strong partnerships, such as those established with the CSIRO through SRFME, will endure.

Through WAMSI, the Western Australian State Government looks forward to further outstanding marine science outcomes, from CSIRO and its collaborators, which contribute to the wise management of Western Australia's marine environment and the sustainable development of its natural resources.

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PREMIER

30 JAN 2007

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Acknowledgements

Many people have contributed to the establishment and management of SRFME and the development of its research portfolio. Many more have participated in the many research projects funded by SRFME. In addition to the SRFME research teams, SRFME PhD students and their supervisors whose names are listed with their contributions to each of the chapters of this volume of the SRFME Final Report, we thank the following people who have contributed to the SRFME Joint Venture in a number of ways over the period of 2000 to 2006.

Kim Anderson, Department of Industry and Resources
Simon Allen, CSIRO
Dr Greg Ayers, CSIRO
Arthur Banks, CSIRO
Louise Bell, CSIRO
Pru Bonham, CSIRO
Dr Bernard Bowen, Chairman Marine Research Taskforce
Dr Nan Bray, CSIRO
Dr Alan Butler, CSIRO
Dr Ed Butler, CSIRO
Dr Nick Caputi, Department of Fisheries
Gary Carroll, CSIRO
Celine Chan, CSIRO
Graham Cobby, Department of Industry and Resources
Ian Cook, CSIRO
Dr Scott Condie, CSIRO
Jeff Cordell, CSIRO
Richard Craddock, Department of Industry and Resources
Dr George Cresswell, CSIRO
Lea Crosswell, CSIRO
Dr Nick D'Adamo, Department of Conservation and Land Management
Carl Davies, CSIRO
Peter Dunn, CSIRO
Siobhan Duffy, CSIRO
John Gunn, CSIRO
Peter Green, CSIRO
Kim Grey, CSIRO
Michael Harrison, CSIRO
Dr Tony Haymet, CSIRO
Dr Chad Hewitt, CSIRO
Dr Bruce Hobbs, Department of the Premier and Cabinet
Dr John Huisman, Murdoch University
Tennille Irvine, CSIRO
Neale Johnston, CSIRO
Lucy Kay, CSIRO
Hiski Kippo, CSIRO
Mark Lewis, CSIRO
Craig McCauley, CSIRO
James McLaughlin, CSIRO
Dr Mike Mackie, Department of Fisheries
Dr Ray Masini, Department of the Environment
Dr Sue Meek, Department of Commerce and Trade
Peter Millington, Department of Fisheries
Dr Des Mills, Department of the Environment
Don Michel, CSIRO
Toni Moate, CSIRO
Tim Mangan, CSIRO
Tim Moltmann, CSIRO
Michael Mulligan, Geraldton Port Authority
Phillip Murray, Department of the Premier and Cabinet
Tim O'Sullivan, CSIRO
Angela Palmer, CSIRO
Dr John Parslow, CSIRO
Val Pearce, CSIRO
Lindsay Pender, CSIRO
Dr Jim Penn, Department of Fisheries
Ms Linda Penny, Department of the Premier and Cabinet
Ron Plashke, CSIRO
Dr Ian Poiner, CSIRO
Jane Pollock, CSIRO
Pam Powell, CSIRO
Dr Andrew Revill
Craig Roy, CSIRO
Dr Keith Sainsbury, CSIRO
Dr Cameron Sim, Department of the Environment
Dr Chris Simpson, Department of Conservation and Land Management
Dirk Slawinski, CSIRO
Dr Peter Thompson, CSIRO
Paul Tzaikos, Department of Industry and Technology
Dr Paul Vogel, Department of Environment and Water
Bernadette Waugh, CSIRO
Dr Paul Wellings, CSIRO
Dr Fred Wells, WA Museum
Dr Kate Wilson, CSIRO
Dr Jackie Zanetti, CSIRO

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Executive summary

The Strategic Research Fund for the Marine Environment (SRFME) is a 6-year (2001-2006), $20 million joint venture between CSIRO and the Western Australia Government. SRFME has the following as its mission:

SRFME will enhance Western Australia's marine research capability and capacity, deliver strategic research outcomes of benefit to Western Australia and enhance collaboration among marine researchers in Western Australia.

SRFME was established with the following high-level goals:

- Build capability and capacity in marine science in Western Australia
- Facilitate strong collaboration among the Western Australian marine science community
- Conduct fundamental and strategic research that is of benefit to Western Australia and Australia

With these goals and focus in mind, SRFME has invested in strategic research on the Western Australian marine environment in a way which enhances capability and capacity for marine science, encourages collaboration amongst the Western Australian research community and delivers strategic research outcomes which will have long-term benefits to the state.

This final report completed in December 2006 is aimed at presenting SRFME's achievements to date to its members, stakeholders and collaborators. Some of the work presented here is still in progress and will be completed over the coming year. Even then much of the work that has been initiated by SRFME will be ongoing. This is a product of both the nature of strategic scientific research and strong and enduring collaborative partnerships that have been developed as a result of SRFME.

By any measure, SRFME has achieved its goals and has set a new benchmark in establishing collaborative research partnerships.

With regard to building capability and capacity in marine science in Western Australia, SRFME has achieved its goal by growing CSIRO's marine research capacity in Western Australia from just 4 scientific and support staff in 2001 to over 25 in 2006. These staff have been relocated or recruited to its Floreat laboratories where they have formed part of a critical mass of over 300 staff within CSIRO's Centre for Environment and Life Sciences. A strong partnership developed between SRFME and CSIRO's Wealth from Oceans Flagship has also ensured strong links between SRFME researchers in WA and those elsewhere in CSIRO working towards Wealth from Oceans ambitious national and international goals in climate science, operational oceanography and multiple use management.

Capability and capacity have also been further developed in Western Australia through SRFME's Postgraduate Scholarship program and the SRFME Collaborative Projects program. SRFME funded 12 PhD students at four Western Australian Universities who have strongly supported the program through co-investing in stipends and operating funds and providing supervision. Many of the SRFME students participated in the SRFME Core Projects and were co-supervised by staff from CSIRO and state research or management agencies. SRFME has also created capability and capacity through the recruitment of 6 postdoctoral researchers at Western Australian Universities as part of its $2 million investment in the SRFME Collaborative Projects.

In terms of facilitating collaboration, SRFME has brought about a range of strong multidisciplinary collaborations to its research programs. Research described in this report outlines the involvement of ten research organisations in SRFME projects with the vast majority of projects having collaborations amongst multiple organisations. In particular the SRFME Core projects and the Jurien Bay Collaborative projects comprise large multidisciplinary teams and include postdoctoral fellows and PhD students in the projects. Through these large multidisciplinary research projects SRFME researchers have also secured a large number of national facility sea days aboard the Southern Surveyor enhancing these collaborations.

Lastly, SRFME has met its goal to conduct fundamental and strategic research that is of benefit to Western Australia and Australia through all of its programs. The highlights of this work are outlined in this final report. Volume 1, Chapter 1 sets out the background to the establishment of SRFME, how it is managed and how its research portfolio was developed. Chapter 2 provides summary reports on each of the SRFME PhD scholarship projects, Chapters 3 and 4 contain the SRFME Collaborative Projects and State Linkage Projects reports respectively and Chapter 5 provides an overview of the large SRFME Core Projects: Biophysical Oceanography, Coastal Ecosystems and Biodiversity and Integrated Modelling. Chapter 6 provides a list of all the publications arising from SRFME to date. Volume 2 covers the SRFME Core Projects beginning with a summary and synopsis of the research in Chapter 1, Chapter 2 on Oceanography, including the Indian Ocean and role of the Leeuwin Current, as well as Inshore Dynamics and Hydrodynamic Modelling, Sediment Dynamics, and Wave Propagation and Dissipation, Chapter 3 on Coastal and Shelf Pelagic Community Structure, including temporal and spatial variability in primary and secondary productivity, Chapter 4 on Biogeochemistry and Modelling, including a review of regional nutrient dynamics, Chapter 5 on Benthic Ecosystem Structure, including spatial and temporal variability in animal and plant diversity, Chapter 6 on Benthic Ecosystem Dynamics, and Chapter 7 on Data Access and Visualisation tools. Much of this work is now completed and has been published in PhD theses, technical reports and the primary literature, and the data, models and tools developed during SRFME are available to researchers and natural resource managers.

Summary of Major Achievements and Findings from SRFME

- CSIRO and the Western Australian government invested $10 million each into the SRFME initiative and coinvestment by SRFME's collaborators added approximately $2.3 million more into SRFME research projects.
- SRFME funded a total of over $2.8 million to 32 projects under its SRFME Collaborative Research Program to Western Australian research organisations in addition to the 3 SRFME Core Projects conducted by CSIRO.
- SRFME has increased Western Australia's marine research capability by increasing CSIRO's permanent WA based marine science staff complement from 4 to 25.
- SRFME has facilitated the training of 12 PhD students, many of whom have already graduated and found employment in WA universities and state government agencies or won overseas postdoctoral fellowships.
- SRFME established collaborative partnerships involving 10 different research organisations across the state and commonwealth governments and the university sector.
- Projects funded wholly or in part by SRFME have so far generated 140 publications (see Chapter 6 of SRFME Final Report Volume 1).
- SRFME held six well attended marine science symposia presenting the results of its research regularly to a wide audience.
- SRFME has produced an on-line interactive data and model output interrogation tool which has been distributed to Western Australia's state government natural resource management agencies.
- SRFME organised and hosted the First International Whale Shark Conference in Perth in May 2005. Delegates from 23 countries attended and the conference proceedings has been accepted for publication as a special issue of the journal *Fisheries Research.*

- SRFME helped fund the Twelfth International Marine Biological Workshop held in Esperance in February 2003. The outcomes of this workshop have produced a two volume proceedings containing 29 scientific papers on the marine flora and fauna of Esperance region.
- A set of 23 scientific papers about the Leeuwin current and its eddies have been submitted for publication in a special issue of the international journal *Deep Sea Research II*. This special issue has been edited by SRFME scientists.
- SRFME was awarded the CSIRO Go for Growth Award 2004 "For the successful promotion and implementation of a new direction in strategic environmental marine science in Western Australia.
- Tony Koslow was awarded an international prize; the Don McAllister Medal for Marine Conservation for contributions to the conservation of deepwater coral environments.
- SRFME has produced a high resolution climatology for temperature, salinity, nitrate, phosphate, silicate and oxygen off the Western Australian coast. From this climatology, the Leeuwin Current, the South Australian Current, and the Zeehan Current off western Tasmania are found to be joined into the longest eastern boundary current (5,500 km) in the world during the austral winter, which has an important effect on poleward transport of tropical biota along the west to south coast of Australia.
- SRFME has quantified the annual and ENSO-related interannual variations of the Leeuwin current. The average flow rate of the Leeuwin Current is about 3.4×10^6 m^3s^{-1}. The strength of the current varies by about a factor of 2 over the year, being weakest in summer, when it is opposed by southerly winds, and strongest in winter. It is also about 40% stronger during a La Nina year than during an El Nino year.
- SRFME has quantified the nature of the linear relationship between the Fremantle sea level and the strength of the Leeuwin Current, with 7.5 cm of sea level corresponding to 1 million m^3s^{-1} of flow. These results justify the wide use of the Fremantle sea level as an index for the Leeuwin Current.
- A SRFME project has found that since 1991, the annual sea level has increased at a rate of 5 mm per annum, a rate more than 3 times the trend over the previous 100 years.
- SRFME has calculated that the water temperature at coastal stations off WA rose by around 0.017 ºC per year over the last 50 years, consistent with the global temperature rise attributed to climate change. At the same time, salinity off the WA coast has also increased. There is also a clear suggestion of a lengthening warm season.
- BLUElink ReAnalysis (BRAN), is a global physical model, and has been run from 1992 to 2004, with 10 km resolution off the WA coast. These data sets provide valuable insights into climate-scale influences on the shelf and coastal dynamics, in particular as boundary conditions for SRFME modelling.
- The "Boxing Day tsunami" was captured by the tide gauge at SRFME Station A. A sharp rise in pressure of 0.3 db, equivalent to a 0.3 m rise in sea-level, occurred at about 1500 on 26 December 2004. Sea-level oscillations with a period of about 1 hour persisted for another two days.
- SRFME has shown that, inshore, in water depths around 20 m, currents follow the wind direction, principally north in the summer and south in the winter, with the water speed close to 3% of the wind speed. At 100 m depth, surface waters tend to follow the wind direction, while waters below 50 m flow south under the influence of the Leeuwin Current. Water temperatures are warmer inshore during the summer but, during the winter the Leeuwin Current keeps the offshore water warmer. In 100 m, the surface water is about 2 ºC warmer than the bottom, but the water is well-mixed during the winter.
- SRFME wave and sediment modelling, calibrated against measurement, suggest that the wave climate in southern coastal waters is sufficient to keep inshore sand mobile for most (> 60%) of the time, with an increase in winter.

- SRFME found that wave amplitude diminishes rapidly across reef platforms typical of south-western Australia, with measurements at Marmion showing 1/3 reduction within 1500 m.
- SRFME has shown how eddies form south of the Abrolhos Islands (29ºS) from meanders of the Leeuwin Current. The eddies are more intense when the Leeuwin Current is flowing strongest, in the winter and in La Nina years. Warm-core eddies drift from the shelf offshore and may persist for months. The eddy drift carries a volume of water roughly equivalent to flushing the southern shelf twice per year. The eddy-induced cross-shelf transport of productive water from the shelf to the open ocean may influence the western rock lobster recruitment process. The relationship between enhanced Leeuwin flow and eddy activity on shelf productivity may explain the positive correlation between Leeuwin flow and recruitment to the western rock lobster.
- The late-autumn and early-winter bloom appears to be at least partially explained by enhanced vertical mixing, and the transport, by eddies, of nutrient-rich water from the shelf. Both of these mechanisms have been demonstrated by simplified, 1-dimensional biogeochemical modelling and fully 3-d modelling. From satellite data, the offshore flux of phytoplankton biomass by warm-core eddies is estimated as equivalent to about 4×10^5 tonnes of carbon per year.
- The first detailed temporal study of biophysical oceanographic dynamics across the Perth continental shelf has revealed a marked contrast between summer and winter plankton dynamics. Low productivity and a deep chlorophyll maximum layer were observed in summer when the upper water column was strongly stratified. Increased Leeuwin flow and eddy activity in late autumn/early winter were associated with enhanced nutrient input to the upper mixed layer, a peak in primary production, increased phytoplankton concentrations and a shoaling of the chlorophyll maximum layer. Distinct onshore/offshore assemblages were found for all major pelagic groups: phytoplankton, microzooplankton, mesoplankton and ichthyoplankton.
- In a comparative study to map the larval abundance & health, and ecosystem structure of two eddies off the west coast of WA, a downwelling (“death-trap”) eddy, possibly dominated by N-fixation, and an upwelling (“nursery”) eddy, possibly dominated by upwelled nitrate, were discovered. The results from this work will be published in a special issue of Deep Sea Research.
- A new method was developed to assess, simultaneously, the grazing of micro- and mesozooplankton on phytoplankton assemblages.
- A rare protist (radiolarian *Coelodiceras spinosum*) was caught in a sediment trap placed within an upwelling eddy in 2003, and has only been identified in six locations globally, three of which are in the Southern Hemisphere. A total of 12 specimens have been identified and its description has not been updated since the original publication by V. Haecker in 1909.
- SRFME has provided one of the most detailed spatial and temporal studies of IOPs (inherent optical property) and AOPs (apparent optical property), for any marine area in Australia. This dataset will provide an excellent base for refining the standard algorithms of the current ocean colour sensors for use in southern Western Australia, thus providing an important tool for scientists and managers of this marine environment.
- At the Kingston Reef Sanctuary area on Rottnest Island, the population of rock lobster greater than minimum legal size has been shown to be more than ten times greater than in areas outside the sanctuary subjected to recreational fishing. Significant differences in the abundances and biomass of target and by-catch fish species (eg. Dhufish and Breaksea Cod) were also found between the sanctuary and adjacent areas open to fishing. Fish predation on grazing invertebrates such as urchins and snails was higher where fishing has reduced fish numbers. However, these differences do not presently appear strong enough to lead to the creation of “barren grounds” such as those that occur on other coasts in Australia and elsewhere worldwide.
- In a SRFME project on the biodiversity of marine fauna on the central west coast, four species of the isopod family Sphaeromatidae collected in this study have not before been recorded in Western Australia. Extended species ranges have been determined for nine

species of echinoderms found in the area: seven northwards from the Fremantle/Rottnest area and two southwards from Dongara and Shark Bay.

- In a “voyage of discovery” on the outer continental shelf and continental slope, WA Museum staff have discovered several new records and range extensions of mollusc species, as well as possible undescribed (new) species. These await investigation and confirmation. Such examples include the first record of a *Conus* species in Australia and a range extension and rare live specimen of *Austroharpa wilsoni* Rehder, 1973.
- Signficant progress has been made towards the ‘Seagrass Epiphyte Interactive Key’, by John Huisman. This is a list of known seagrass epiphytes (over 200 species) which will take the form of a interactive identification key on CD.
- SRFME scientists John Huisman, Julia Phillips and C Parker produced a 72 page booklet which is an illustrated guide entitled *Marine Plants of the Perth Region.*
- An introduced isopod species *Sphaeroma serratum* was found in high densities in the Jurien Bay marina.
- A new species of macroalgae, named Sargassum kendrickii was described by N. Goldberg and J. Huisman, and named after SRFME researcher and Sargassum expert from UWA, Dr Gary Kendrick.
- The extremely rare red alga *Gelidiella ramellosa* (Kützing) Feldmann & Hamel was found in SRFME specimens collected off Perth. This species was originally described from collections made over 150 years ago from Western Australia, and has not been found in the region since that time.
- In a pilot study, a seagrass species, *Amphibolis griffithii* and its epiphytes responded rapidly to severe, short-term reductions in light availability but the shoot- and meadow-scale responses allow the plant to respond rapidly to improved light conditions after a short period of time. This work will allow us to better predict and manage. the responses of seagrass meadows to the effects of dredging.
- The structure of reef algal communities in eastern Geographe Bay, the as well as their seasonal cycles, was found to differ strongly from that of other parts of the west coast, mainly as a consequence of seasonal sediment and detritus re-suspension.
- Modelling of wave climate at Jurien Bay indicated that almost 75% of the variation in species diversity of algae could be explained by the strength of the wave exposure. This has implications for the creation of representative systems of marine protected areas, as well as for the understanding the impacts of climate change and climate variation in the region.
- SRFME has described several characteristic algal community types and shown that some habitat types are much more important and widespread than previously thought. Many reefs are a patchwork of different algal communities, rather than being dominated by kelp forests. These findings may have important implications for our understanding of how reef ecosystems function.
- SRFME has characterised reef algal and invertebrate communities at sites from Jurien Bay to Cape Naturaliste. The character of these communities is largely similar along this gradient, justifying their inclusion in a single bioregion, but important differences were described at smaller scales.
- The role and importance of reef algae in marine food webs was shown to be disproportionately higher than that of seagrass. Importantly, because algae can be dislodged and drift many kilometres from their reef of origin, reefs can provide very important food subsidies for distant seagrass and sand habitats.

Publications arising from SRFME

While these two volumes of the SRFME Final Report summarise and some cases detail the extensive research activities undertaken by SRFME, there has been an extensive effort made to publish the findings from SRFME in the primary scientific literature. In addition, much of the extensive detail of projects that have been undertaken is included in a number of unpublished reports. Chapter 6 of this volume lists the 140 publications, reports and manuscripts which have arisen from SRFME and allied projects to date. While this listing includes some as yet unpublished manuscripts it is also an as yet incomplete listing of all the publications which will eventually arise from SRFME. More publications will be produced as SRFME students begin to write up more papers from the research included in their theses (Volume 1, Chapter 2). In addition, those yet-to-be-concluded SRFME Collaborative Projects (Volume 1, Chapter 3) will also give rise to more publications as will the research from the SRFME Core Projects described in Volume 2.

CHAPTER 1

1. INTRODUCTION

1.1 About SRFME

1.1.1 Role and Purpose of SRFME

SRFME is a 6-year (2001-2006), $20 million joint venture between CSIRO and the Western Australia Government. The State Government is represented in the joint venture by the principal agencies involved in marine resource development and conservation: Department of Fisheries, Department of Conservation and Land Management, Department of Environment, Department of Industry and Resources, and Office of Science and Innovation.

SRFME was established with the following high-level goals:

- Build capability and capacity in marine science in Western Australia (in particular through re-establishing CSIRO's marine research capacity in Western Australia and a postgraduate fellowship program)
- Facilitate strong collaboration among the Western Australian marine science community
- Conduct fundamental and strategic research that is of benefit to Western Australia and Australia

The most important characteristic of SRFME is that it has been established to invest in and carry out "strategic" research rather than "applied" or "tactical" research. A strategic approach allows us to gain a broad understanding of the WA marine ecosystem and in particular how it functions and varies over time.

With these goals and focus in mind, SRFME has invested in strategic research on the Western Australian marine environment in a way which enhances capability and capacity for marine science, encourages collaboration amongst the Western Australian research community and delivers strategic research outcomes which will have long- term benefits to the state.

As a result of this foundation SRFME adopted the following as its mission:

SRFME will enhance Western Australia's marine research capability and capacity, deliver strategic research outcomes of benefit to Western Australia and enhance collaboration among marine researchers in Western Australia.

1.1.2 Background to SRFME

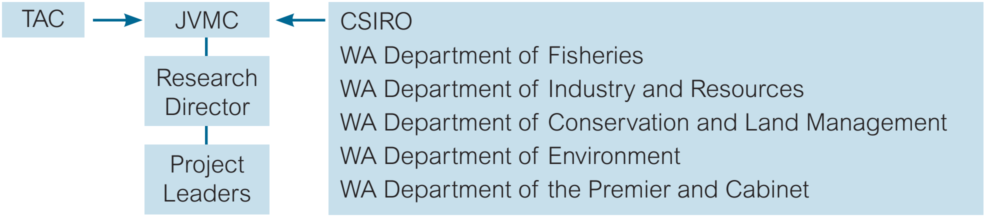
In July 1998 CSIRO approached the Western Australian Government and began a dialogue aimed towards strengthening CSIRO's presence in Western Australia. The State government formed the Marine Research Taskforce, which conducted a two-day workshop in October 1998 to identify the State's marine science priorities. The workshop involved over ninety representatives from peak industry bodies, research, academic and training institutions, community bodies and state and federal government agencies.

A major outcome of the workshop was a strong identification of the need for strategic research to support decision making for ecologically sustainable development and conservation in the marine environment. Additionally, the limited funding available to support such research was identified as a major constraint. In June 1999, the outcomes of the workshop were handed to the Coordination Committee on Science and Technology (CCST) by the Marine Research Taskforce for implementation and the CCST established a Marine Science Working Group to work with CSIRO to develop a solution to this funding situation.

In January 2000, the Western Australian Government agreed to jointly establish and manage the Strategic Research Fund for the Marine Environment (SRFME) with CSIRO. In July 2000, following the Western Australian Government's endorsement of the structural and administrative arrangements for the fund, a Joint Venture Management Committee was established with the immediate task of negotiating the Joint Venture Agreement. This Joint Venture Agreement was entered into on 4 January 2001 pledging $10 million from each of the joint venture partners over six years.

1.2 Structure and Governance of SRFME

SRFME is managed by a Joint Venture Management Committee (JVMC) made up of the joint venture partners. There is also a SRFME Technical Advisory Committee (TAC) with members having a high level of technical expertise in marine science also drawn from the joint venture partners.



1.2.1 SRFME Joint Venture Management Committee

The Joint Venture Management Committee (JVMC) comprises senior executives from each of the Department of Premier and Cabinet, Department of Conservation and Land Management, Department of Fisheries, Department of Environment, Department of Industry and Resources, and the Office of Science and Innovation; and the CSIRO Chief and Deputy Chief, Marine and Atmospheric Research. The role of the JVMC is to set the strategic direction for SRFME, approve the research portfolio and project investments, oversee the operations of SRFME and monitor its performance.

Joint Venture Management Committee (JVMC) Members

DR SUE MEEK (Chair) (2001-2002)	Head, Science and Technology, Department of Commerce and Trade
DR BRUCE HOBBS (Chairman) (2003-2004)	Chief Scientist and Executive Director, Office of Science & Innovation, Department of Premier & Cabinet
MR PHILLIP MURRAY (Chairman) (2004-2006)	Manager, Science Policy, Office of Science, Technology and Innovation, Department of Industry and Resources
DR CHRIS SIMPSON (2001-2006)	Manager, Department of Marine Conservation, Conservation & Land Management
DR PAUL VOGEL (2001-2002)	Department of Environment and Water Catchment Protection.
DR RAY MASINI (2003-2006)	Manager of Marine Management & Protection, Department of Environment
MR PETER MILLINGTON (2001-2006)	Director of Fisheries Management Services, Department of Fisheries WA
MR RICHARD CRADDOCK (2001-2004)	General Manager, Safety & Environment, Petroleum Division, Department of Industry and Resources
MR GRAHAM COBBY (2005-2006)	Director, Environment Division, Department of Industry and Resources
DR NAN BRAY (2001-2002)	Chief of Marine Research, CSIRO
DR TONY HAYMET (2003-2005)	Chief of Marine and Atmospheric Research, CSIRO
MR JOHN GUNN (2005-2006)	Deputy Chief, Research, Marine and Atmospheric Research, CSIRO
DR PAUL WELLINGS (2001)	Deputy Chief Executive, CSIRO
DR IAN POINER (2001-2004)	Deputy Chief, Research, Marine Research, CSIRO
MR TIM MOLTMANN (2004-2006)	Deputy Chief, Business, Marine and Atmospheric Research, CSIRO
DR JOHN KEESING	Research Director, SRFME
MS LINDA PENNY (Observer)	Senior Policy Officer, Office of Science & Innovation, Department of Premier & Cabinet
MS LUCY KAY (Secretary)	PA to the Research Director, SRFME

1.2.2 SRFME Technical Advisory Committee

This committee comprises the Project Leaders and technical experts from the relevant State Government agencies and CSIRO, and is chaired by the SRFME Research Director. The role of the TAC is to provide technical scientific advice to the JVMC and to review of project proposals.

Technical Advisory Committee (TAC) Members

DR JOHN KEESING (Chairman)	Research Director, SRFME
DR ALAN BUTLER (2001-2002)	SRFME Project Leader, CSIRO
DR PETER THOMPSON (2001-2002)	SRFME Project Leader, CSIRO
DR PETER CRAIG	SRFME Project Leader, CSIRO
DR RUSS BABCOCK	SRFME Project Leader, CSIRO
DR TONY KOSLOW	SRFME Project Leader, CSIRO
DR JIM PENN	Director, Fisheries Research, Department of Fisheries, WA
DR DES MILLS	Principal Environmental Officer, Department of Environment
DR NICK D'ADAMO	A/Manager Senior Oceanographer, Marine Conservation Branch, Dept of Conversation & Land Management
MR GRAHAM COBBY (2001-2003)	Manager, Safety & Environment, Department of Industry and Resources
MS KIM ANDERSON (2003-2006)	Manager, Safety & Environment, Department of Industry and Resources

1.2.3 SRFME Research Director and Project Leaders

The day to day management of the SRFME Joint Venture is carried out by the SRFME Research Director who reports to the JVMC. Project Leaders are responsible for the conduct of projects funded by SRFME and report on the performance of those projects through the SRFME Research Director to the SRFME JVMC.

1.3 The SRFME Framework and Research Portfolio Structure

1.3.1 The SRFME Framework

Research carried out through funding from SRFME has been focused within a framework of priorities developed by the CSIRO together with Western Australian government researchers, marine resource managers and academics. This framework was developed over a two-year period during the planning period leading up to the beginning of SRFME.

The SRFME Framework consisted of two components; a framework of priority research outcome areas and a framework of relative emphases.

The five areas in the framework of priority research outcome areas were:

1. Broad scale oceanography – where the aim is to develop enhanced understanding of Indian Ocean oceanographic processes, which may lead to benefits in greater understanding of:

- fisheries recruitment processes
- climate variability and rainfall prediction
- slope and deep ocean currents
- regional interconnectedness
- continental shelf circulation characteristics

2. Continental shelf and coastal processes – these studies should lead to an improved understanding of the marine ecosystem providing a number of benefits in relation to:

- sustainable management of areas of high productivity
- regional interconnectedness with relevance to MPAs
- fisheries recruitment processes
- catchment-related impacts
- cumulative impacts of human activity

3. Living marine resource inventories – this priority area acknowledges the importance of biodiversity studies and will provide increased information about:

- broad scale benthic habitats and marine flora and fauna distributions
- surrogates for measuring biodiversity which can lead to benefits in:
  - managing impacts in multiple use environments
  - site selection for aquaculture or industry development
  - fine scale mapping of areas of specific interest; and to,
  - assist with identification of marine protected areas

4. Baseline monitoring and defining natural variability of ecosystem function and change over time - will be important in order to:

- develop or identify appropriate natural variability parameters/indicators which are representative of key values or processes
- design and implementation of cost-effective systems to monitor these parameters in areas representative of undisturbed ecosystems and bioregions in the state.

5. Planning tools for Ecologically Sustainable Development – improved decision-making for agencies will be facilitated by the planned strategic research which will form the basis for the development of user-friendly and reliable management and decision-making tools.

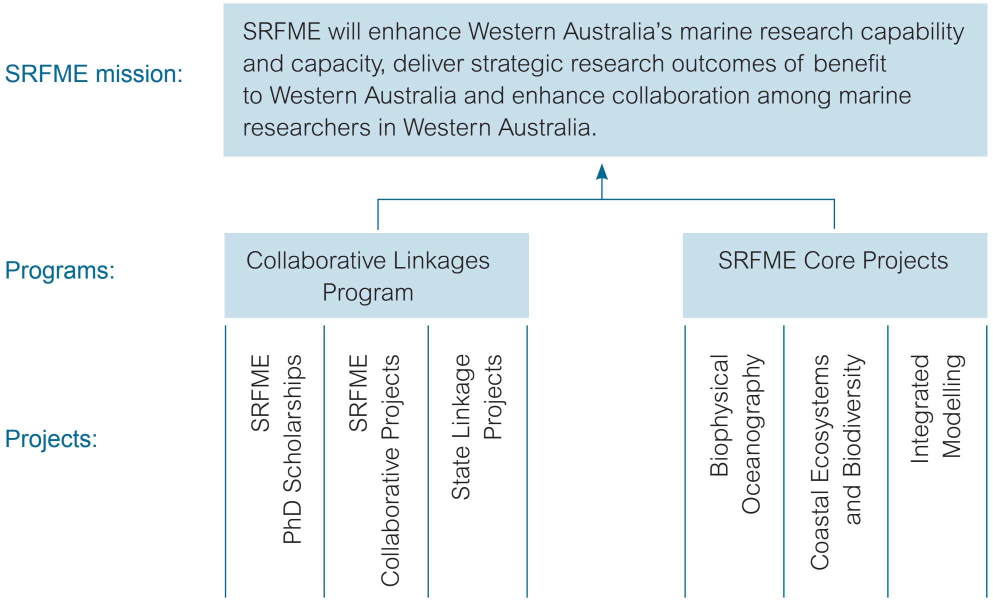
The framework of relative emphases consisted of the following:

- A relative emphasis between the five priority research outcome areas favouring Biological Inventory/Baselines (50-70%), Continental Shelf and Coastal Processes (10-30%), Broadscale Oceanography (5-15%) and Management Tools (5-15%).
- A geographic emphasis favouring the south coast through to the Gascoyne for Biological Inventory, Baselines and research on Continental Shelf and Coastal Processes.
- A relative emphasis extending seaward from the coastline that favoured about 50% of the effort in coastal waters less than 50 m deep, 30% on the continental shelf and 20% offshore.
- A relative emphasis along “measurement-understanding–prediction” continuum which favoured a predictive focus on projects with a primarily physical focus and an emphasis favouring measurement or new observations for primarily biological projects. Understanding physical and biological processes was given equal emphasis.
- A relative emphasis favouring physical studies on pelagic ecosystems and biological studies on benthic ecosystems.

It is within this framework that the SRFME research portfolio was developed.

1.3.2 SRFME Research Portfolio Structure

SRFME’s research portfolio is structured around a Collaborative Linkages Program and Core Projects Program, which each have three projects or schemes.



SRFME will enhance Western Australia’s marine research capability and capacity, deliver strategic research outcomes of benefit to Western Australia and enhance collaboration among marine researchers in Western Australia.

1.4 Collaborative Linkages Program

The SRFME Collaborative Linkages Program seeks to build on existing research activities in Western Australia and to complement the SRFME Core Projects in ways which strengthen the breadth (both scientifically and geographically) of research outcomes from SRFME. The following are the main components of the collaborative linkages program.

1.4.1 SRFME PhD Scholarships

The SRFME Research Portfolio provides for the award of scholarships for full time postgraduate research leading to the award of a PhD by research at one of Western Australia's four publicly funded universities. The SRFME PhD Scholarship scheme has had the objective of strengthening and broadening the outcomes from SRFME Core projects, engaging the marine research capacity of WA Universities in SRFME and encouraging collaboration between Universities and scientists/managers in Commonwealth and State Government agencies.

The PhD scholarship scheme involves SRFME and WA universities co-investing in 15 PhD stipends and operating funds to a total value of about $1.2 million. SRFME's investment into the scheme was about $650,000 with WA universities contributing the balance in stipend, operating and supervision costs. Many of the students who are carrying out the work towards a PhD degree are co-supervised by CSIRO scientists and staff from state research and management agencies.

SRFME has held three annual symposia where the SRFME PhD Scholars presented results on the progress of their projects.

1.4.2 SRFME Collaborative Research Projects

The other major component of the Collaborative Linkages Program is the SRFME Collaborative Research Projects scheme which invested about $2 million in projects which tackle interdisciplinary projects in a collaborative way and add to the realisation of capacity building goals of SRFME by providing opportunities for the appointment of Post-doctoral scientists.

Among the objectives of the SRFME Collaborative Research Projects were to address the gaps in the JVMC Framework not addressed by the Core SRFME Projects, leverage greater funding and research capacity for the SRFME research portfolio and to strongly engage with state and commonwealth research organisations, WA Universities and the private sector. The total value of the SRFME Collaborative Research Projects is about $4.3 million including coinvestment by SRFME's research partners, collaborators and the private sector. Some of these projects are still ongoing and will finish in 2007.

1.4.3 State Linkage Projects

The final component of the SRFME Collaborative Program is the State Linkage Projects scheme. SRFME invested $155,000 in this scheme with the objective of enabling WA State Government agencies to engage actively in SRFME through small projects which link new or existing initiatives to other parts of the SRFME Research Portfolio.

1.5 SRFME Core Projects

The largest components of SRFME are the SRFME Core Projects. These were established to enable SRFME to achieve its principal objective which was to deliver an enhanced marine research capability to Western Australia through re-establishing CSIRO's marine research capability in Western Australia by relocating and recruiting 20 CSIRO marine research staff to Western Australia and by funding the capacity to carry out research by both CSIRO and other Western Australia research providers. SRFME Core Projects were carried out at a cost of $15.3 million.

1.5.1 Development of the SRFME Core Projects

Core Project outlines were developed by CSIRO and considered by the Technical Advisory Committee. Projects developed were to be non-sectoral with research outcomes directed primarily at ensuring the strategic information requirements of the Western Australian Government were met. Projects were not to be developed for which existing dedicated funding mechanisms were in place or where the research would be more appropriately funded by other funding mechanisms. Additionally, it was determined that projects chosen must meet three criteria approved by the WA Government. These were that projects must be of high priority to the Western Australian Government *and* of high priority to CSIRO *and* best undertaken through a local CSIRO presence in WA. Through an iterative process spanning the period from July 2000 to May 2001, the projects were refined to an extent that they were broadly consistent with the strategic priorities for the WA Government priorities within the SRFME framework and delivered a strong CSIRO research capability into Western Australia which complements rather than duplicates existing capability. The process of developing Core Projects was completed on 22 May 2001 and is documented in Anon (2001).

1.5.2 Biophysical Oceanography Core Project

The Biophysical Oceanography project sought to characterise the continental and shelf/slope pelagic ecosystem off south-western Western Australia: its productivity and dynamics, and the physical, chemical and biological factors driving spatial and temporal variability.

1.5.3 Coastal Ecosystems and Biodiversity Core Project

The Coastal Ecosystems and Biodiversity project was established to characterise the coastal benthic ecosystems of south-western Western Australia, with a particular focus on benthic reef ecosystems, their productivity and dynamics, and the physical, chemical and biological factors driving variability on a range of spatial and temporal scales.

1.5.4 Integrated Modelling Core Project

The Integrated Modelling project was developed with the objective of working closely with the other SRFME Core Projects to provide quantitative descriptions of the Western Australian and shelf ecosystems that will assist environmental managers to predict and monitor natural and human induced change.

CHAPTER 2

2. COLLABORATIVE LINKAGES PROGRAM: PhD PROJECTS

2.1 SRFME PhD Scholarship Program

The objective of this program is to deliver strategic research outcomes and capacity building through postgraduate training. A total of $650,000 has been awarded to the funding of fifteen scholarships, which started in 2002 and 2003, and of these, twelve scholars remained enrolled during SRFME, including two at Curtin University, two at Edith Cowan University, two at Murdoch University, and six at the University of Western Australia.

Three SRFME scholar symposia have been held at the Floreat Centre for Environment and Life Sciences of CSIRO, in June 2003, 2004, and 2005. At these symposia, each student presented an up-to-date account of their research activities. To date, seven PhD scholars have completed their degrees. The remainder of the students plan to submit their theses in 2007.

2.2 SRFME PhD Projects, Students, and Affiliations

1. Morphological responses of seagrass meadows to light limitation and their application to environmental quality criteria. Catherine Collier, Edith Cowan University.
2. The role of detached macrophytes for fish production & biodiversity in coastal ecosystems. Karen Crawley, Edith Cowan University.
3. Use of surrogates for the rapid assessment of marine biodiversity. Nisse Goldberg, University of Western Australia.
4. Biogeochemical processes in seagrass sediments. Kieryn Kilminster, University of Western Australia.
5. The development and validation of algorithms for remotely sensing case II waters. Wojciech Klonowski, Curtin University.
6. Temporal and spatial variation of sediment composition, redox potential and benthic photosynthesis in semi-enclosed coastal embayments subject to different catchment loading regimes. Alicia Loveless, University of Western Australia.
7. Remotely sensing seasonal and interannual oceanic primary production for WA waters. Leon Majewski, Curtin University.
8. Ichthyoplankton assemblage structure in coastal and shelf waters off Western Australia. Barbara Muhling, Murdoch University.
9. The Biophysical Oceanography off Western Australia: Microzooplankton. Harriet Paterson, University of Western Australia.
10. Physical and chemical forcing of primary production in shallow coastal waters off southwestern WA. Florence Verspecht, University of Western Australia.
11. Comparisons of benthic macroinvertebrate communities in marine environments and nearby estuaries in south-western Australia. Michelle Wildsmith, Murdoch University.
12. The influence of microphytobenthos on nitrogen cycling in sediments. Hugh Forehead, University of Western Australia.
13. Uncertainty associated with alternative ecosystem representations. Sara Belmont, Murdoch University (withdrawn).
14. Enhancing zooplankton and micronekton biomass estimation and size and species classification based on acoustic remote sensing. Chris Van Etten, Curtin University (withdrawn).
15. Investigation of the cycling of trace metals and metalloids as contaminants in WA coastal ecosystems. Yi Yuan, Murdoch University (withdrawn).

2.2.1 Responses of the seagrass *Posidonia sinuosa* to light reduction: A mechanistic approach

Investigator / Institution

Catherine Collier	Faculty of Computing, Health and Science, School of Natural Sciences, Edith Cowan University

Supervisors

Prof. Paul Lavery, Dr Ray Masini, Assoc. Prof. Peter Ralph
Edith Cowan University

Introduction

Seagrasses are demonstrably sensitive to light reduction which induces a range of responses at the physiological level followed later by morphological changes (Longstaff et al. 1999) in order to achieve a balance between carbon gains and losses. These are usually insufficient to completely offset the effects of light reduction and reduced growth and eventually seagrass loss results. Seagrasses occur in a variety of forms with different growth and reproductive strategies and models have been developed which aim to predict response according to these but are based on disparate data and remain untested (Walker et al. 1999). The dominant seagrass species in Cockburn Sound, *Posidonia sinuosa,* has slow growth rates and a poor capacity to recover following loss (Fitzpatrick & Kirkman 1995) therefore the processes enabling its tolerance to reduced light is crucial to enable its survival. Management frameworks, such as the State Environment (Cockburn Sound) Policy 2005, aim to preserve the integrity of marine ecosystems including seagrasses. Due to their sensitivity to disturbance, such as light reduction, and ecological importance they form the basis of coastal health indicators, but sensitive seagrass parameters that explicitly link their response to a cause are required to bring about management actions. Knowledge of the mechanisms to endure light reduction is central to the positive identification of reliable monitoring tools that identify an effect of light reduction.

Aims

1. Explore a range of *P. sinuosa* attributes (both physiological and morphological) down a depth gradient in order to infer responses to long-term light reduction.
2. Monitor the rate and sequence of *P. sinuosa* responses to imposed light reduction and monitor recovery following return to ambient light conditions.
3. Trace the movement of carbon and nitrogen through seagrass plants during shading to identify the importance of translocation and clonal integration for shade tolerance.
4. Assess the appropriateness of currently employed seagrass indicators of light reduction and derive (if appropriate) a suite of complementary indicators for use in monitoring programs.

Major Findings

1. Morphological and physiological characteristics of *Posidonia sinuosa* along a depth-related gradient of light availability

The first research phase examined a range of physiological and morphological parameters down a depth gradient in Cockburn Sound and Warnbro Sound. The minimum light requirement (MLR) of *P. sinuosa* determined from one year of on-going light monitoring was 8.5% of sub-surface light. Shoot density and biomass exhibited the greatest differences between the depths sampled, reducing by 61-fold from the shallow (>1500 shts m^{-2}) to deep sites (<30 shts m^{-2}) and conformed to *a priori* expectations (Fig 2.1A). Its slow growth rate (compared to other species) did not reduce with depth in summer and in winter differed only between the shallowest and all other depths (Fig 2.1B) while morphological parameters such as canopy height and leaf width demonstrated far more complex differences as the differences observed were dependant on sampling time or location. Some physiological parameters examined, such as carbohydrate concentration in the rhizome but not leaves, showed seasonal variation but little difference between depths (Fig 2.1C). Of the pigments analysed, antheraxanthin (a product of the photoprotective mechanism), was reduced in winter but there was no significant difference between depths. Total Chlorophyll concentration and chlorophyll *a*/*b* ratio as well as a number of photosynthetic parameters showed no consistent pattern between depths, being dependant on a combination of site and season sampled (Fig. 2.1D). This study highlighted that shoot density is the parameter most consistently affected by depth for *P. sinuosa*. This probably allows the long-term persistence of this species at deeper sites by reducing self-shading effects of the canopy and the respiratory load of leaves. Validation that these observations reflect differences in light availability between depths required experimental manipulation of light availability (shading).

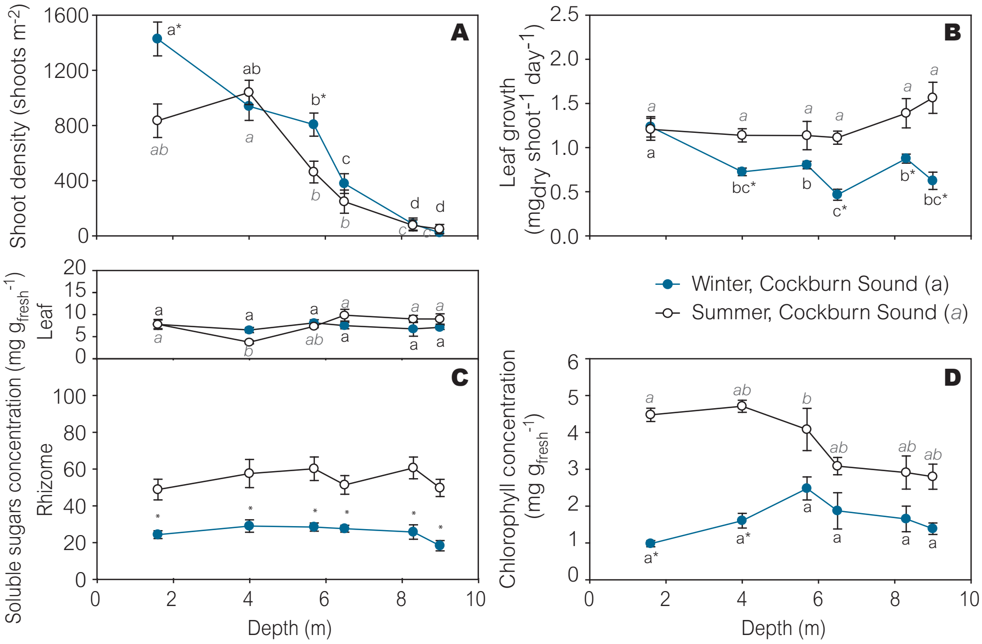


Figure 2.1: Shoot density (A), leaf growth (B), soluble sugar concentration in leaf and rhizome material (C) and total chlorophyll concentration (D) at six depths in Cockburn Sound in winter 2002 and summer 2002-2003. n=12 (A) and n=6 (B-D) ±SE. Values with the same letter are not significantly different at $p<0.05$. Dark letters are for winter (a), grey italicized letters are for summer values (*a*). * denotes a significant effect of season.

2. Shade induced response and recovery of *Posidonia sinuosa*

In situ shading including light (LS; receiving 81% of control), moderate (MS; 28%) and heavy shade (HS; 9%) were applied at two depths in Cockburn Sound in early spring 2003; HS at the shallow and MS at the deep sites were below MLR. Only data for the shallow site are shown below. Within 106 d, shoot density was reduced in the MS and HS treatments and after 206 d 38% (MS) and 6% (HS) of shoots still remained. Shoot loss reduced the attenuation co-efficient of the canopy from 2.8 m^{-1} in the control to 0.5 m^{-1} in the HS, reducing the effects of self-shading and therefore shoot loss is considered a meadow-scale response. Carbohydrates in the rhizome increased within the first 15 d of shading (seasonal accumulation cycle) and continued increasing over summer and autumn in the control but were then reduced in all shade treatments after 106 d, probably to supplement growth and respiration (Fig. 2.2D).

Recovery of the carbohydrates began in the LS and MS treatments after 106 d, coinciding with shoot loss in the MS. In MS the meadow-scale response (shoot loss) acted to offset changes in the light environment and few other physiological and morphological responses were observed; instead, these responses were the most pronounced in treatments below MLR (HS at the shallow and MS at the deep site). For example, photosynthetic characteristics demonstrated a shade response including reduced relative maximum electron transport rate ($rETR_{max}$) in HS (Fig 2.2C). Leaf growth per shoot again remained unaffected by light reduction (Fig 2.2B), although meadow-scale growth was significantly reduced.

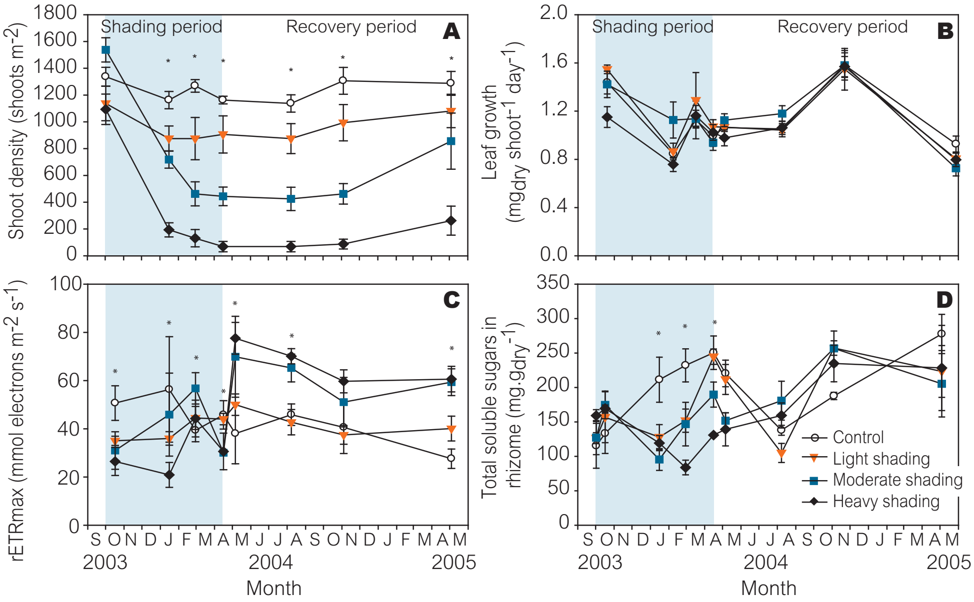


Figure 2.2: Shoot density (A), leaf growth (B), $rETR_{max}$ (C) and rhizome sugars (D) in Cockburn Sound during a shading and recovery period. n = 4 ± SE. *denotes significant difference between treatment at each time.

Shoot density showed signs of recovery after 384 d without shade but the MS and HS still remained significantly lower than the control (Fig. 2.2A). Recovery of the meadow is dependant largely on vegetative reproduction from live shoots (*P. sinuosa* has low flowering density) and recovery rate was related to remaining shoot density i.e. lowest shoot density equated to a slower shoot production rate. A number of physiological characteristics demonstrated a rapid response to removal of shade screens including $rETR_{max}$ which showed a high-light response (Fig 2.2C). This was attributed to: 1) a return to ambient light levels above the canopy; and 2) increased light penetration through the canopy resulting in measurably higher light at the bottom of the canopy in the shade pre-treatments. Carbohydrates in HS reached concentrations equal to the control in winter after 115 d of recovery. These data indicate that some shoot-scale responses occur (e.g. carbohydrates and photosynthetic characteristics below MLR) but for *P. sinuosa*, shoot-scale responses to light availability are less pronounced and consistent than meadow-scale responses (shoot loss), a finding consistent with our earlier field observations for this species (previous section).

3. Shade effects on carbon and nitrogen translocation in *P. sinuosa*

Nutrient transfer from mature leaves (ML) to young growing leaves (YL) during the early shade response of *P. sinuosa* was investigated. The ML of shoots with one ML and YL (~10cm long) was incubated *in situ* in a solution of $^{13}CO_3$ and $^{15}NH_4^+$. After 2 h the majority of ^{13}C was found in the ML (94-98%) (Fig. 2.3A). The total mass of ^{13}C within the shoot (ML + YL + rhizome) did not reduce throughout the 29 d experiment, although the percentage of ^{13}C in the YL + rhizome continued to increase while decreasing in the ML (Fig 2.3A). After 29 d there was more ^{13}C in the YL than the rhizome (Fig. 2.3B&C); they contained 36-44% and 20-21%, respectively of the total in the shoot with over half of the C taken up by the ML being exported. These results indicate that within a shoot, the transfer of newly incorporated C (and N), from the ML to the YL is important for subsidizing growth requirements of the YL, but that shading does not lead to a significant increase in the contribution of C from the ML to the YL as hypothesised.

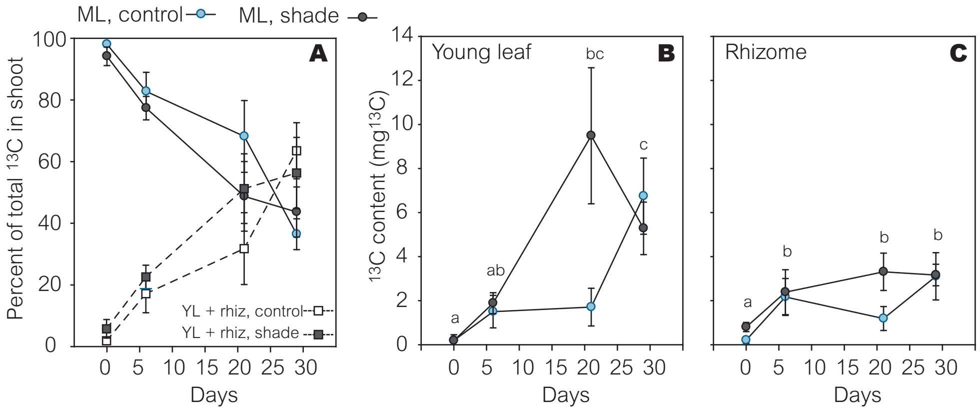


Figure 2.3: A) Percentage of the total shoot ^{13}C excess in the mature leaf (ML) and young leaf (YL) + rhizome, and B) total ^{13}C excess in the YL and C) total ^{13}C in the rhizome, in control and shaded treatment throughout the 29 d experiment. n=4, ± SE. Values with the same letter are not significantly different.

To determine nutrient translocation to shoots towards or away from the rhizome apex and the effects of shade on this process, a whole shoot (aiming for the 5th shoot back from the apex) was incubated *in situ* in $^{13}CO_3$ and $^{15}NH_4^+$ for 4 h. After 8 and 15 d, the whole seagrass plant was collected, aiming for four shoots forward and four back from the labeled shoot. There was more C translocation in ramets (shoot + rhizome) back from the labeled shoot than towards the rhizome apex (Fig. 2.4A), while for N there was no significant effect of direction. Of the total C retrieved, the majority was found in the rhizome (55-89%) of control and shade plants (Fig. 2.4B). This suggests that at the time of the experiment (January), C reserves develop, consistent with our earlier findings in which carbohydrates accumulated during summer (Fig. 2.2D). In the early shading phase (1-1.5 mo), light reduction does not appear to affect this process.

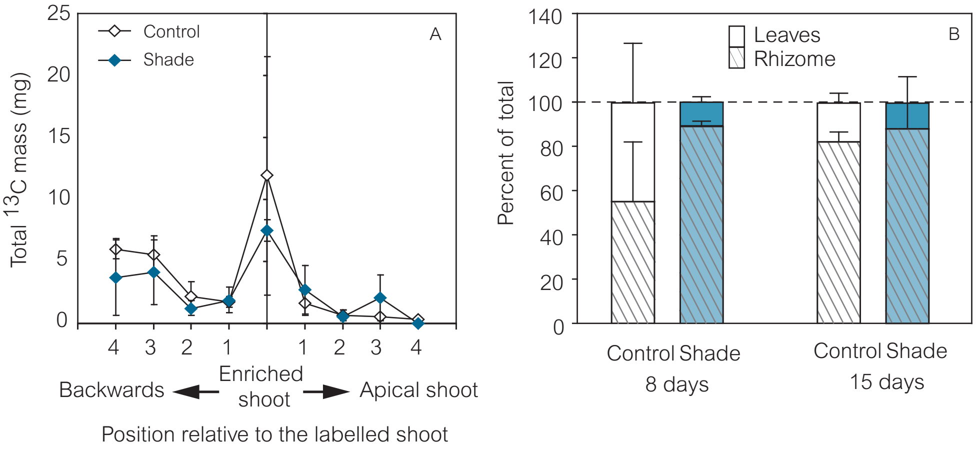


Figure 2.4: (A) ^{13}C mass of ramets (shoot + adjacent rhizome) of *P. sinuosa* towards and back from the rhizome apex 8 d after labeling and (B) percent of ^{13}C retrieved in the shoots (blank) or rhizome (diagonal lines) in control (white) and shaded conditions (grey) 8 and 15 d after labeling.

Summary and Conclusions

This study has significantly progressed our understanding of the response mechanisms of seagrasses, with particular reference to *P. sinuosa* and significantly contributed to our capacity to carry out effective knowledge-based monitoring. *P. sinuosa* forms dense meadows which create intense self-shading. The dominant response was shoot reduction in response to long-term light reduction (depth gradient) and short-term imposed shading. As this reduces self-shading this can be considered a meadow-scale response, but is also likely to reduce respiratory consumption. At light levels above minimum light requirements (MLR) (along the depth gradient and light and moderate shade (at the shallow site), few other responses consistently occur in *P. sinuosa* (Fig 2.5) with reduced shoot density appearing to off-set light reduction above the canopy. Below MLR (heavy shade and below depth limit) other morphological and physiological responses become more pronounced, but eventually complete shoot loss will result. Carbohydrate reserves are important for supplementing growth and respiration during shading and seasonal cycles of light reduction and are likely to enable *P. sinuosa* to survive considerable periods of light reduction (>206 d). Shoot density emerged as the most appropriate indicator of light reduction as it responds consistently and is central to the response mechanism of *P. sinuosa*, while other physiological responses (e.g. carbohydrate concentration) also have potential as indicators of short-term light reduction.

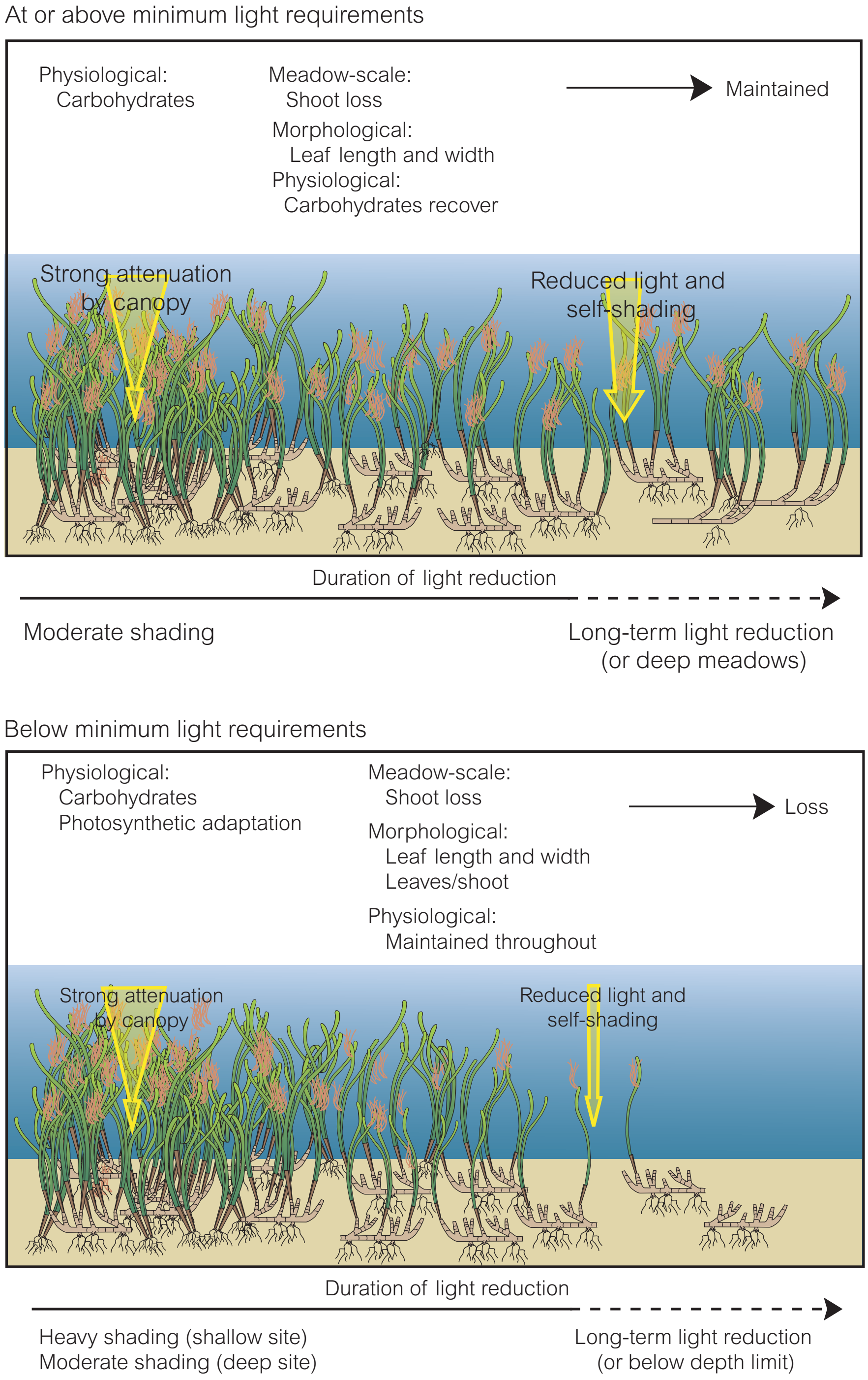


Figure 2.5: Conceptual illustration of *P. sinuosa* responses to light reduction to levels that are at or above minimum light requirements (left) or below minimum light requirements (right).

Thesis submitted March 2006 and PhD subsequently awarded.

Courses attended

Transmission Electron Microscopy and Optical Microscopy at UWA 2003, Name that Seaweed Murdoch University February 2004.

Conferences attended

International Seagrass Biology Workshop (ISBW5) 2002 Ensenada, Mexico; SRFME Symposium 1; AMSA July 2003 Brisbane Australia; SRFME Symposium 2; AMSA WA Student workshop June 2004; ISBW6 2004 Townsville Australia; SRFME Symposium 3

Awards

Awards for seminars: SRFME 2003 Award for presentation; SRFME 2004 Award for presentation; International Seagrass Biology Workshop (ISBW) 2004 Excellence award for presentation; and SRFME 2005 Award for presentation.

Funding awards: SCUBA equipment funding from Centre for Ecosystem Management (CEM) at ECU 2002; Travel award from CEM to attend AMSA in Brisbane 2002; Equipment support for underwater light loggers from CEM 2003; Equipment support for laboratory equipment from CEM 2004; Travel award for travel to ISBW 6 from ISBW6 and from CEM; Travel award from CEM to visit laboratories in Spain; Postgraduate Completion Scholarship awarded by the Faculty of Computing, Health and Science ECU 2005.

Publications

Collier, C.J., Lavery, P.S., Masini, R.J., Ralph, P.J. (in press) Morphological characteristics of the seagrass *Posidonia sinuosa* along a depth-related gradient of light availability. Submitted to Marine Ecology Progress Series.

Mackey, P., Collier, C.J., Lavery, P.S. (in press) Effects of experimental reductions in light availability on the seagrass *Amphibolis griffithii*. Submitted to Marine Ecology Progress Series.

Collier, C.J., Lavery, P.S., Ralph, P.J. Masini, R.J., (in prep.) Physiological characteristics of the seagrass *Posidonia sinuosa* along a depth-related gradient of light availability.

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Longstaff BJ, Loneragan NR, O'Donohue MJ, Dennison WC (1999) Effects of light deprivation on the survival and recovery of the seagrass *Halophila ovalis* (R.Br.) Hook. Journal of Experimental Marine Biology and Ecology 234:1-27

Walker DI, Dennison WC, Edgar G (1999) Status of Australian seagrass research and knowledge. In: Butler A, Jernakoff P (eds) Seagrass in Australia; Strategic review and development of an R & D plan. CSIRO Publishing, Victoria

2.2.2 Detached macrophyte accumulations in surf zones: significance of macrophyte type and volume in supporting secondary production

Investigator / Institution

Karen Crawley School of Natural Sciences, Edith Cowan University

Supervisor

Dr Glenn Hyndes School of Natural Sciences, Edith Cowan University

Executive summary

Detached seagrasses and macroalgae (wrack) are transported from more offshore areas and accumulate in large volumes in surf zones. This study investigated how wrack transported from one habitat to a second habitat can be considered as a spatial subsidy for the recipient habitat, with significant consequences for community dynamics and food webs (Polis and Hurd 1996, Polis *et al*. 1997). The primary aim of this study was to determine the significance of the different components of wrack (i.e. seagrass and brown, red and green algae) as a direct and indirect food source and habitat for invertebrates and fish in surf zones of south-western Australia. The importance of different volumes of surf zone wrack on fish abundance and composition was also investigated. These aims were achieved by examining the food and habitat preference of invertebrates and the habitat preference of fish through laboratory trials and field experiments, as well as stable isotope, fatty acid and lipid class analysis. The dominant macroinvertebrate in surf zone wrack, the amphipod *Allorchestes compressa* showed a preference for consuming brown algae. Stable isotope and lipid analyses also indicated that *A. compressa* assimilates nutrients predominantly from brown algae, which in turn are consumed by second-order consumers, particularly juveniles of the fish species *Cnidoglanis macrocephalus* (cobbler) and *Pelsartia humeralis* (sea trumpeter). *Allorchestes compressa* showed a strong preference for different types of detached macrophytes as a habitat, with seagrass ranking below other types of macrophytes in the field. In contrast, neither *C. macrocephalus* or *P. humeralis* showed a preference for inhabiting different types of detached macrophytes, but were strongly influenced by the volume of wrack in the surf-zone. The study revealed that both the type and volume of detached macrophytes in surf zones subsidizes consumers and plays a crucial role in supporting secondary production in less productive surf-zone habitats of south-western Australia.

Introduction

Accumulations of detached macrophytes within nearshore surf-zones and on beaches are commonly referred to as wrack (Kirkman and Kendrick 1997). Detached macrophytes can be an important source of food and habitat for juveniles of some fish species, and their invertebrate prey (Robertson and Lucas 1983). In south-western Australia, wrack comprises a mixture of seagrasses and macroalgae (Hansen 1984). The broad objective of this study was to investigate the links between detached macrophytes, invertebrates and fish in terms of food supply and habitat, in particular, to determine the role of different types of wrack (i.e. seagrass, brown, red and green algae) as a habitat and food source for fish and invertebrates in nearshore waters. The influence of different volumes of surf-zone wrack on fish abundance and composition was also investigated.

Invertebrate research

Aims and objectives

The focus of the invertebrate research for this study was on the semi-aquatic amphipod

Allorchestes compressa, which in south-western Australia constitutes more than 90% of the macroinvertebrate fauna and is one of the main prey of juvenile fish in wrack habitats (Robertson and Lucas 1983; Robertson and Lenanton 1984). The aim was to determine the habitat and food preference of *Allorchestes compressa* for different types of macrophytes. The plant type(s) that contribute most to the detached macrophyte – amphipod – fish food chain in nearshore regions in south-western Australia was also investigated.

Methods and study sites

A habitat preference experiment was conducted using different types of detached macrophytes in aquaria. To test which type of macrophyte *Allorchestes compressa* uses as a habitat in the field with the presence of fish predators, an experiment was conducted with different types of detached macrophytes contained in cages in surf-zone wrack at Two Rocks and Shoalwater Bay in south-western Australia.

A feeding preference experiment offering different species of detached macrophytes to *A. compressa* over four days was carried out in the laboratory. To investigate which types of wrack *A. compressa* consumes and assimilates, samples of detached macrophytes, *A. compressa* and 2 key fish predators (sea trumpeter and cobbler) were collected at 3 sites (Two Rocks, Hillarys and Shoalwater Bay) for biomarker analysis. The samples were analysed for stable isotopes ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$), as well as fatty acids and lipid classes. The stable isotope values ($\delta^{13}C$ and $\delta^{15}N$) of *A. compressa,* after being fed on different plant types under controlled conditions, were also investigated to determine the expected enrichment between *A. compressa* and different types of wrack (both fresh and decomposed plant material) over 3 weeks. Plant material and amphipods were subsampled weekly to determine how these signatures change over time.

Fish research

Aims and objectives

The aim of this aspect of the research was to determine the influence of different volumes of surf-zone wrack on fish abundance and composition in surf zones of south-western Australia. Habitat preferences for two of the dominant fish species in beaches containing wrack, namely the cobbler *Cnidoglanis macrocephalus* and the sea trumpeter *Pelsartia humeralis* (Robertson and Lenanton 1984), were also investigated.

Methods and study sites

Fish were sampled in surf zones using a 21 metre long seine net in nearshore areas containing high, medium or low volumes of wrack, as well as in bare sand areas at both Hillarys and Shoalwater Bay. The data were analysed using nMDS ordinations and Analysis of Variance (ANOVA). A habitat preference experiment was conducted in a series of outdoor aquaria. Different types of macrophytes (i.e. seagrass only, brown algae only and a mixture of both types) were placed at either end of aquaria and the number of fish in each plant type recorded at the end of each trial. Data analyses from this experiment were performed using a non-parametric goodness of fit binomial test.

Results

Invertebrate research: Results of the habitat preference trials revealed that *Allorchestes compressa* prefers seagrass as a habitat under laboratory conditions. However, in contrast to those laboratory trials, *A. compressa* showed a strong preference for either brown algae, red algae or a mixture of different types of plants over seagrass as a habitat in the field (Figure 2.6).

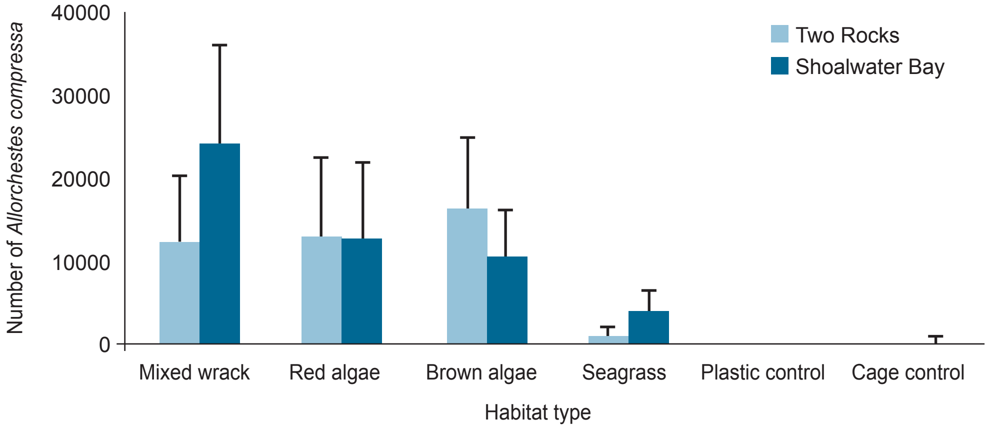

Figure 2.6: Mean abundance of *Allorchestes compressa* (+ S.E.) in different caged macrophyte habitats in caging experiments at Two Rocks and Shoalwater Bay.

Feeding preference trials revealed that *Allorchestes compressa* preferred brown algae (*Ecklonia* and *Sargassum*) compared to other detached macrophyte types as food. While *A. compressa* showed a preference for feeding on brown algae, other types of wrack may be assimilated. Results of stable isotope analysis revealed that *A. compressa* feed on macroalgae rather than seagrass. Fatty acid analysis revealed that the consumers (amphipods and fish) are most similar in fatty acid composition to brown algae *Ecklonia* and *Sargassum* (Figure 2.7) and therefore brown algae are likely to contribute more to the food chain than other types of macroalgae.

Fish research: In surf zones, fish abundance and biomass increased as the volume of wrack increased (Figure 2.8). The types of fish also differed between wrack volumes. Bait species were common in areas of bare sand, or those with low amounts of wrack. In contrast, species such as sea trumpeter (*Pelsartia humeralis*) and cobbler (*Cnidoglanis macrocephalus*) were abundant in areas with mid to high levels of wrack. Habitat preference trials for fish showed that neither sea trumpeter nor cobbler had a clear preference for different types of macrophytes.

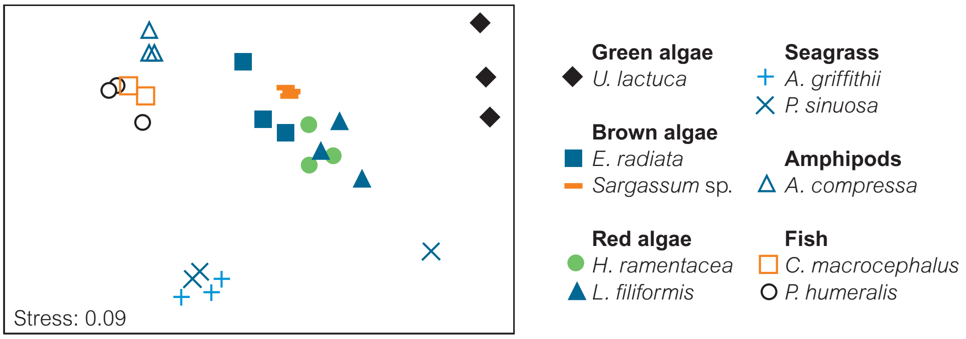

Figure 2.7: Two dimensional ordination of fatty acid composition of macrophyte, amphipod and fish species from three sites in south-western Australia.

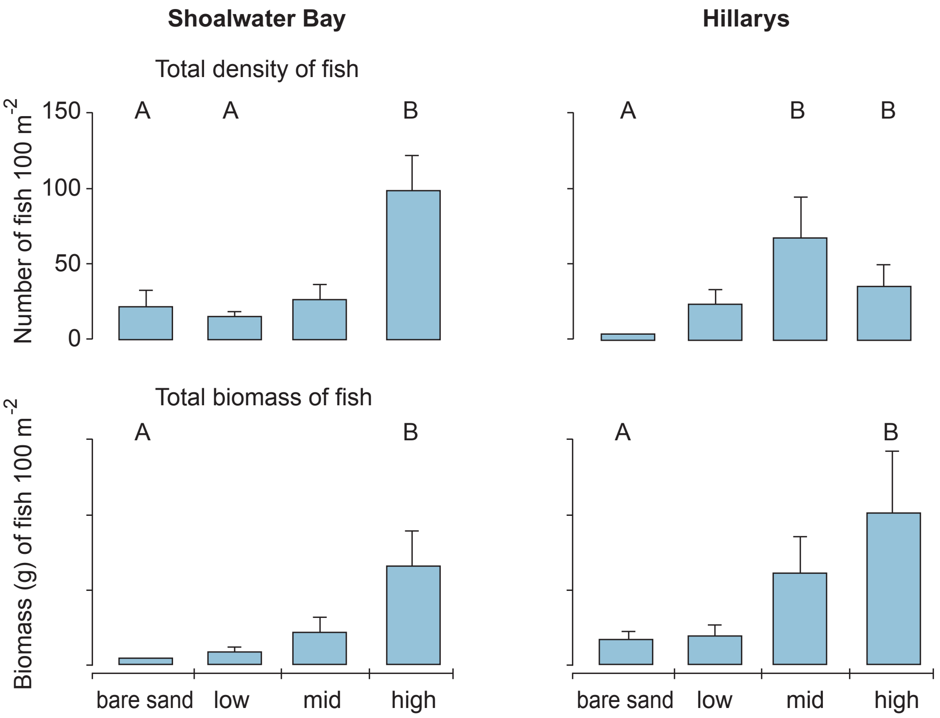

Figure 2.8: Mean (+SE) density and biomass of fish found in bare sand, low, mid and high wrack volumes at Shoalwater and Hillarys. Different letters denote volume categories that are significantly different ($P<0.05$).

Discussion

This study showed that different types of detached macrophytes are important for the amphipod *Allorchestes compressa*, which uses different types of plants as food or habitat. *A. compressa* shows a strong preference for feeding on brown algae, with this plant type contributing more than any other type of macrophyte in the detached macrophyte – amphipod – fish food chain in nearshore areas. In terms of shelter, brown and red algae and mixed wrack are important in providing a habitat for *A. compressa*. For fish, the volume, rather than the type, of wrack present in surf-zones has a strong influence on fish assemblages. Dense wrack accumulations are an important habitat for some fish species, particularly juvenile cobbler and sea trumpeter and could be critical for productivity and biodiversity in nearshore areas. Detached macrophytes transported from highly productive offshore areas subsidizes consumers in less productive surf-zone habitats in south-western Australia, where it enables consumer populations to reach greater densities than would be supported by *in situ* production. Removal of wrack could have a detrimental impact on the biodiversity and abundance of some fish species and their invertebrate prey, which rely on wrack for food and shelter.

Acknowledgements

Glenn Hyndes is gratefully acknowledged for his supervision. Mat Vanderklift and Julia Philips (CSIRO Marine, Floreat) and Suzy Ayvazian (Dept of Fisheries) assisted with planning and practical aspects of the research. Andy Revill and Peter Nichols (CSIRO Marine, Hobart) assisted with fatty acid and lipid class analyses. Many staff and students at Edith Cowan University (ECU) assisted with field work, running stable isotope samples and statistical advice. The School of Natural Sciences and the Centre for Ecosystem Management at ECU, CSIRO Strategic Research Fund for the Marine Environment, The Karrakatta Club and The Australian Society of Fish Biology provided financial assistance for the project.

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Conference attendance and presentations

July 2005: Australian Marine Science Association Conference (Darwin). Oral presentation "*Trophic transfer of carbon, nitrogen, sulfur and fatty acids between detached macrophytes, the amphipod* Allorchestes compressa *Dana and its fish predators in south-western Australia*".

June 2005: SRFME Postgraduate Symposium (CSIRO, Perth). Oral presentation "*Trophic transfer of carbon, nitrogen, sulfur and fatty acids between detached macrophytes, the amphipod* Allorchestes compressa *Dana and its fish predators in south-western Australia*".

March 2005: Rockingham/Kwinana/Mandurah Naturaliste Club. Oral presentation.

November 2004: Seagrass monitoring volunteer group, Rockingham. Oral presentation.

September 2004: Australian Society of Fish Biology Conference (Adelaide). Oral presentation "*The importance of volume and type of wrack on nearshore fish assemblages*".

June 2004: 2nd SRFME Postgraduate Symposium (CSIRO, Perth). Oral presentation "*The importance of volume and type of wrack on nearshore fish assemblages*".

March 2004: The Karrakatta Club (Perth). Oral presentation "*The importance of wrack in nearshore areas*".

July 2003: Australian Marine Science Association Conference (Brisbane). Oral presentation "*The role of different types of detached macrophytes for* Allorchestes compressa*, a surf-zone inhabiting amphipod*".

June 2003: 1st SRFME Postgraduate Symposium (CSIRO, Perth). Oral presentation "*The role of detached macrophytes for nearshore fish production and biodiversity*".

Date of thesis submission and PhD conferred: Thesis submitted 30 September 2005, corrections accepted 27 January 2006 and graduation 26 March 2006.

Publications and awards

Crawley, K.R. and G.A. Hyndes (in press). The role of different types of detached macrophytes in the food and habitat choice of a surf zone inhabiting amphipod. *Marine Biology.*

Crawley, K.R., G.A. Hyndes and S.G. Ayvazian (2006). The influence of different volumes and types of detached macrophytes on fish community structure in surf zones of sandy beaches. *Marine Ecology Progress Series* 307: 233-246.

June 2005: Symposium of the SRFME Postgraduate Scholarship Program (3rd prize).

March 2004: Dame Mary Gilmore Award offered by The Karrakatta Club and Edith Cowan University.

June 2003: Symposium of the SRFME Postgraduates Scholarship Program (3rd prize).

2.2.3 Ecological and historical processes maintaining macroalgal diversity in the Recherche Archipelago, Western Australia

Investigator / Institution

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Supervisors

Dr Gary Kendrick, Prof. Di Walker	University of Western Australia
Dr Alan Butler	CSIRO

Executive Summary

The macroalgal flora of the Recherche Archipelago was characteristic of the flora of the southern coast of Australia. Subtidal macroalgal assemblages were similar to assemblages found east of the Great Australian Bight. Patterns in macroalgal diversity in the Recherche Archipelago were presumably related to past speciation events and shared biogeography along the southern coast of Australia. The structure of subtidal macroalgal assemblages consisted of two layers: a locally-maintained, diverse, and abundant canopy layer; and an understory layer that was species-rich. Understory species, with their widespread distributions contributed to high species diversity for macroalgae across the southern coast of Australia.

Introduction

The macroalgal flora of southern Australia is among the richest globally. Records of macroalgal distributions and abundances remain incomplete because of the length and remoteness of the south coast. This thesis provides a comprehensive description of the diverse subtidal flora found in the Recherche Archipelago (RA), links patterns of diversity to dispersal potential, and assesses contemporary diversity in context with biogeography.

Aims

1. Document the subtidal flora recorded in the Recherche Archipelago in relation to island location, depth, and exposure to wave energy.

The distribution of subtidal macroalgae was surveyed in the western islands of the RA, Western Australia. Nine islands (four islands located inside and five islands located outside Esperance Bay) were sampled in three depth zones (<10, 10-20, and >20 m) and two exposures (sheltered and exposed to southwesterly wind and swell). In addition, one rhodolith bed was sampled within two nautical miles of Esperance harbour, in Esperance Bay, to identify the species making up individual rhodoliths and epiphytes. Of the 242 species recorded, there were 148 Rhodophyta, 65 Phaeophycaeae, and 29 Chlorophyta. A new species *Sargassum kendrickii* (Fig. 2.9; Goldberg and Huisman 2004) was described. Thirty-nine species had reported range extensions and two were presumably new species. Encrusting coralline species were not identified to species but represented three to five genera.

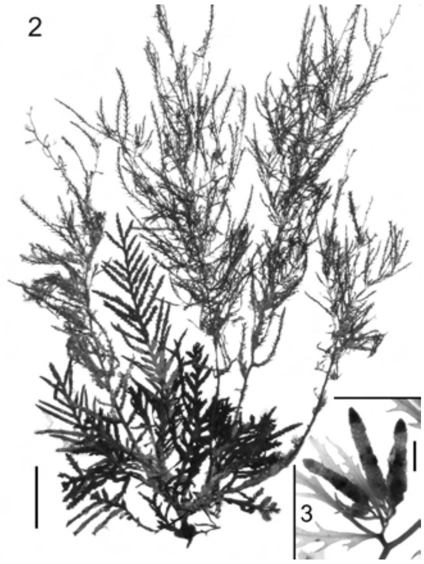

Figure 2.9: 2. *Sargassum kendrickii*. Scale = 3 cm.
3. Detail of receptacles. Scale = 2 mm.

2. Evaluate spatial and temporal variation in macroalgal diversity (species distribution and abundance).

This study explores the influence of geographical isolation between islands, depth and exposure to ocean swells on the diversity of macroalgae in this region as tested in the RA. Macroalgae were harvested (0.25 m^2 quadrats) from sites at two exposures (sheltered and exposed to wave energy), three depths (<10, 10-20, and 21-28 m), and two island groups (three islands within Esperance Bay and three islands outside the bay). A total of 220 species were collected. Species richness and biomass were significantly different at the smallest spatial scale (0.25 m^2), and density of canopy species decreased with depth (Fig. 2.10). Macroalgal assemblages differed with depth and exposure, and to a lesser extent island group. Assemblage differences were often associated with a particular canopy or understory taxa and not the entire assemblage composition. Average species richness•0.25 m^{-2} ranged from 13 to 29 species, typically with a few species contributing more than 50% of average biomass. Species richness was maintained by species turnover at the 0.25 m^2 spatial scale.

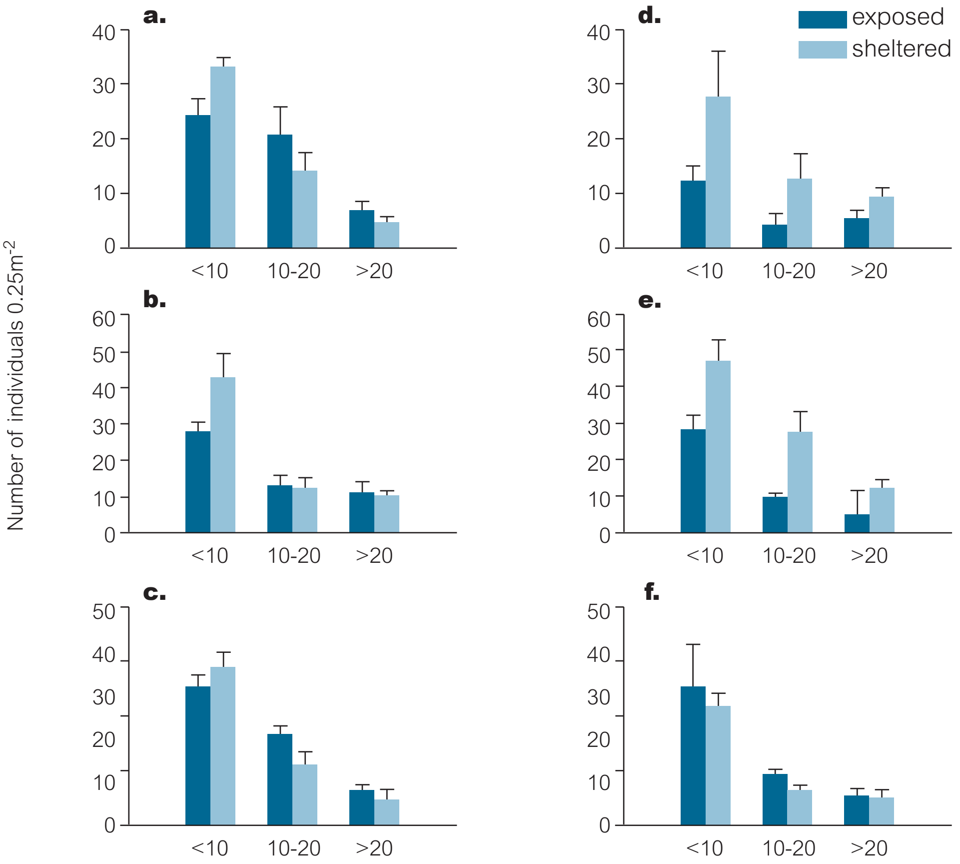

Figure 2.10: Density of canopy individuals (+ SE) in three depth strata (m) and two exposures at a. Black Island, b. Woody Island, c. Thomas Island, d. Remark Island, e. Long Island, and f. Frederick Island. N = 6 within each depth and exposure combination.

To characterize temporal variation in species diversity, subtidal macroalgal assemblages were compared between austral spring and autumn collections from Black Island, Western Australia. Macroalgae (>1 cm in length) from 0.25 m^2 quadrats were harvested from the south-eastern and southern sides of the island in depths <10 m and 10-20 m in October 2002 and 2003 and April 2003 and 2004. A total of 254 species of macroalgae were recorded, consisting of canopy, understory, and epiphytic species. Average total biomass was not significantly different among sampling times. Density of thalli per 0.25 m^2 was greater and more variable in depths <10 m than in depths 10-20 m. Macroalgal assemblages differed significantly among sampling times (Clarke's R values > 0.5, P = 0.001), and between samples collected from the same season but in different years. Each species was present, on average, in only 15% of the sampled quadrats. Chlorophyll *a*, seawater temperature, and salinity estimates did not vary much throughout the year with a range of 0.6 mg m^{-3} for chlorophyll *a*, 2.3 °C for seawater temperature, and 0.2 ppt for salinity. Year-round exposure to wind and wave energy from Southern Ocean gales and storms may drive the high species turnover and variability in density of thalli in depths <10 m.

3. Identify surrogates for macroalgal diversity in the Recherche Archipelago

Higher taxonomic levels and dominant taxa were evaluated as surrogates for detecting patterns in macroalgal species diversity in the RA. Data were stratified by two island groups (inshore and offshore), three depth intervals (<10 m, 10-20 m, >20 m), and two exposures to wave energy. Correlations between similarity matrices from surrogate and species diversity data matrices were analysed using a modified Spearman rank correlation (r_s). Species diversity data were aggregated to higher taxonomic levels and were either fourth-root or presence/absence (richness) transformed. Species richness was the most consistent surrogate (r_s-values > 0.69, $P = 0.001$) (Fig. 2.11). Genus-level richness was also strongly correlated to species diversity in the RA, except in depths <10 m where patterns in diversity were characterized by species turnover (Fig. 2.11). At offshore islands in depths 10-20 m and >20 m, family- and order-level biomass data were suitable surrogates due to the abundance of Alariaceae (Order Laminariales) represented by a single genus and species. At inshore islands in depths 10-20 m and >20 m, genera from the orders Gigartinales, Fucales, and Ceramiales were strongly correlated to species biomass data. Surrogates, like species richness, that were strongly correlated to species biomass data were also able to distinguish between exposures to wave energy, based on analysis of similarity tests. Sampling effort would be reduced if collecting richness data in species-rich macroalgal assemblages such as those found in temperate Australia.

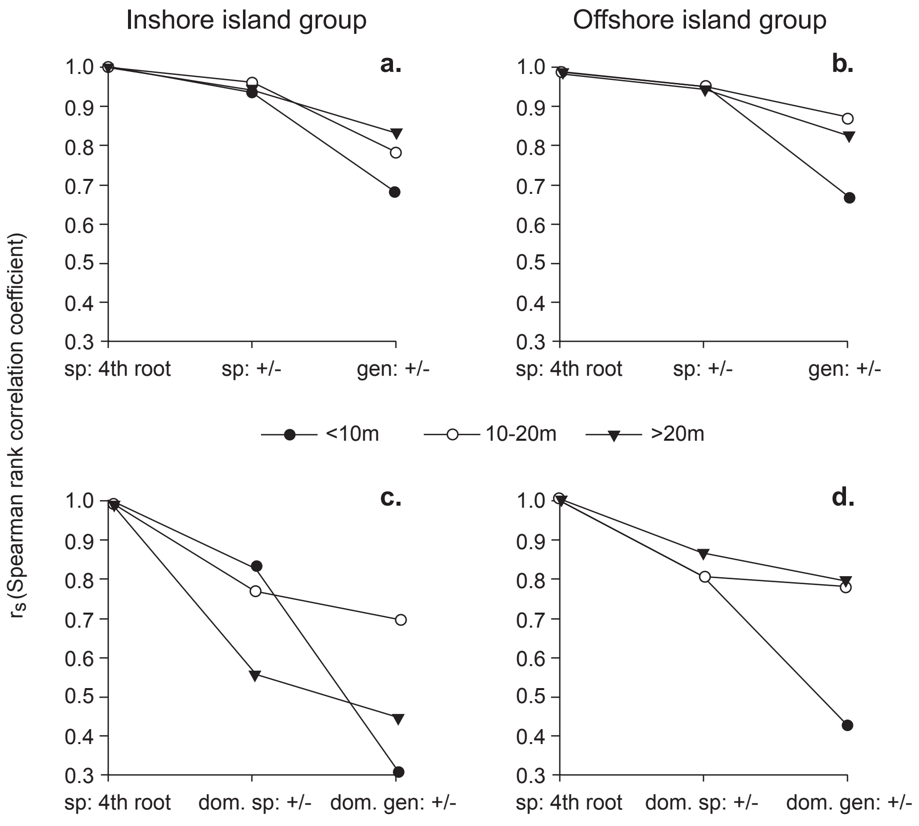

Figure 2.11: Correlation (modified Spearman rank, r_s) between similarity matrices of species diversity[a] and surrogate data collected from inshore and offshore islands in three depth strata. Surrogates: a., b. species (sp) and genus (gen) presence/absence (+/-) data[b]; c,d. dominant (dom.) species (sp)-level and genus (gen)-level +/- data[b]. N = 36- 0.25 m^2 quadrats per depth stratum within each island group. P = 0.001 for all tests. [a]Diversity data were 4th root transformed. [b]Diversity data were transformed to +/- data.

4. Link patterns of diversity with dispersal potential of macroalgae

Subtidal macroalgal assemblages differed among islands within the RA, Western Australia, with respect to species biomass. To investigate whether macroalgal populations were maintained locally, settlement plates were moored in 10 to 15 m depths at a reef sampled for macroalgal diversity, and 20, 50, 100, and 500 m away from the reef. Plates were retrieved after 8 months and assemblage differences were compared with distance from the sampled reef. Macroalgal richness decreased with distance from an island assemblage and molluscan richness increased. At 500 m away, the number of algal recruits was negligible and the number of bivalves was relatively high. Diversity in the RA may be maintained via dispersal within island reefs for canopy species and among island reefs for many understory species.

5. Link patterns of diversity with interspecific interactions

The influence of fucalean canopy species and dominant understory macroalgae on the maintenance of macroalgal diversity was investigated. Recruitment and growth were compared among four -0.25 m^2 treatments (total clearing, understory taxa removed, canopy taxa removed, and undisturbed control), using a randomized block design in depths <10 m and 10-20 m at Woody Island, Western Australia. To evaluate if propagules were available in the water column above the canopy layer, settlement plates (0.04 m^2) were deployed in depths <10 m, 10-20 m, and >20 m. The understory species *Osmundaria prolifera* and *Botryocladia sonderi* had greater biomass in depths 10-20 m, regardless of the presence of a canopy. Diversity of macroalgae was not significantly different between understory and canopy removal treatments. Total understory richness was similar between the two depth strata: 97 species in depths <10 m; 98 species in depths 10-20 m. Taxa found in the canopy showed different patterns in recruitment: Cystoseiraceae recruited predominantly in cleared treatments and Sargassaceae recruited where canopy taxa were present and most abundantly in depths <10 m. Recruitment of canopy taxa on settlement plates was similar with depth (20-30 recruits/0.04 m^2). Maintenance of diversity in fucalean beds was less associated with the presence of canopy or understory layers, but appeared to be more a function of depth-associated factors and post-recruitment processes.

6. Assess contemporary diversity in context with biogeography

To investigate if local and/or regional processes drive contemporary patterns of species diversity in the RA, macroalgal floras were compared between the RA and temperate Australia. In addition, species diversity was compared among three island groups in the RA. Subtidal macroalgal assemblages in the RA were similar to those along the southern coast of Australia (Shepherd and Womersley 1981, Collings and Cheshire 1998, O'Hara 2001, Baker and Edyvane 2003, Goldberg and Kendrick 2004), indicating that contemporary conditions along the coast have not changed disproportionally over the millennia to result in different assemblages. However canopy assemblages in the RA were more similar to assemblages east of the Great Australian Bight (Shepherd and Womersley 1981, Collings and Cheshire 1998, O'Hara 2001, Baker and Edyvane 2003) than to the southwestern corner of Western Australia (Wernberg *et al*. 2003). High species turnover was typical within island groups, a pattern that has been documented elsewhere along the south coast. High regional species richness in temperate Australia influenced the flora in the RA, with little indication of ecological processes depressing diversity at the local scale.

Discussion

The macroalgal flora of the RA was characteristic of the flora of the southern coast of Australia, in particular, with assemblages found east of the Great Australian Bight. Patterns in macroalgal diversity in the RA were presumably related to past speciation events and shared biogeography along the southern coast of Australia.

Richness in temperate Australia appears to be maintained by turnover of broadly-distributed species. More dominant species in assemblages were associated with differences in depth and exposure to ocean swells. Our findings support the hypothesis of a geographical transition of dominant species from kelp-dominated in the west to a fucalean-dominated assemblage in the RA and east of the Great Australian Bight.

Acknowledgements

I would like to thank my supervisors Gary Kendrick, Di Walker, and Alan Butler. In addition, this work could not have been accomplished without the assistance from John Heine, Euan Harvey, Simon Grove, Hai Ngo, folks at CALM and the marine group. I would like to express my gratitude to the University of Western Australia, the Strategic Research Fund for the Marine Environment (CSIRO-WA government), Fisheries Research and Development Corporation, Australian Marine Science Association, Phycological Society of America, and Australasian Society for Phycology and Aquatic Botany.

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Conference attendance and presentations

Phycological Society of America, (2004); Strategic Research Fund for the Marine Environment symposium, 2003, 2004; 2005; Australian Marine Sciences Association, 2003; Australasian Society for Phycology and Aquatic Botany, 2002 and 2004.

PhD conferred with distinction, August, 2005.

Publications and awards

Goldberg, N.A. (in press). Age estimates and description of rhodoliths from Esperance Bay, Western Australia. *Journal of the Marine Biological Association of the United Kingdom*.

Goldberg, N.A. (in press). Colonization of subtidal macroalgae in a fucalean-dominated algal assemblage, southwestern Australia. *Hydrobiologia.*

Goldberg, N.A. and G. Collings (in press) Macroalgae. In: S. McClatchie, J. Middleton, C. Pattiaratchi and G. Kendrick (eds.) *The South-west marine region: ecosystems and key species groups*. National Oceans Office.

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Awards

Australasian Society of Phycology and Aquatic Botany, Phycological Society of America and the University of Western Australia travel awards, August 2004; Australian Institute of Nuclear Science and Engineering research awards, December 2004, 2005; Australian Marine Sciences Association grant to attend International Marine Biological Workshop held in Esperance, Western Australia, February 2003; Australian Marine Sciences Association travel award, July 2003; Strategic Research Fund for the Marine Environment: oral presentation, June 2003 (2nd place); paper award, June 2004. Whitfield Fellowship, UWA, 2005.

2.2.4 Biogeochemical processes in sea grass sediment

Investigator / Institution

Kieryn Kilminster	School of Plant Biology, University of Western Australia

Supervisors

Professor Di Walker	School of Plant Biology, UWA
Professor John Raven FRS FRSE	University of Dundee, Scotland
Dr. Peter Thompson	CSIRO, Hobart

Executive Summary

Early work on organic matter enrichment of coastal ecosystems suggested that seagrass growth may be constrained by biogeochemical parameters, possibly sulphide stress. Sulphide concentrations in aquatic sediments are likely to increase with increased organic matter fluxes (eutrophication) and increased temperatures (global warming). *Halophila ovalis* was chosen as a model to investigate the role of biogeochemistry in seagrass sediments both on growth and nutrient dynamics. *H. ovalis* cultured in controlled conditions subject to either organic matter enrichment or light reduction showed reduced growth and increase in leaf phosphorus concentration. Exposure of *H. ovalis* to sediment sulphide in the field caused significant reduction in growth, average leaf weight and internode-distance of *H. ovalis*. Reduced growth rate was correlated with an increase in leaf P. The response of *H. ovalis* to unfavourable sediment conditions may enable its use as a bio-indicator of estuary or coastal marine health, allowing observation of unhealthy sediment conditions before die-back of the major meadow forming seagrasses occurs.

General Background

Seagrass meadows are dynamic and productive environments. Interactions within seagrass habitats, between seagrasses, epiphytic algae, benthic microalgae, sedimentary bacteria, and a large diversity of protists and invertebrates, are complex and often not well understood. Seagrasses manipulate sediment characteristics by detritus accumulation, root oxygen loss (Connell et al., 1999), dissolved organic matter exuded from roots during photosynthesis (Holmer et al., 2001) and demand for nutrients (Short and McRoy, 1984). These processes may influence the fluxes of nitrogen (N) and phosphorus (P), and the subsequent availability of nutrients to the seagrass. Western Australia has some of the most extensive seagrass meadows in the world, with a large diversity of species represented. Many of these species are unique to Australia (Kirkman and Walker, 1989). Understanding the processes maintaining seagrass nutrition is particularly pertinent for research in coastal waters of Western Australia where residual nutrient concentrations in water columns are low.

General aims and study site

This work focused on a small species of seagrass, *Halophila ovalis*, from the Swan River Estuary. Research was undertaken both in the laboratory (with collected samples) and in the field. *H. ovalis* was chosen as a model to investigate the role of biogeochemistry in seagrass sediments both on growth and nutrient dynamics. An advantage of *H. ovalis* is that response time to perturbations is quick, since growth rate is fast, so this makes it an ideal seagrass to investigate parameters affecting growth and nutrition.

Manipulations affecting growth of *Halophila ovalis*

Organic matter addition to *H. ovalis*, in culture

It was hypothesised that seagrass may benefit nutritionally from organic matter additions stimulating heterotrophic mineralization. Cores of *Halophila ovalis* were grown under controlled conditions (18 °C, 12 hr light / 12 hr dark, ~ 300 μmoles of photons $m^{-2}s^{-1}$ PAR) for ~ 4 weeks. Unvegetated sediment was also incubated in the same manner. Cores was enriched with either particulate organic matter (POM) added as ground wrack to top surface (0, 1, 5, 12 g $core^{-1}$), or dissolved organic matter (DOM) added with sucrose diffusion tubes (0, 0.8, 2.4, 5.8 g $core^{-1}$).

Following enrichment with POM, growth rate and average leaf mass reduced (Table 2.1), total ammonium and phosphate pools in porewater increased, seagrass utilized phosphorus (P) preferentially to nitrogen (N) from the porewater, average leaf N concentration increased by 15 % and average leaf P concentration increased by 30 %. Following enrichment with DOM, growth rate reduced but average leaf mass increased (Table 2.1), proportion of root biomass decreased but the proportion of leaf biomass increased, porewater concentrations showed little change except for an increase in phosphate in porewater for highest DOM enrichment, average leaf N increased by 13 % and average leaf P increased by 28 %. Patterns of N and P distribution in plant parts were very similar for POM and DOM enriched *H. ovalis* (Fig. 2.12), with nutrient concentrations of leaves approximately twice that observed in roots or rhizomes.

Light reduction of *H. ovalis*, in culture

H. ovalis was grown under controlled conditions (18 °C, 12 hr light / 12 hr dark, ~ 300 μmoles of photons $m^{-2}s^{-1}$ PAR unless otherwise stated) for 2 - 7 weeks. Aquaria were covered with Hessian to reduce light levels for treatments to 100 and 40 μmoles of photons $m^{-2}s^{-1}$ PAR.

Growth rate and average leaf weight reduced (Table 2.1), average leaf N increased by 18 % and average leaf P increased by 25 % following light reduction of *H. ovalis*. Patterns of nutrient distribution (N and P) within seagrass tissues followed a similar pattern to that observed following organic matter enrichment (Fig. 2.12).

Table 2.1 Average growth rate and leaf mass for *Halophila ovalis* grown under perturbations of either organic matter addition, or light reduction. (mean ± SE)

Experiment	**Growth rate** (mg DW $apex^{-1}day^{-1}$)		**Leaf mass** (mg)	
	Control	**Treatment**	**Control**	**Treatment**
POM addition	1.33 ± 0.15	0.82 ± 0.10	3.9 ± 0.3	3.2 ± 0.1
DOM addition	1.22 ± 0.27	0.58 ± 0.15	3.7 ± 0.2	5.1 ± 0.6
Light reduction	1.32 ± 0.26	0.98 ± 0.21	3.3 ± 0.6	2.4 ± 0.5

* Treatment for POM = 12 g wrack $core^{-1}$, DOM = 5.2 g sucrose $core^{-1}$, and LIGHT = 40 μmoles of photons $m^{-2}s^{-1}$ PAR

Conclusions of growth manipulation experiments

Seagrass grown in culture showed very similar responses for either addition of organic matter (POM or DOM) or light reduction. Although seagrass may acquire nutrients from organic matter enrichment, growth may be constrained by sediment conditions. The strongest indicator of this stress appeared to be increase in leaf P. Similarly, an increase in leaf P was demonstrated for plants subject to reduced light. These common responses led me to consider sulphide as an underlying cause of negative plant response to either organic matter enrichment (stimulating microbial sulphate reduction) or light reduction (reducing photosynthesis and thus the ability of roots to oxygenate sediment).

Comparison to other seagrasses

Data on nitrogen and phosphorus concentrations in above-ground and below-ground plant parts of 19 species of seagrass world-wide was compiled from published sources. Nutrient concentration of *Halophila ovalis* shows a central tendency when compared to data on seagrass nutrient concentrations for both above-ground and below-ground plant parts collated from published sources (Fig. 2.13). Concentration of nutrient within leaf tissue is higher than that of below-ground plant parts. Variability in seagrass nutrient concentrations has been attributed to differences arising within and among species with most variability due to within-species differences (Duarte, 1990). Although *Halophila* is an oddity in the spectrum of seagrass species (it is small, fast growing, has oval leaves and plant tissue which is not recalcitrant in ecosystems), its nutrient concentrations show a central tendency compared with the range of concentrations observed for all seagrasses. I propose the use of *H. ovalis* as a model to explore processes which determine nutrient concentration variability within seagrasses.

Nitrogen and phosphorus concentrations within *H. ovalis* tissues showed similar trends despite being grown in culture under three different experimental manipulations (POM and DOM enrichment or light reduction). Nitrogen and phosphorus concentrations were not strongly correlated for above-ground or below-ground plant parts of seagrass world-wide (Fig. 2.13). The ratio of nitrogen and phosphorus is more tightly constrained for the roots and rhizomes of *H. ovalis* than the leaves (linear relationships in Fig. 2.12). N:P observed for rhizomes is lower than for roots, and indicates that rhizomes contain more phosphorus relative to nitrogen than roots (Fig. 2.12). When roots and rhizomes are combined into one below-ground compartment the linear relationship between N and P is no longer observed (Fig. 2.13). Most data on nutrient concentrations for other seagrass species has combined roots and rhizomes to below-ground parts, so I can only speculate that different N:P constraints for roots and rhizomes may exist for other seagrass species.

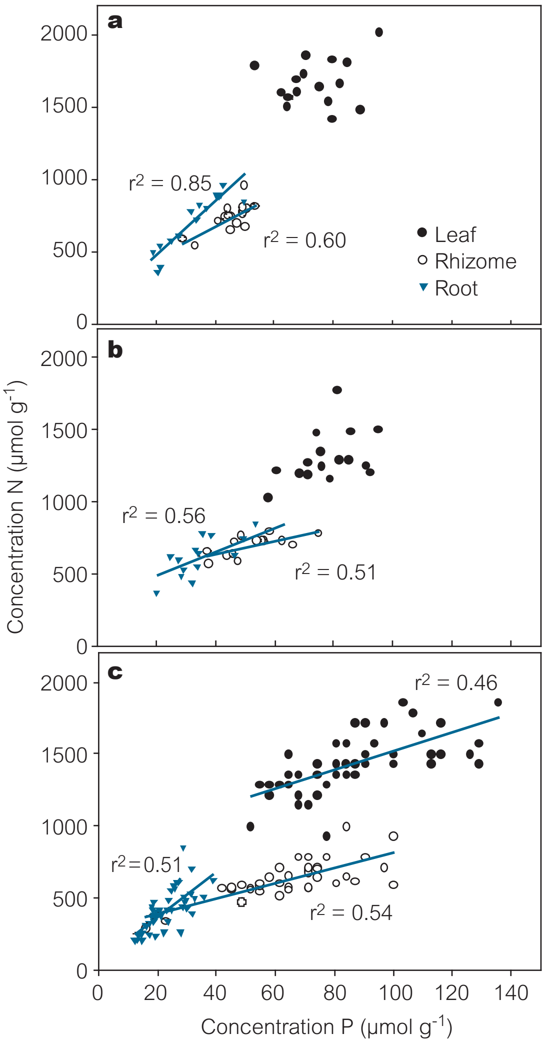

Figure 2.12: Nitrogen *vs.* phosphorus concentrations in leaves, rhizomes and roots of *Halophila ovalis* grown in culture with particulate organic matter addition (A), dissolved organic matter addition (B) and light reduction (C).

Leaf nitrogen and phosphorus were shown to increase significantly following either organic matter enrichment or light reduction (Fig. 2.14), with phosphorus increasing almost twice as much as nitrogen. These natural tendencies for seagrass to retain or acquire N and P under non-optimal growth conditions may lead to the over-estimation by researchers of minimal requirements of nitrogen and phosphorus for growth.

Field response to sulphide

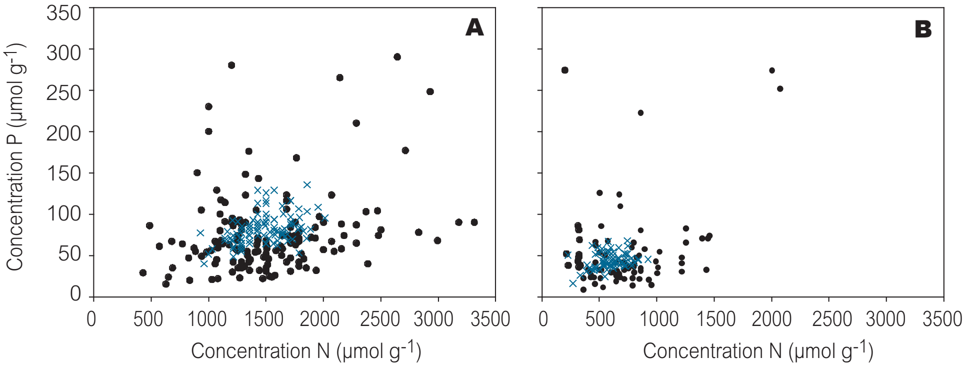

Figure 2.13: Concentration of nitrogen and phosphorus in seagrass tissue for A. leaf and B. below-ground plant parts, for published data from 19 species of seagrass (•) and *Halophila ovalis* from the Swan River Estuary (x). Leaf concentrations of N and P are typically 2-3 times higher than for below-ground parts, and *Halophila ovalis* shows a central tendency within the global data set.

Exposure of below-ground roots and rhizomes of seagrass to "free" sulphides depends on the rate of sulphate reduction (SRR), porewater pH, potential of plant produced oxygen to re-oxidize sulphides and availability of transition metals in sediment capable of sequestering sulphides.

The short-term effect of sediment sulphide on the growth, nutrition and morphology of *H. ovalis* was investigated at Pelican Point, in the Swan River Estuary. Sediments were enriched with Na_2S (equivalent to 0, 1.1 and 4.2 g m^{-2}) and plant growth was monitored over ~3 weeks. Biomass, internode-distance and growth rate were determined, and plant material analysed for soluble carbohydrate, carbon, nitrogen and phosphorus.

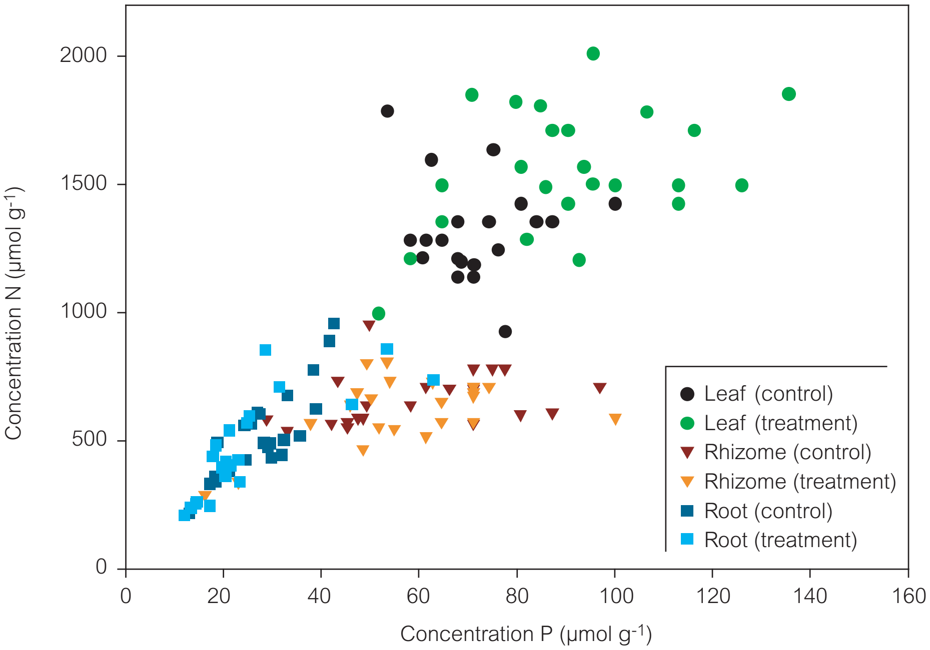

Figure 2.14: Nitrogen *vs* phosphorus concentrations in cultured *Halophila ovalis* tissue for control and treatment (highest organic matter enrichment or strongest light reduction). Leaf P increases with exposure to organic matter, or light reduction, relative to the control.

Following sulphide enrichment of sediments, growth rate, internode-distance and average leaf mass was lower than in control ($p<0.05$) as determined by one-way ANOVA with treatment as a fixed factor. There was no significant effect of sulphide treatment on the nutrient constituents (C, N, P, or soluble carbohydrates), however sulphide did negatively influence growth rate. Growth rate was negatively correlated with leaf P ($r^2=0.373$, $p<0.001$) and positively correlated with internode-distance ($r^2=0.414$, $p<0.01$). Together internode-distance and concentration of phosphorus in leaves accounted for 63 % of the variability in the growth rate of *H. ovalis* (by multiple linear regression).

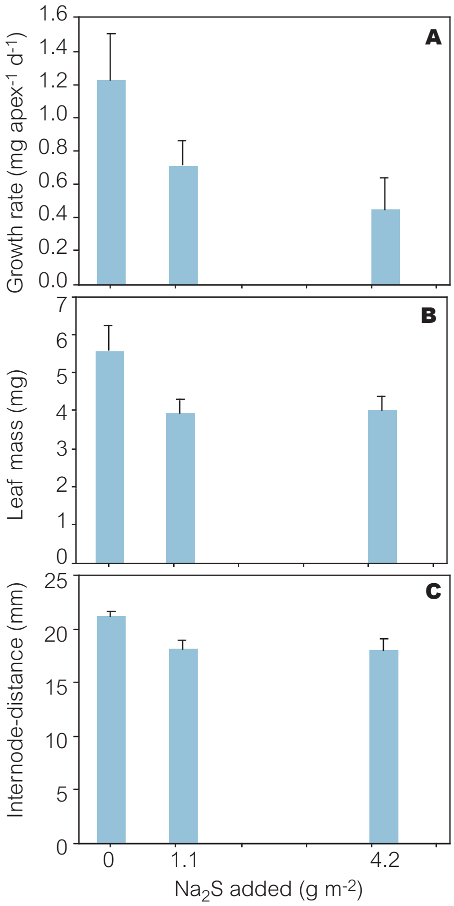

Figure 2.15: A. Growth rate of *H. ovalis*, B. average leaf and C. internode–distance reduces following sediment enrichment with sodium sulphide

H. ovalis had reduced growth rate and reduced areal production but showed morphological acclimation to sulphide exposure, producing smaller, lighter leaves and reduced internode-distance. The plasticity demonstrated by *H. ovalis* of adjusting internode-distance in response to sulphide loading may provide a survival advantage. Reduced internode-distance would increase root and shoot density, since *H. ovalis* has a predominantly linear growth pattern with one root for every leaf pair. Since oxygen is lost diffusively through the roots of *H. ovalis* with photosynthesis, reduced internode distance and subsequent increase in root density may be an acclimation to counteract increased sulphide concentration. Response time to sulphide stress would be expected to be faster for *H. ovalis* relative to other larger, slower growing seagrasses. The response of *H. ovalis* (increased leaf P, reduced internode-distance and reduced average leaf weight) may enable its use as a bio-indicator or estuary or coastal marine health, allowing observation of unhealthy sediment conditions before dieback of the major meadow forming seagrasses occurs.

General discussion

Biogeochemical constraints on the growth of *Halophila ovalis* were hypothesised following laboratory experiments (organic matter enrichment and light reduction) where reduced growth rate was observed. Increased sulphide exposure was suggested as the mechanism of growth constraint, and this was tested in the field with a direct addition of sodium sulphide to the sediment. Sediment sulphide clearly inhibits plant growth rate, and results in smaller internode-distances and leaves - responses similar to those observed in the laboratory experiments. The effect on leaf nutrient (N and P) concentrations was less pronounced than in the laboratory experiments and may indicate that changes in sediment chemistry (not just presence of sulphide) may also determine nutrient concentrations within seagrass.

Acknowledgements

This work was funded by the Strategic Research Fund for the Marine Environment (SRFME), the School of Plant Biology and the Graduate Research School, University of Western Australia.

Conferences attended and presentations

Strategic Research Fund for the Marine Environment Symposia, *Floreat 2003, 2004, 2005*

Plant Biology Postgraduate Summer School, *Rottnest 2003, 2004, 2005, 2006*

GRDC Root and Soil Biology Workshop, *Canberra, 2003*

International Society for Plant Anaerobiosis (ISPA) *Perth, 2004*

SEAGRASS 2004 *Townsville, 2004*

Thesis submitted July 2006 and PhD subsequently awarded.

Publications and awards

Kilminster K.L., D.I. Walker and J.A. Raven (submitted). Changes in growth, internode-distance and nutrient concentration of the seagrass *Halophila ovalis* with exposure to sediment sulphide. (Submitted to *Marine Ecology Progress Series*)

Kilminster K.L., D.I. Walker, P.A. Thompson and J.A. Raven J.A. (2006). Limited nutritional benefit of the seagrass *Halophila ovalis*, in culture, following sediment organic matter enrichment. *Estuarine, Coastal and Shelf Science* 68: 675-685.

Travel award towards travel to attend GRDC Workshop in Canberra 2003

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2.2.5 The development and validation of algorithms for remotely sensing case II waters

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Introduction

Coastal embayments and estuaries are important ecosystems containing a number of critical habitats and resources that are important for sustaining fisheries and ecosystem health. Although there has been a wealth of new knowledge generated over the last decade about these ecosystems, the spatial and temporal patterns of biological and physical processes are not fully mapped or understood. Remotely sensed data offer a unique perspective on these processes because of the synoptic view over time and quantitative algorithms that can be used to extract geophysical and biophysical information from them.

In this study, the approach taken in retrieving benthic cover type and bathymetry from remotely sensed imagery is to derive an algorithm from an in-water radiative transfer model. The model includes the spectral reflectance of benthic cover, the water column constituents (Chlorophyll-a, Coloured Dissolved Organic Matter and Suspended Sediments) and the bathymetry. The model permits the hyperspectral observations to be formally inverted using a non-linear optimisation scheme to yield a benthic classification, the bathymetry and the concentrations of in-water constituents.

Aims/Objectives:

The aims of this PhD research were to,

1. Develop and validate a coastal water reflectance model that will permit the simultaneous retrieval of the concentrations of in-water constituents (Chl-a, CDOM, SS), water column depth as well as the composition of the seafloor, from remotely sensed data.
2. Acquire *in situ* hyperspectral data from SRFME field programs to permit the testing of the coastal water reflectance model.
3. Implement the coastal water reflectance model to appropriate satellite/aircraft data sets and compare the retrieved products to *in situ* data.

Model Approach

A coastal water reflectance model that incorporates the reflectance spectra of three common benthic types, found off WA coastal waters, was developed based on the work of Lee *et al*, 1999. In their work, they have demonstrated that their model can retrieve concentrations of in-water constituents and depth to a relatively high accuracy. Essential to their model was the use of the spectral shape of the sea bottom and only sandy bottom environments were studied. The question is can this model approach be used to retrieve the contributions of more than one bottom type, namely sand, seagrass and brown algae, and hence generate a bottom classification map? The validity of the coastal water reflectance model with the inclusion of the three benthic types has been explored in this PhD research and the results are summarised below.

Model Evaluation with Synthetic Data

A large database of remote-sensing reflectance spectra corresponding to a range of water depths, bottom reflectance spectra and water column properties was constructed. The remote-sensing reflectance spectra were generated using the Hydrolight radiative transfer numerical model, which provides an exact solution of the radiative transfer equation for the given input conditions. The Hydrolight simulated reflectance database provides a particularly useful means of evaluating the retrieval capabilities of the coastal water reflectance model. It permits comparison between model-retrieved parameters with the corresponding Hydrolight inputs.

The coastal water reflectance model was applied to each generated reflectance spectrum incorporating the Levenburg-Marquardt optimisation scheme. The scheme involves adjusting the model parameters until the difference between the model spectrum and Hydrolight reflectance spectrum reaches a minimum. Once a minimum is reached the model parameters are considered derived.

Comparison between the model-retrieved bottom coefficients of sand, seagrass and brown algae and the Hydrolight input coefficients show very promising results. Figures 2.16a, b and c display the retrieved bottom weighting coefficients of sand, seagrass and brown algae (Square symbols), corresponding to the bottom type used in the Hydrolight simulations, respectively. The dotted lines represent the reflectance value at the 550nm centre wavelength for the corresponding bottom type spectrum used in the Hydrolight simulations. In these graphs, it is evident that for a sandy bottom type (Figure 2.16a) the coastal water reflectance model retrieved bottom weighting coefficients of sand, B_{Sand}, equivalent to the Hydrolight input value and zero for both the seagrass, $B_{Seagrass}$, and brown algae, $B_{Brown\ Algae}$, coefficients. For simulations where the bottom type input was seagrass (Figure 2.16b), the model returned $B_{Seagrass}$ values comparable to the Hydrolight input value and zero for the sand and brown algae coefficients. For the brown algae case (Figure 2.16c), the model returned $B_{Brown\ Algae}$ values close to the Hydrolight input value and zero for B_{Sand} and $B_{Seagrass}$.

The above results demonstrate the potential for the coastal water reflectance model to distinguish between sand, seagrass and brown algae. Figure 2.17 shows the comparison between Hydrolight input depth and model-retrieved depth from the simulations. The results indicate that the model-retrieved depth agree very closely with the input depths for the simulated depth range.

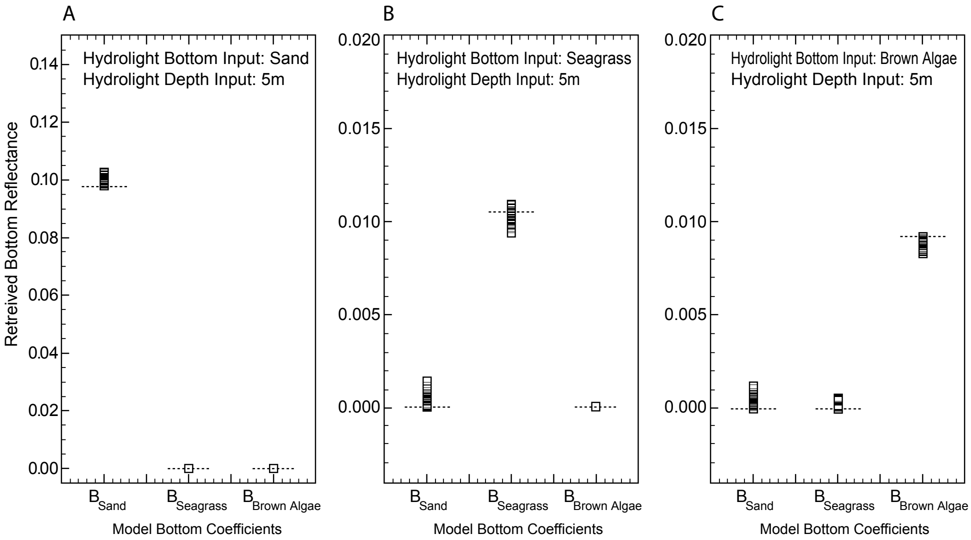

Figure 2.16: Model retrieved bottom coefficients, B_{Sand}, $B_{Seagrass}$ and $B_{Brown\ Algae}$ over Hydrolight bottom input spectra, a) sand, b) seagrass and c) brown algae.

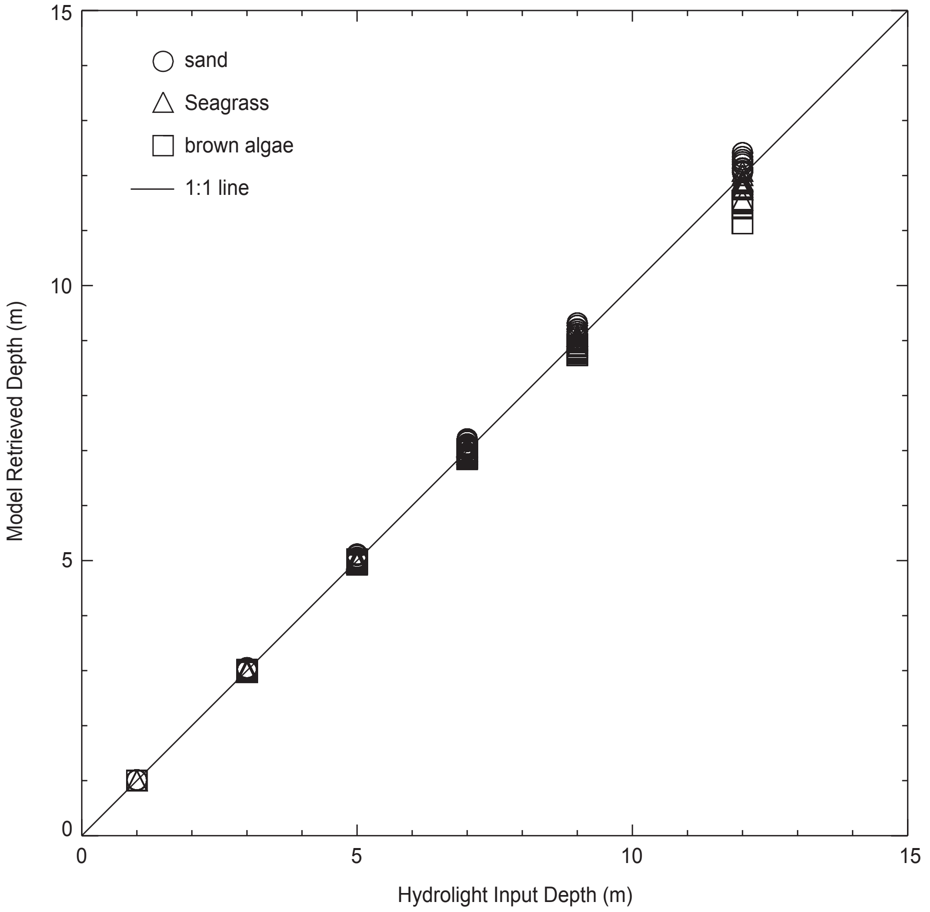

Figure 2.17: A comparison scatter plot of Hydrolight input depth against model-retrieved depth over the various simulated bottom types.

Model Application to Hymap Imagery

Two flight lines of HyMap (HyVista Corporation) spectral imagery over Jurien Bay were captured on 23rd of April 2004 to study the possibility of bottom type retrieval from shallow, coastal waters. The study area selected for evaluation in this PhD research encompasses a small portion of the recently designated Jurien Bay Marine Park, located approximately 300km north of Perth, Western Australia (Figure 2.18). The bottom composition within this selected region is highly variable, composed largely of sediment, seagrass and pavement/reef. The most commonly found sediment is white carbonate sand. The dominant seagrass species is *Posidonia australis*. Small pockets of the seagrasses *Amphibolus griffithii* and *Halophila ovalis* also occur in this region. The brown algae, *Sargassum.* sp. and *Ecklonia*, are very abundant in this region and reside mainly on the reef and pavement areas with varying density. Occurring in much sparser growth is the fleshy and coralline red epiphytes. These epiphytes attach themselves onto seagrass shoots and also survive independently over the pavement/reef areas.

The topography of the area is also highly variable and includes extensive shallow water areas with depths ranging 1m to 15m.

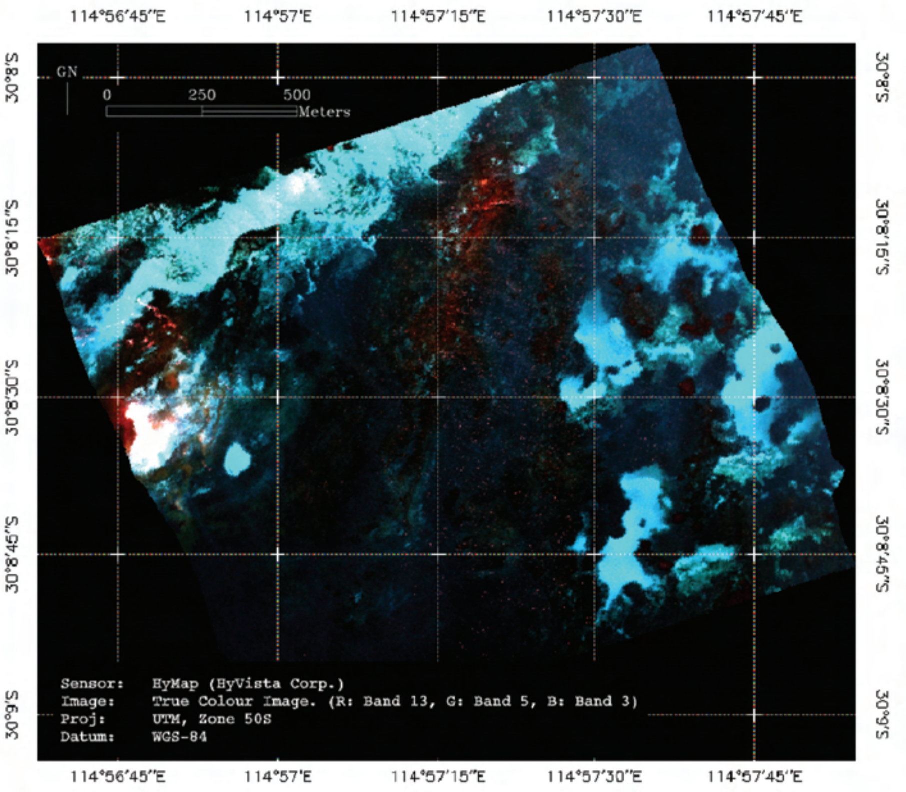

Figure 2.18: A true colour representation of the HyMap captured image over the "Scientific Reference Zone". The colour variation within the image scene is due to spatial changes in water attenuation (depth) and benthic cover.

The coastal water reflectance model was applied to a small section of the image scene covering the "scientific reference zone" (Figure 2.18). Each pixel element within the atmospherically corrected reflectance data set, provided by HyVista Corp., was inverted by implementing the coastal water reflectance model in conjunction with a Levenberg-Marquardt optimisation scheme. The retrieved bottom weighting coefficients of sand, seagrass and brown algae were used to generate a false colour bottom type classification image, representing our results of benthic cover (Figure 2.19).

The classification image was constructed using the ENVI package distributed by Reasearch Systems Inc. (RSI). Model-retrieved bottom weighing coefficients of sand, seagrass and brown algae were related to the blue, green and red components of the ENVI colour table. From the Hydrolight modelling results, we anticipate that blue, green and red pixel colours of the classification image would represent benthic cover representative of sand, seagrass and brown algae, respectively. These results would only be valid for situations where only one bottom type is captured within the image pixel. For situations where the image pixel is occupied by two or more benthic cover types, we expect the model to retrieve bottom weighting coefficients such that a combination of the three bottom spectra (model) are utilized in the non-linear fit. For these instances, the values of the individual bottom weighting coefficients would be reduced and hence be represented by darker image pixels. Similarly, for the situations where the benthic cover type (eg, coral or rock) imaged within a pixel is spectrally different to the bottom type spectra utilized in the model, the model would retrieve a combination of bottom type weighting coefficients which best fits the imaged bottom type reflectance. This would result in pixel colours that are made up of a combination of blue, green and red.

The model-retrieved depth was used to generate a bathymetric map of the evaluation site and comparisons with hydro-acoustic sounding determined depths were made.

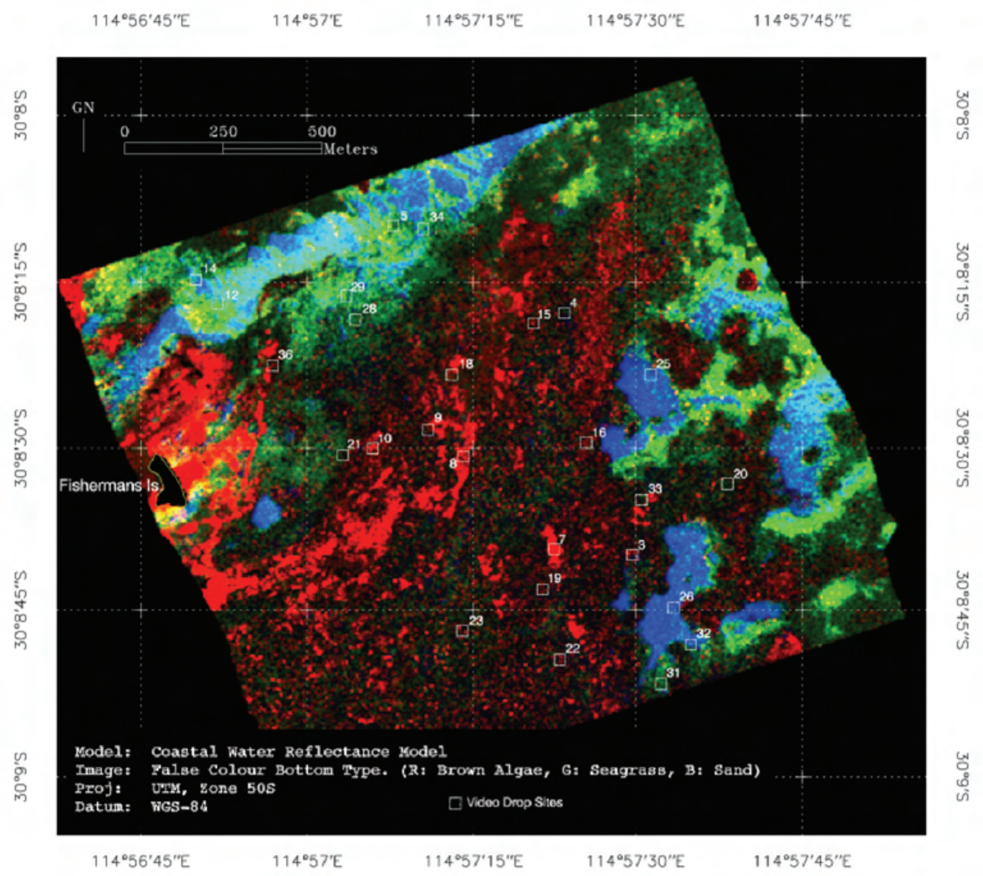

Figure 2.19: A false colour benthic cover representation of the "Scientific Reference Zone". Sand, seagrass and brown algae are represented by blue, green and red coloured pixels, respectively. Darker coloured pixels indicate a mixture of benthic cover. Locations of 26 ground-truthing stations are marked out as squares.

Benthic Cover Validation

To study the validity of the generated bottom type classification image, a SRFME field campaign was undertaken whereby video drops over 26 sites within the image scene (Figure 2.19) were deployed to identify the bottom composition. The location of the image pixels corresponding to the field sites were extracted and their colour was compared to the bottom composition identified with the video data (Table 2.2).

Table 2.2 A tabulated comparison of image (classification) pixel colour with the benthic cover identified in video footage over selected ground-truthing sites.

Station #	Pixel colour	Bottom cover identified in video drops
14	🟦 Blue	Sand
32	🟦 Blue	Mostly Sand/Patchy Halophila
26	🟦 Blue	Sand
25	🟦 Blue	Sand
12	🟦 Blue	Sand/Patchy Halophila
34	🟦 Blue	Sand/Patchy Halophila
29	🟩 Green	Sand/Halophila
28	🟩 Green	Sand/Halophila
5	🟩 Green	Seagrass(dense)/Sand
31	🟩 Green	Sand/Seagrass/Light Brown Epiphytes
21	🟩 Dark Green	Purple Sargassum/Seagrass/Brown+Yellow Epiphytes/Sand
33	🟩 Dark Green	Bare Reef/Purple Sargassum (Sparse)
20	🟩 Dark Green	Bare Reef/Purple Sargassum (Sparse)
4	🟩 Dark Green	Bare Reef/Purple Sargassum (Sparse)
10	🟥 Red	Sargassum (Dense cover)
8	🟥 Red	Ecklonia (Dense cover)
3	🟥 Red	Brown Sargassum/Brown Epiphytes (Dense cover)
7	🟥 Red	Ecklonia (Dense cover)
36	🟫 Dark Red	Ecklonia/Seagrass/Brown+Purple Sargassum
9	🟫 Dark Red	Purple Sargassum/Sand/Patchy Ecklonia/Epiphytes
19	🟫 Dark Red	Purple Sargassum/Sand/Patchy Ecklonia/Epiphytes
23	🟫 Dark Red	Purple Sargassum/Brown+Yellow Epiphytes
22	🟫 Dark Red	Purple Sargassum/Sand/Brown Epiphytes
16	🟫 Dark Red	Brown Sargassum
15	🟫 Dark Red	Purple+Brown Sargassum/patchy Sand

Referring to Table 2.2, we can see that blue pixels correspond to sandy bottom environments, green pixels were associated with mainly seagrass with some stations containing a small proportion of sand. Red pixels were associated with dense cover of the brown algae, *Ecklonia* and *Sargassum.* Dark green pixels were associated with mixtures of sparse brown algae and bare reef (rock). Dark red pixels were associated with mixtures of brown algae, sand and epiphytes.

These results are promising and demonstrate a potential for the coastal water reflectance model to provide benthic cover classification maps identifying sand, seagrass and brown algae, which are of interest to end users such as coastal water managers and environmental scientists.

Depth Validation

A historical hydro-acoustic data set of bathymetry was used to validate the model-retrieved depth. Image derived depths were co-located with the hydro-acoustic sounding depths and presented as a scatter plot (Figure 2.20). Figure 2.20 shows that depth retrieval capability of the model work well for the selected region. The mean difference in depth was calculated to be ~7%.

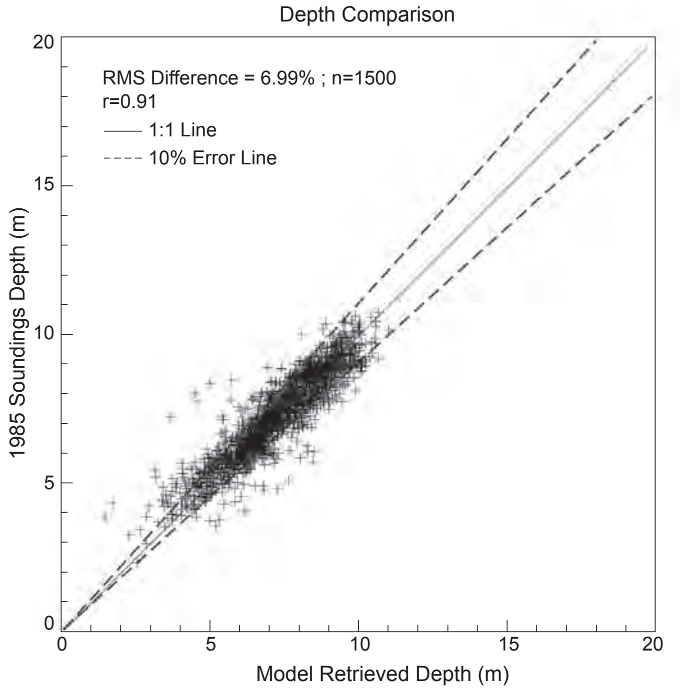

Figure 2.20: A scatter plot of the model-retrieved depth over the “scientific reference zone” compared with hydro-acoustic soundings.

Summary and Conclusions

A shallow water reflectance model that incorporates 3 bottom type spectra, typical of WA coastal waters, was developed during this PhD research. The model retrieval capabilities of bottom type were tested with a synthetic reflectance data set. The results indicate that the model has the ability to select the appropriate bottom type cover (sand, seagrass or brown algae) to water column depths ranging from 1 to 5m.

The model was then applied to HyMap reflectance data collected over Jurien Bay coastal waters. The model-retrieved bottom coefficients were used to generate a bottom type classification map identifying coverage of sand, seagrass and brown algae. A SRFME ground-truthing exercise was undertaken to validate the classification image. Comparison between *in situ* determined bottom type cover and model generated bottom type classification correlate well with each other, especially for dense cover of sand, seagrass and brown algae. The accuracy of the retrieved water column depth was evaluated by comparing historical hydro-acoustic soundings with the model-retrieved depth. The results indicate that the model is capable of estimating water column depth, accurate to around 10% up to depths of 15m.

These results are very promising and show potential for the routine mapping and monitoring of sea floor composition and bathymetry over coastal western Australian waters.

Acknowledgements

Thank you to the Strategic Research Fund for the Marine Environment (SRFME) for the financial support and opportunity to participate in CSIRO field cruises. A special thank you to Peter Brooker for his machining expertise utilised in the radiometer construction. Thank you to Peter Fearns for his continued assistance in passing knowledge in all aspects of remote sensing science. Thank you to my supervisors, especially Mervyn Lynch, for his encouragement and support. Thank you to Glen Lawson for his assistance in setting up the photonics lab designed for radiometric calibration and a final thank you to all my colleagues at RSSRG.

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List of Conference Presentations

Australian Marine Sciences Association, Fremantle, 10-12 Jul 02, "The Development and Validation of Algorithms for Remotely Sensing Case II Waters"

Australian Meteorological and Oceanographic Society, UWA, 10-12 Feb 03, "Hyperspectral Remote Sensing of Western Australian Coastal Waters"

SPIE - The International Society for Optical Engineering, San Diego, 3-8 Aug 03, "Hyperspectral Remote Sensing of Western Australian Coastal Waters"

Ocean Optics, Fremantle, 25-29 Oct 04, "Bottom Type Classification using Hyperspectral Imagery"

Australian Remote Sensing and Photogrammetry Conference, Fremantle, 18-21 Oct 04, "Characterisation of Seagrass Beds using HyMap Imagery"

Intended Thesis Submission Date: 24th of September 2007.

Publications

Klonowski, W., (2003). Hyperspectral remote sensing of Western Australian coastal waters, The International Society for Optical Engineering *5515,* 201-210.

2.2.6 Spatial, temporal and biogeochemical dynamics of submarine groundwater discharge in a semi-enclosed coastal basin

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Supervisor

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Executive Summary

This PhD study applied a variety of field sampling techniques in conjunction with surface water hydrodynamic modelling to achieve a process-based understanding of spatial, temporal and biogeochemical dynamics of groundwater discharge in marine waters. Field investigations were carried out in Cockburn Sound, a semi-enclosed marine basin located approx. 12 km south of Fremantle, Western Australia. This site was selected in part for its topical relevance to Western Australian marine health, but also for the complexity of groundwater discharge dynamics that arises from complex interactions between chemistry, hydrogeology, bathymetry and oceanography.

Results indicated that groundwater discharge was highly spatially and temporally heterogeneic. Additionally, the availability of post-discharge groundwater in marine surface waters was seasonally dependant on coastal conditions and hydrogeologic forcing. Biogeochemical studies of groundwater nutrient dynamics prior to discharge also indicated that, an understanding of the groundwater nutrient climate was essential for estimating groundwater input of dissolved materials to marine waters. The seasonal and spatial dynamics discovered by this work suggest that mid-winter is a key time of contaminant availability to surface water biota.

Introduction

This study aimed to traverse land and marine hydrogeology in order to examine biogeochemical and oceanography dynamics at the convergence of groundwater and marine water. A two-year groundwater and surface water sampling program was applied to capture the spatial, seasonal and biogeochemical dynamics of SGD in a sheltered, oligotrophic marine basin.

Objectives

Objective 1: Quantify groundwater discharge volume into a marine basin. This estimate will improve on past estimates of SGD by accounting for geological heterogeneity and unknown sources of groundwater input.

Objective 2: Identify if nutrient concentrations are altered on the pathway to discharge in the subterranean predischarge environment. Understanding nutrient biogeochemistry enables confident estimation of nutrient input to surface waters via groundwater discharge.

Objective 3: Identify spatial and temporal patterns of groundwater availability in the surface environment.

Study Site

The seasonal climate and occurrence of contaminated groundwater discharge in Cockburn Sound, Western Australia (Figure 2.21a) made this location an ideal site to study groundwater biogeochemistry. Superficial groundwater flows westerly from recharge zones to discharge into Cockburn Sound (Figure 2.21a). The superficial aquifer consists of an unconfined 5-10 meter surface layer of sand, underlain by a ~10 m layer of Tamala limestone (Figure 2.21b). Discharge from the sand aquifer occurs at the beach on the eastern shoreline, through a narrow (~5m wide) discharge zone (Smith *et al*., 2003).

West Australian ocean waters are nitrogen limited, with some elevation of nutrient concentrations occurring at the coast. Natural regional groundwater nutrient concentrations are near analytical detection limits, however up to 11,000 μmol.N/L of NO_x and 27,000 μmol. N/L of NH_4^+ have been measured in contaminated groundwater in the Cockburn Sound industrial strip (this study, and Smith et al., 2003). Nitrogen contamination of the surface waters from point and non-point sources have caused significant water quality decline and seagrass mortality. Despite removal of point-sources and the re-establishment of low surface water DIN concentrations, chlorophyll-*a* (Chl-*a*) concentrations still indicate elevated phytoplankton, and no recovery of seagrasses (Pearce et al., 2000, Kendrick et al., 2002). This uncoupling between remediation effort and ecosystem response prompted this study of the dynamics of contaminated groundwater discharge in Cockburn Sound.

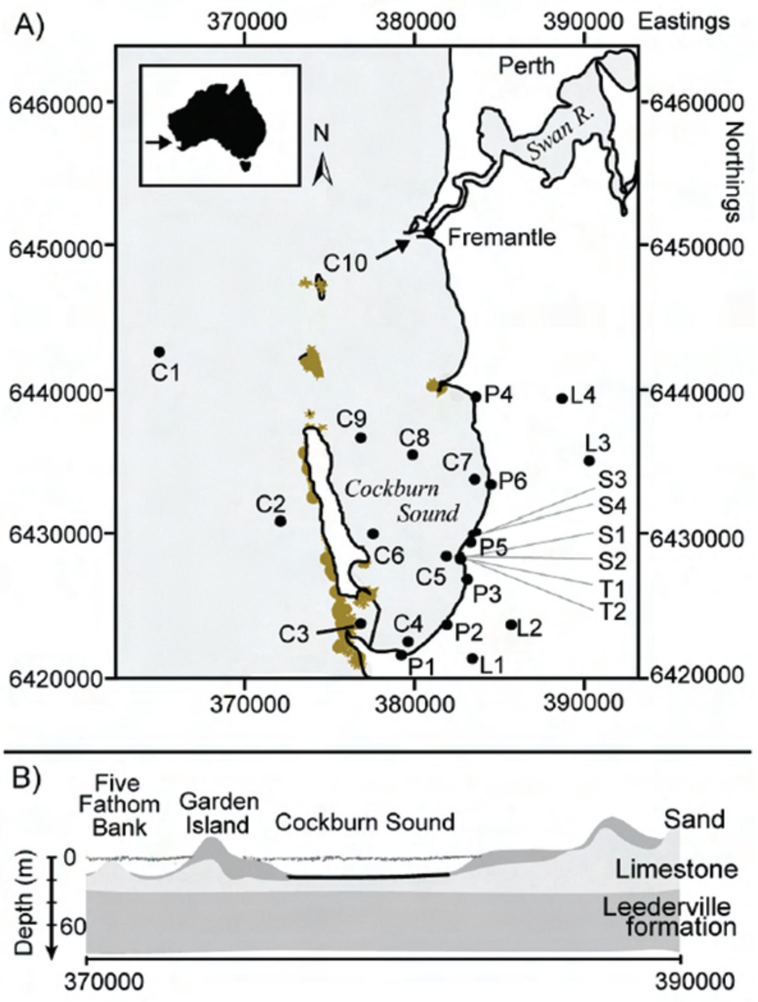

Figure 2.21: Surface water and groundwater sampling locations for geochemical tracers.

Methods

Geochemical Tracers in surface and ground waters

A seasonal sampling program of 10 marine (C1-C10, 2m depth) and 15 groundwater stations (4 'S' Sand aquifer, 2 'T' Limestone, 3 'L' Leederville and 6 'P' beach porewater) was conducted for radium and nutrient analysis (Figure 2.22a). Sampling dates were 22-24 Sept 2003 (End of Winter), 30 Nov-2 Dec 2003 (Early Summer), 8-10 Mar 2004 (Late Summer), and 15-20 Jul 2004 (Mid Winter). Salinity, temperature, pH and DO were measured at all marine and groundwater sampling stations. Ratios of short and long lived Ra isotopes were examined to identify sources and regions of groundwater discharge, and a Ra mass-balance was applied to estimate volume flux to surface waters.

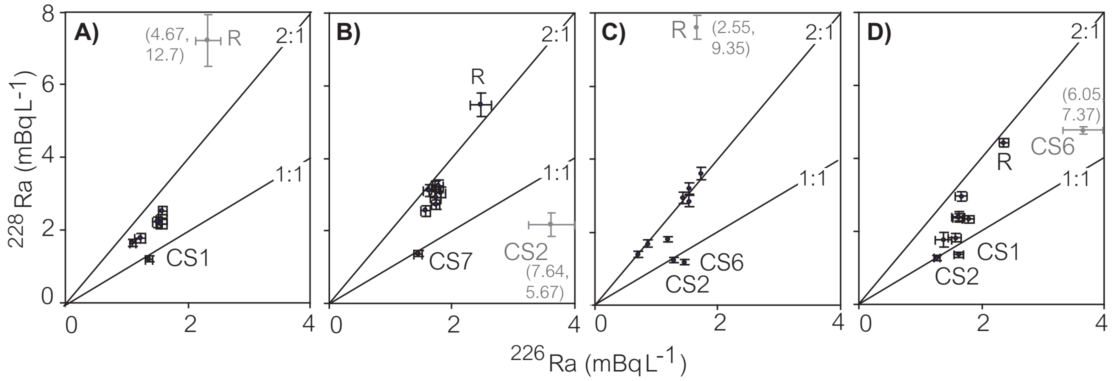

Figure 2.22: Spatial separation of surface water ^{226}Ra/^{228}Ra at different times of the year: A) end of winter, B) early summer, C) late summer, D) mid-winter. Riverine signal denoted by large R. Error bars are one standard error of instrumental counts. Off-scale values are written in grey type and are shown relative to ratio lines.

Nutrient chemistry in surface and ground waters

A 50 m transect of groundwater monitoring wells and nested beach piezometers were installed perpendicular to the shore and normal to the groundwater flow at an identified site of nitrogen groundwater contamination at Cockburn Sound. The transect facilitated a two-dimensional study of the predischarge environment, sampling groundwater from 2 or 3 depths beneath the water table in the unconfined sand aquifer (Figure 2.21b) at 5 inland locations and one surface water sampling location. Groundwater samples were collected during low tide on November 15 2004, April 8 and August 15 2005. These months correspond to an early summer, late summer and mid-winter seasonal sampling regime. Water samples were collected for nutrient and physical-chemical concentrations. A conservative mixing model and Dämkohler calculations were applied to the chemical data obtained in the sampling program to investigate the role of transport and biogeochemical reaction with discharge.

Hydrodynamic modelling of surface waters

A HAMSOM (Hamburg Shelf Ocean Model, Backhaus 1985, Stronach et al. 1993) model had been previously written for Cockburn Sound (Pattiaratchi, pers. comm.). HAMSOM is a three dimensional model employing Navier Stokes equations at Z coordinates and an hourly forcing (wind direction and speed). Hourly wind data was obtained from the meteorological station at Garden Island. The Cockburn HAMSOM model domain is a grid size of 100x100m, through 10 layers of 2m thickness. We applied this model to determine the surface water flow regimes for the four field-sampling periods, and to determine the origin and fate of water at the field stations.

Results

Geochemical Tracers in surface and ground waters

Groundwater from different geological sources display different ratios of Ra (^{228}Ra/^{226}Ra) and different ratios of these isotopes in marine surface waters act as a fingerprint of different groundwater inputs. Shallow groundwater and embayment surface water had a similar ^{228}Ra/^{226}Ra fingerprint of 2, while samples outside the marine embayment demonstrated a ^{228}Ra/^{226}Ra fingerprint of 1 (Figure 2.22). The ^{228}Ra/^{226}Ra ratios of water samples collected from deeper in the sand and limestone aquifers (1-20 m below the water table) were variable and did not indicate a clear origin of the ^{228}Ra/^{226}Ra = 1 groundwater (Figure 2.23). Vertical mixing between aquifers may be extensive and responsible for the spatially and temporally variable ratios. The presence of $^{228}Ra/^{226}Ra = 1$ at a number of sites within the embayment in summer also suggested that groundwater discharge pathways change seasonally.

From a mass-balance of ^{228}Ra activities in the embayment and groundwater, we calculated lower seasonal estimate of SGD ($0.27 – 0.87 \times 10^7$ L day^{-1}) than previous hydraulic groundwater calculations (Smith et al., 2003). We propose that we detected lower SGD than inland hydraulic calculations due to heterogeneic discharge: a proportion of the regional groundwater bypasses the embayment via preferential pathways/conduits in limestone, and discharges through limestone reefs and islands beyond the embayment.

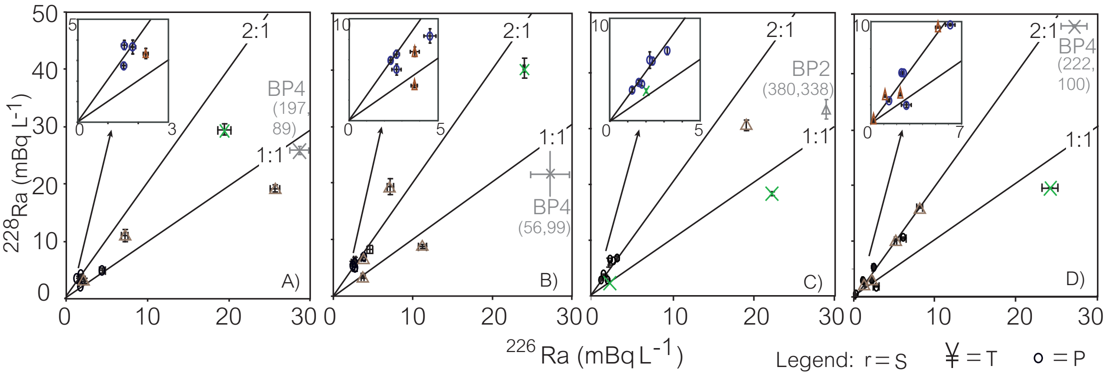

Figure 2.23: Mixed $^{226}Ra/^{228}Ra$ signal in groundwater from Safety Bay Sand aquifer (S), Tamala Limestone aquifer (T) and beach pore water (P) samples at different times of the year: A) end of winter, B) early summer, C) late summer, D) mid-winter. Error bars are one standard error of instrumental counts. Off-scale values are written in grey type and are shown relative to ratio lines.

Nutrient chemistry in surface and ground waters

An analysis of predischarge groundwater chemistry identified shifting gradients of dissolved inorganic nitrogen (DIN) species (nitrate + nitrite, NO_x, and ammonium, NH_4^+) in a sandy beach. Nutrient concentrations decreased with distance toward discharge. Elevated NO_x concentrations at the water table and elevated NH_4^+ in the mid-depths (Figure 2.24) corresponded to high and low oxygen conditions respectively, and suggested that both oxidation and reduction of DIN occurred prior to discharge. A two end-member mixing model revealed non-conservative behaviour of the DIN and identified regions of NO_x and NH_4^+ production and removal. Dissimilatory nitrate reduction to ammonium (DNRA) may be the dominant microbial process utilising N in the suboxic predischarge groundwater. Nitrification was limited to the top layer and denitrification only potentially occurred in winter. Dämkohler calculations reveal that the beach biogeochemistry was controlled by reaction processes at all times.

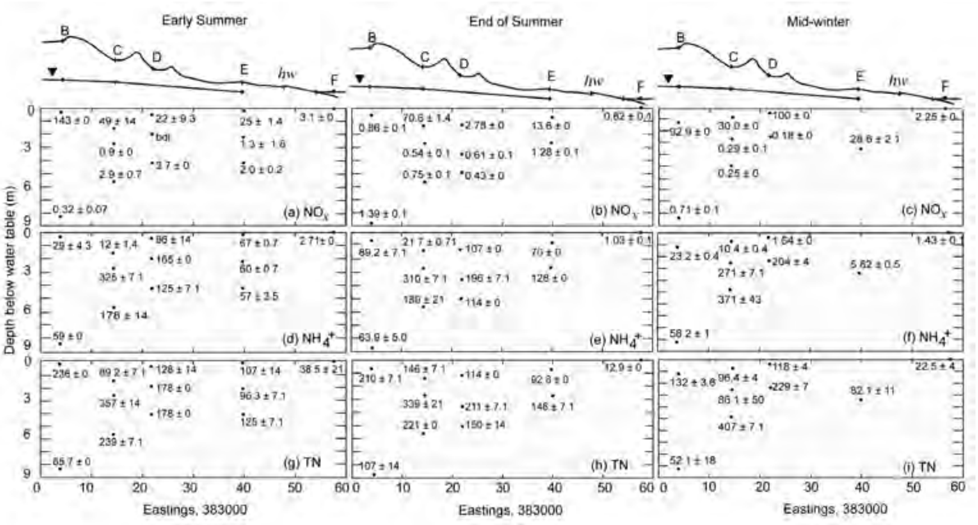

Figure 2.24: Seasonal groundwater predischarge nitrogen concentrations a-c) NOx (μmol N L^{-1}) at the end of winter, end of summer and mid-winter; d-f) NH_4^+ (μmol N L^{-1}) at the end of winter, end of summer and mid winter; g-i) TN (μmol N L^{-1}) at the end of winter, end of summer and mid winter.

Hydrodynamic modelling of surface waters

Activities of short-lived Ra geochemical tracers (^{224}Ra and ^{223}Ra) in 10 surface water sampling locations indicated a greater presence of groundwater at the eastern shoreline and on the west side of the island and limestone reefs. This spatial pattern was observed during the end of winter, early summer and late summer. In mid-winter the tracers demonstrated an opposite spatial pattern, with high levels away from shorelines and lower "marine-like" signals at groundwater discharge localities. Surface water circulation modelling showed that the same northward-flowing current regime dominated in the embayment during the end of winter, early summer and late summer, while southward flowing currents dominated surface currents in mid-winter. Particle tracking modelling of tracer movement away from sampling stations indicated that surface water currents at the end of winter, early summer and late summer would confine discharged groundwater at the shoreline, to be flushed northward out of the system (Figure 2.25 A-C). In mid-winter, westerly tracer movement away from the shoreline and across the embayment (Figure 2.25 D) suggests groundwater and contaminants are made more widely available across the system at this time.

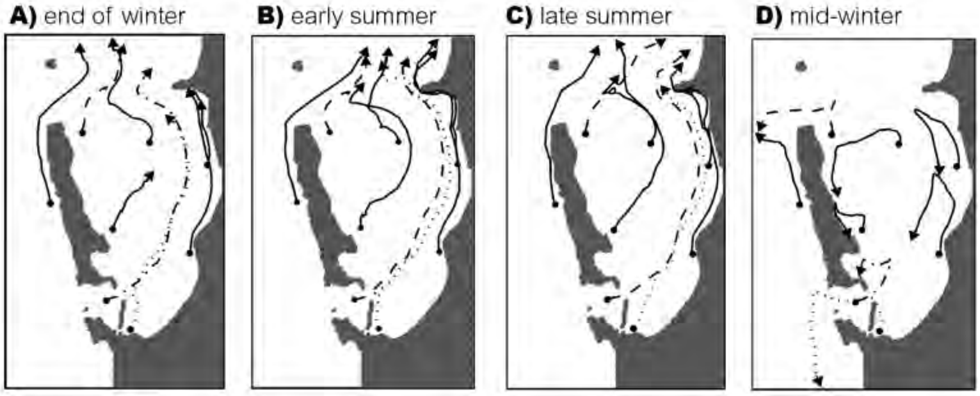

Figure 2.25: HAMSOM simulation of water transport from surface sampling stations over 10 day during: A) the end of winter, B) early summer, C) late summer , D) mid-winter.

Discussion

The outcomes of each research objective were synthesized into an overall process understanding of SGD in a marine embayment where there were multiple groundwater sources. Radium geochemical tracers from two different groundwater sources were identified in the surface waters, and the prevalence of the tracers varied spatially and seasonally. Minimum groundwater discharge was quantified at the end of winter, and a maximum in the early summer. We also showed that during summer, biogeochemical reactions in the groundwater may cause an elevation of NH_4^+, possibly by DNRA conversion of the NO_x or ammonification of organic nitrogen within the system. The end-of-summer profile of the beach groundwater showed a pool of NH_4^+ that spread out to resemble a subterranean plume again in mid-winter. From surface water modelling we demonstrated that, in mid-winter, shoreline surface waters were transported across the system prior to flushing. Calculated residence times did not vary for the different times of the year, however transport pathways and extent of availability of groundwater did vary significantly and this may be more important than flushing time to the surface water quality of this system. Groundwater nutrients may be more available to primary producers throughout the embayment in mid-winter than at other times of the year. Environmental guidelines recommend that monitoring of these marine surface waters is performed during summer, yet from this study it was apparent that groundwater source, biogeochemical composition and surface transport switched seasonally and that mid-winter may be a potentially key time of nutrient delivery within the system.

Acknowledgements

This study was supported by grants from CSIRO SRFME, Kwinana Industries Council (KIC) and The Centre for Groundwater Studies. Logistical support and provision of field equipment provided by the Department of Environment Marine Division, Dr Martin Lourey (CSIRO SRFME). HAMSOM modelling assistance provided by Prof Chari Pattiaratchi, Dr Alexis Berthot (UWA) and Prof Jan Backhaus (Universität Hamburg). Field assistance volunteered by Deb Read, Nikki Grieve, Kelsey Hunt, Alisa Krasnostein and Selva Marimuthu is very gratefully acknowledged.

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Conference attendance and presentations

Australian Society for Limnology. Margaret River, Western Australia. October 2002

Australian Marine Sciences Association 2002: Tropical Temperate Transitions. Fremantle, Western Australia. July 2002

Gordon Research Conference Permeable Sediments. Lewiston, Maine, USA. June 2003

Planned date for thesis submission: March 2007

Awards

2003	Postgraduate Travel Scholarship, Gordon Research Conferences – Permeable Sediments
2004	Best Presentation, CSIRO SRFME Symposium, Floreat, Western Australia
2005	Centre for Groundwater Studies International Travel Award
2006	Postgraduate Travel Scholarship, Gordon Research Conferences – Permeable Sediments

Publications

Loveless, A. and Oldham, C.E. (submitted) Biogeochemical reactions control groundwater DIN concentrations in coastal permeable sediments. *Biogeochemistry*, submitted March 2006.

Loveless, A., Oldham, C. and Hancock, G. (in prep) Radium isotopes reveal a bottom end estimate of groundwater volume flux and heterogeneic patterns of discharge in a complex semi-enclosed coastal basin.

Loveless, A. and Oldham, C.E. (in prep) Short-lived radium isotopes and HAMSOM surface water modelling reveal significant episodes of contaminant transport in a semi-enclosed marine basin.

Loveless and Moore (in prep) Scales and Assumptions of the Radium Technique for estimating Submarine Groundwater Discharge.

Evans, M., Loveless, A. and Oldham, C. (in prep) Estimation of residence time of groundwater in the marine-groundwater mixing zone using field data and modelling.

W. Burnett, W., Bokuniewicz, H., Cable, J., Charette, M., Kontar, E., Krupa, S., Loveless, A., Moore, W., Oberdorfer, J., Povinec, P., Stieglitz, T., Taniguchi, M. (submitted) Quantifying Submarine Groundwater Discharge in the Coastal Zone via Multiple Methods. *Science of the Total Environment*, submitted January 2006.

2.2.7 Remotely sensing seasonal and interannual oceanic primary production for Western Australian waters

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Executive Summary

An algorithm was developed to estimate phytoplankton primary production from remotely sensed sea surface reflectance data (collected *in situ* or via space based platforms). MODIS-Aqua ocean colour data were input to the algorithm to obtain estimates of phytoplankton absorption, the light field within the water column and primary production at three SRFME field sites over the course of the SRFME field program (2002-2004). At the two deep validation sites (stations C, 100-m, and E, 1000-m), the outputs of the algorithm agree, within uncertainty, with observed co-located *in situ* measurements. Retrievals at shallow sites (<15-m) remain problematic.

Introduction

Our knowledge of phytoplankton production in the southeast Indian Ocean near Western Australia is limited by the very few measurements of carbon uptake made in this region during the last 50 years. This data set is not sufficient to form an understanding of the seasonal or interannual variability present in production, a key variable in current global biogeochemical models.

Space based remote sensing provides broad scale measurements of ocean properties with high spatial and temporal resolution, allowing the dynamic nature of the ocean surface and its properties to be observed. Figure 2.26 displays a typical June scene with the Leeuwin Current flowing along the edge of the continental shelf and meandering offshore south of 29°S. Figure 2.26 demonstrates the fine structure present in both sea surface temperature and surface chlorophyll-a (a proxy for phytoplankton biomass) and indicates the variability that may be found in primary production on both small and basin scales.

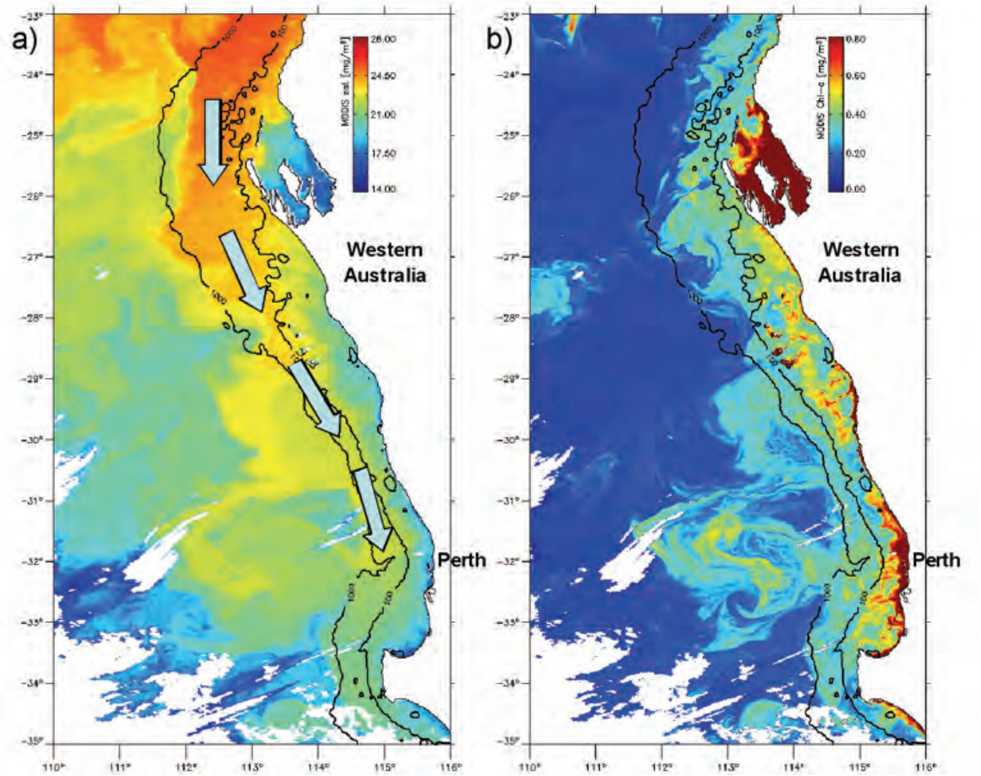
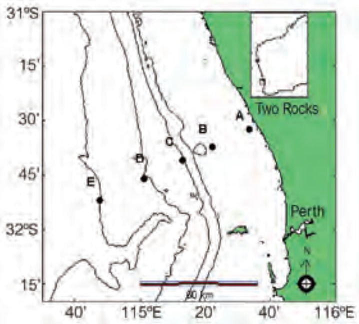


Figure 2.26: Remotely sensed data from MODIS-Aqua for the west coast of Australia on 19 June 2003; a) Sea surface temperature b) chlorophyll-*a* (phytoplankton proxy). The black lines indicate the 100 and 1000-m isobars. The path of the Leeuwin Current is denoted by the large blue arrows.

Study Site

To support the development of a remotely sensed primary production algorithm, measurements of primary production (24 hour ^{14}C incubations) and bio-optical properties were obtained during the multidisciplinary SRFME field experiments conducted along the SRFME Two Rocks Transect (TRT, Figure 2.27) between early 2002 and late 2004. Primary production was routinely measured at stations A, C and E, while optical profiles were conducted at these sites opportunistically.



Station	Longitude (°E)	Latitude (°S)	Depth (m)
A	115.598	31.520	15
B	115.463	31.577	40
C	115.296	31.648	100
D	115.123	31.722	300
E	114.909	31.812	1000

Figure 2.27: Map and table indicating the location of SRFME field sites (A-E). Primary production measurements (24 hour ^{14}C incubations) were carried out at stations A, C and E.

Algorithm Development

A model was developed to estimate phytoplankton production from remotely sensed variables. The model is applicable to both *in situ* and space based measurements of sea surface reflectance (SSR). The conceptual framework is shown in Figure 2.28 and detailed below.

The measured reflectance is used to retrieve the in-water inherent optical properties (IOPS; including backscattering, b_b, absorption by coloured dissolved organic matter, a_g, and phytoplankton, a_j) through the inversion of an appropriate optical model. The Semi-Analytical model (SAM, Lee *et. al*., 1999) is employed for *in situ* measurements of SSR, while the Quasi-Analytic Algorithm (QAA, Lee *et al*, 2002) is used for space based SSR measurements. The QAA was developed to retrieve IOPs within the constraints of multi-spectral sensors, while the SAM can take advantage of the additional information within hyperspectral data sets. The retrieved IOPs are combined with the sub-surface irradiance, $E_d(0^-)$, and an optical model to propagate the surface light field through the water column.

These light field statistics and IOPs are then used to estimate photoinhibition and the quantum efficiency of photosynthesis, Φ_m. Photoinhibition occurs when phytoplankton are exposed to intense light fields; the photo-systems necessary for photosynthesis are degraded/destroyed and photosynthesis decreases. The quantum efficiency of photosynthesis, Φ_m, is used to link energy absorption by phytoplankton with primary production. The model of Finenko *et. al*. (2002) was employed to form an estimate of Φ_m. While the model was developed for the Black Sea it was found to be applicable in the Atlantic (Finenko *et. al*. 2002), thus it has been assumed that the model is generally applicable. It should be noted that no measurements of photoinhibition or Φ_m were carried out during the SRFME field experiments.

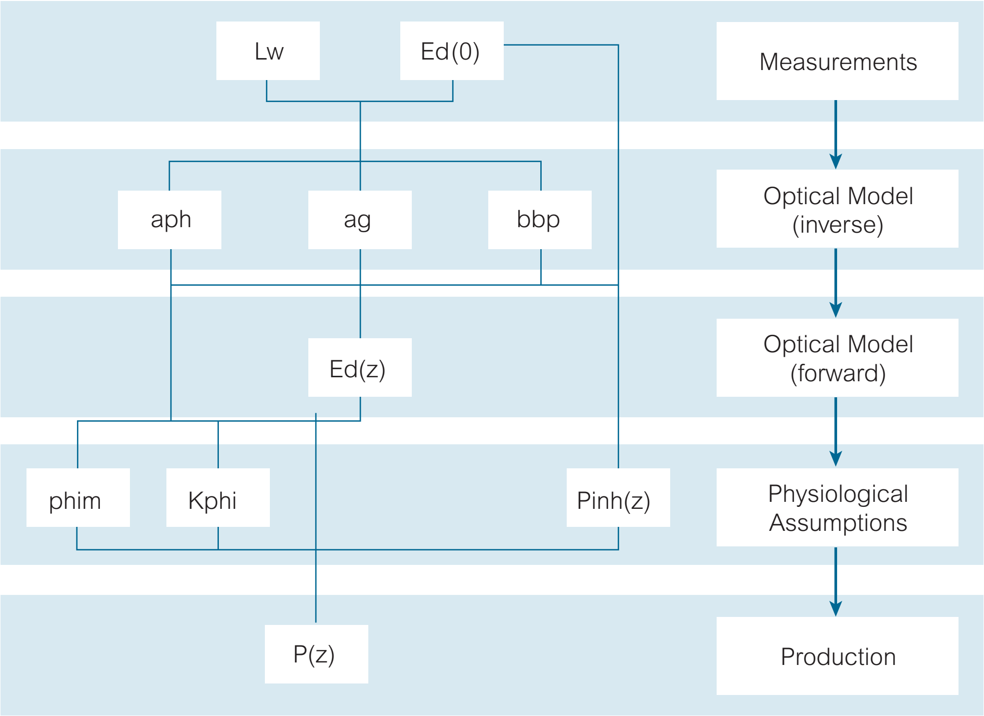


Figure 2.28: Conceptual framework of the algorithm. Optical measurements are inverted to obtain in-water properties. These in-water properties are then propagated through the water column and combined with physiological parameters to obtain an estimate of production at depth.

The final stage of the algorithm computes integrated primary production. This is achieved by calculating production at depth and then integrating over the region where production is possible (the euphotic zone). Production at depth is computed through,

$$P(z)=\frac{k_{\phi}\exp(-vQ(z))}{k_{\phi}+Q(z)}\int_{400}^{700}\Phi_{m}a_{\varphi}(\lambda,z)E(\lambda,z)\,d\lambda$$

where k_{f} is a constant that represents the change in Φ_{m} with depth (Kiefer and Mitchell, 1983) and v accounts for photoinhibition (Lee et. al., 1996), Φ_{m} is obtained from the model of Finenko et. al. (2002) and a_{f} is retrieved from SSR through SA or QAA.

$$Q(z)=\int_{400}^{700}E(\lambda,z)\,d\lambda \text{ and } E(\lambda,z)=E_{d}(\lambda,0^{-})\exp(-k(\lambda)z),$$

where $E_d(\lambda,0^-)$ is the downwelling irradiance just below the sea surface and $k(\lambda)$ is the diffuse attenuation coefficient. Integrated production is simply

$$P=\int_{0}^{Z_{eu}}P(z)\,dz,$$

where Z_{eu} is the depth of the euphotic zone, estimated as the depth where Photosynthetically Available Radiation (PAR) is diminished to 0.1% of the surface value.

Results

The *in-situ* model was applied to data collected using a hyperspectral profiling radiometer (HydroRad-2) and compared to co-located measurements of primary production. An example of the output for the three SRFME production sites (A, C and E) from the January 2004 field experiment aboard the Southern Surveyor (SS2004/01) is displayed in Figure 2.29. In general, retrievals at sites C and E fall within 25% of collocated measurements. Retrievals at station A are problematic, with consistent underestimation of production in the shallow (< 15-m) coastal waters.

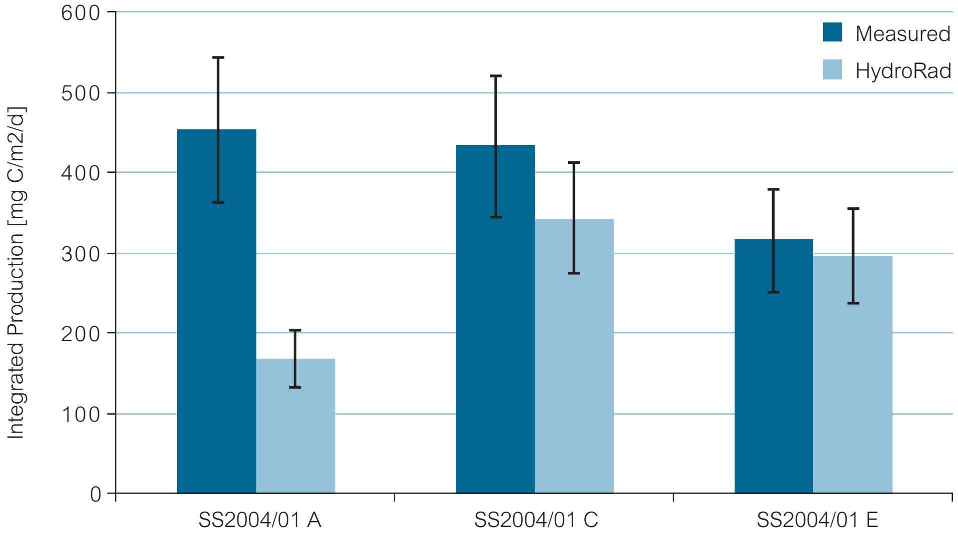


Figure 2.29: Comparison of measured and modelled primary production at three SRFME stations (A, C and E) during SS2004/01. The dark bars represent 24 hour ^{14}C incubations (courtesy of S. Pesant), while light bars indicate results from the model using *in situ* HydroRad profiles. Agreement (within uncertainty) is not achieved at the shallow, coastal site (depth of 15m).

The model to estimate production from space-based platforms (using QAA rather than SA) was applied to MODIS-Aqua data over the course of the SRFME field experiments. As an initial check of the algorithm, the reconstructed light field was compared to a series of measurements. Depth dependence of PAR is of primary importance to many ecological studies. Figure 2.30 displays the measured and modelled PAR at Station C over the course of the SRFME field experiments. It should be noted that 1) measurement time varied, 2) the instrument was sometimes shaded, 3) the instrument cannot provide accurate measurements below 0.05 μE/m^2/s and 4) retrievals are obtained for clear sky conditions only. Bearing these limitations in mind, PAR retrievals yield temporal patterns at Stations C and E (not shown) similar to those observed during the field program.

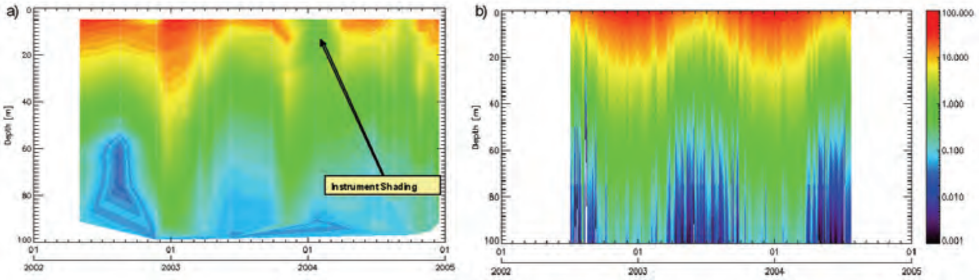


Figure 2.30: Photosynthetically available radiation (PAR, units of μE/m^2/s) at Station C as a function of time and depth a) measured on CTD and b) as output by the model using remotely sensed data (MODIS-Aqua). Near surface values from the CTD are rejected due to poor data quality and are affected by instrument/ship shading. Note the logarithmic scale.

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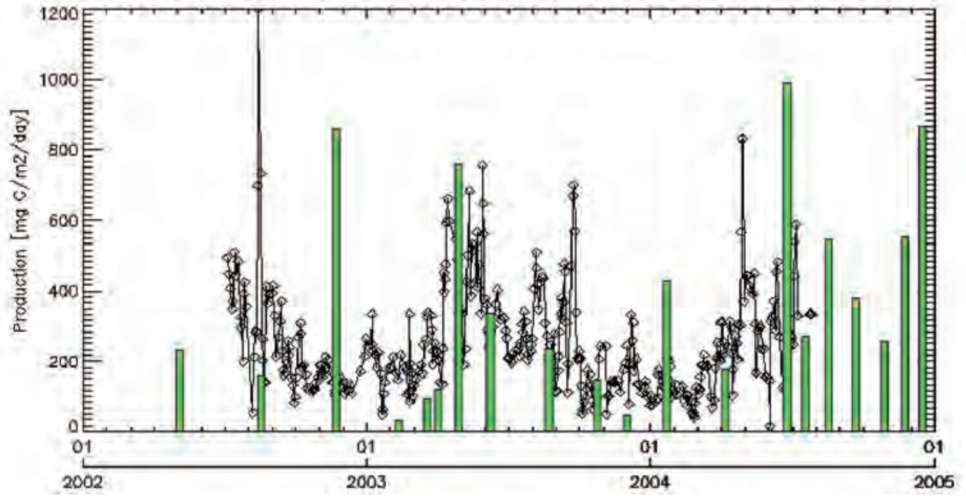

Figure 2.31: Integrated phytoplankton primary production at station C for the period of the SRFME field experiments. Green bars indicate the results of 24 hour ^{14}C incubations (courtesy of S. Pesant), connected black diamonds are remotely sensed estimates (MODIS-Aqua).

Discussion

To achieve the goals of this research, aspects of the biological and bio-optical oceanography of the southeast Indian Ocean have been investigated using data from SRFME field experiments and space based platforms. The field data were used to validate the remotely sensed ocean products (including the water-leaving radiance, surface chlorophyll a concentration and column-integrated phytoplankton biomass).

A spectral, depth resolved, model of primary production was developed, independent of field data, for use with *in situ* and remotely sensed SSR data. The outputs of the model have been compared to field measurements and display general agreement at sites with depths greater than 15-m.

Acknowledgements

I would like to thank my supervisors and Curtin colleagues for their invaluable assistance; Tony Koslow for the opportunity to participate in a number of field experiments; Stephane Pesant for access to primary production data; Lesley Clementson, Christine Hanson and Tim Harriden for laboratory analysis; the masters, crew and science staff aboard the *R/V Southern Surveyor*, *Naturaliste*, and *Maritime Image* for their assistance during SRFME field experiments.

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Planned date for thesis submission: January 2007

Publications

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Majewski, L.J. (in prep.). Remote sensing of phytoplankton production at the Abrolhos Islands, Western Australia.

Majewski, L.J. and S. Pesant (in prep.). Structure and dynamics of the pelagic ecosystem along an onshore-offshore transect off southwestern Western Australia, 2002-2004: primary production models and validation of remote sensing algorithms.

2.2.8 Ichthyoplankton assemblage structure in coastal, shelf and slope waters off south-western Australia

Investigator / Institution

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Supervisors

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Executive summary

Spatial and temporal variation in larval fish assemblages collected from the Two Rocks transect has been characterized, and related to available environmental variables. Assemblages were shown to vary primarily with water depth, with different families dominating inshore, shelf, and offshore assemblages, and with season. Correlation of larval fish assemblages from summer, and from winter, with environmental variables highlighted the strong influence of water depth, and water mass on broadly structuring assemblages. In winter, microzooplankton cell densities and water temperature had a further structuring influence on assemblages, while in summer, water mixing rates for the five days prior to sampling, and surface salinities were also correlated to assemblage structure.

Introduction

Project aims

This project aimed to document the seasonal and spatial variability in ichthyoplankton (larval fish) assemblages in inshore, shelf and offshore waters off Western Australia, and to relate this variability to environmental (physical, biological and meteorological) parameters.

Methods

Sample collection

Sampling for this study was carried out along an 84km transect, located off the town of Two Rocks (Figure 2.32). Five sampling stations (A - 18m depth, B - 40m, C - 100m, D - 300m, E - 1000m), were sampled along the transect line. The sampling program involved monthly sampling (where possible) for a period of two and a half years; August 2002 to December 2004. All stations were sampled on a quarterly basis, and the three inshore stations were sampled monthly. Samples were taken with replicated oblique bongo net tows fitted with 355µm mesh (mouth area 0.196m^2). Larval fish were removed from preserved plankton samples with the aid of a dissecting microscope, and then identified to family, and species where possible, using relevant literature (e.g., Leis and Carson-Ewart, 2000; Neira *et al.*, 1998).

Data analyses

Using the flowmeters fitted to the plankton nets, the volume of water sampled in each tow was calculated, allowing the expression of larval fish numbers as densities per cubic metre of seawater. Where replicate bongo tows existed, mean densities and standard errors were calculated. The relationship between larval fish assemblage structure and selected environmental variables was compared using the BIOENV procedure, in the Primer-6 software package (Clarke and Warwick., 2005).

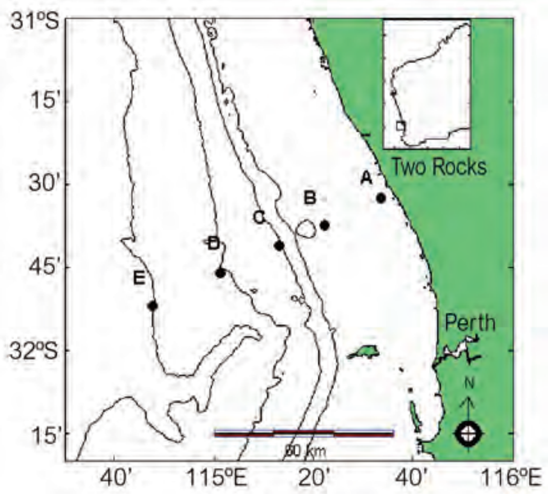

Figure 2.32: Study area off south-western Australia, showing transect and stations sampled (H. Paterson).

The directional effects of the environmental variables identified using the BIOENV procedure on larval fish assemblages were then examined using Principle Components Analysis (PCA), also in Primer-6. The PCA procedure uses the Euclidean distance similarity measure to plot points in space, and is therefore suitable for use with environmental data (Clarke and Warwick, 2001). All environmental data were fourth-root transformed prior to analysis, to remove skew effects, and then normalised. Normalisation of environmental data removed the effect of different units of measurement. CTD and nutrient data from the SRFME Biophysical Oceanography project was used (Koslow *et al.*, Vol. 2, see Ch. 3), as well as microzooplankton cell densities (Paterson et al., this volume, see section 2.2.9). The environmental variables used in all BIOENV analyses are shown in Table 2.3. Meteorological data was obtained from the Bureau of Meteorology.

Table 2.3 Environmental variables used in BIOENV analyses to compare with larval fish assemblages. Variables which used a mean value for the three days prior to sampling are denoted by "avg. 3", those representing a mean value for five days prior to sampling are denoted by "avg. 5". CM denotes chlorophyll maximum layer.

Physical and biological variables	Meteorological variables
Water depth (m)	Max. air temperature (°C) (avg. 5).
Sea surface temperature (SST)	Rainfall (mm) (avg. 5)
Salinity: surface	Solar radiation (MJ/m^2) (avg. 5)
Photosynthetically available radiation (PAR): surface	Hours of sun (avg. 5)
Water temperature: CM	Mean air temperature (°C) (avg. 5)
Salinity: CM	Wind speed (m/s) (avg. 5)
PAR: CM	Wind direction (to) (avg. 5)
Water Mass	Mixing (m/s^3) (avg. 5)
Nitrates/nitrites (NO_x): Surface	Max. air temperature (°C) (avg. 3).
NO_x: CM	Rainfall (mm) (avg. 3)
Julian day	Solar radiation (MJ/m^2) (avg. 3)
Microzooplankton cells/L: surface	Hours of sun (avg. 3)
Microzooplankton cells/L: CM	Mean air temperature (°C) (avg. 3)
Maximum chlorophyll α	Wind speed (m/s) (avg. 3)
	Wind direction (to) (avg. 3)
	Mixing (m/s^3) (avg. 3)

Results

A total of 24 865 fish larvae were identified from samples over the two and a half years of sampling, comprising 148 taxa from 93 families. Taxa collected included those from inshore reef families, such as the Blennidae, Gobiidae and Monacanthidae, larvae of small pelagic families, such as the Clupeidae and Carangidae, and many oceanic taxa, from the Myctophidae, Phosichthydae and Gonostomatidae. Some tropical vagrant larvae were found, mostly from outer shelf stations during summer and autumn, such as *Chromis* sp. 1 (Pomacentridae) and *Psenes whiteleggii* (Nomeidae). Calculation of the percentage composition of each sampling station (A to E) by family revealed strong spatial separation in larval fish assemblages with water depth (Figure 2.33). Fish larvae from the Gobiidae (20%), Clinidae (16%) and Tripterygiidae (13%) were the most abundant inshore (Station A). On the shelf, at stations B and C, fish larvae from the Clupeidae were the most abundant (18% and 22% respectively), followed by those from the Labridae (18% and 15% respectively). However, station B assemblages contained a higher percentage of Engraulidae (9%) and Creedidae (7%) fish larvae than station C, while station C assemblages contained more larvae from the Myctophidae (14%), and Acropomatidae (4%). Offshore, at stations D and E, larval fish assemblages were dominated by species from the Myctophidae (57% and 58% respectively). Fish larvae from the Phosichthydae (13% and 10%), and Gonostomatidae (3% and 7%) were also abundant at these stations.

Larval fish densities/m^3 were highly variable, and often seasonal (Figure 2.34). Densities at station A were the most predictable with season, being highest in the summer months (up to 4.14 fish larvae/m^3 in December 2004), and lowest during winter (down to 0.06 fish larvae/m^3 in July 2004). Densities at stations B and C were more variable, with very high densities in the last three months of 2004 (up to 7.43 fish larvae/m^3 at station B in October 2004). Stations D and E had lower, less variable densities, ranging from 0.03 fish larvae/m^3 in August 2003 to 0.73 fish larvae/m^3 in December 2003, both at station E. Some inter-annual variability in densities was evident, particularly at stations B and C, during spring and summer.

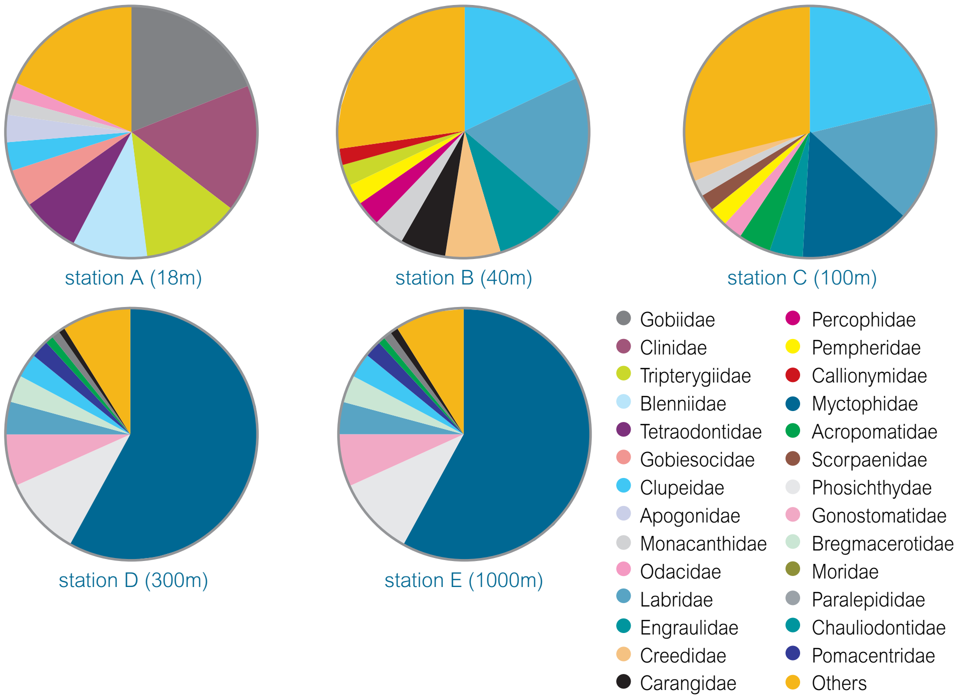

Figure 2.33: Percentage composition by family of the larval fish assemblage found at sampling stations A to E along the Two Rocks transect.

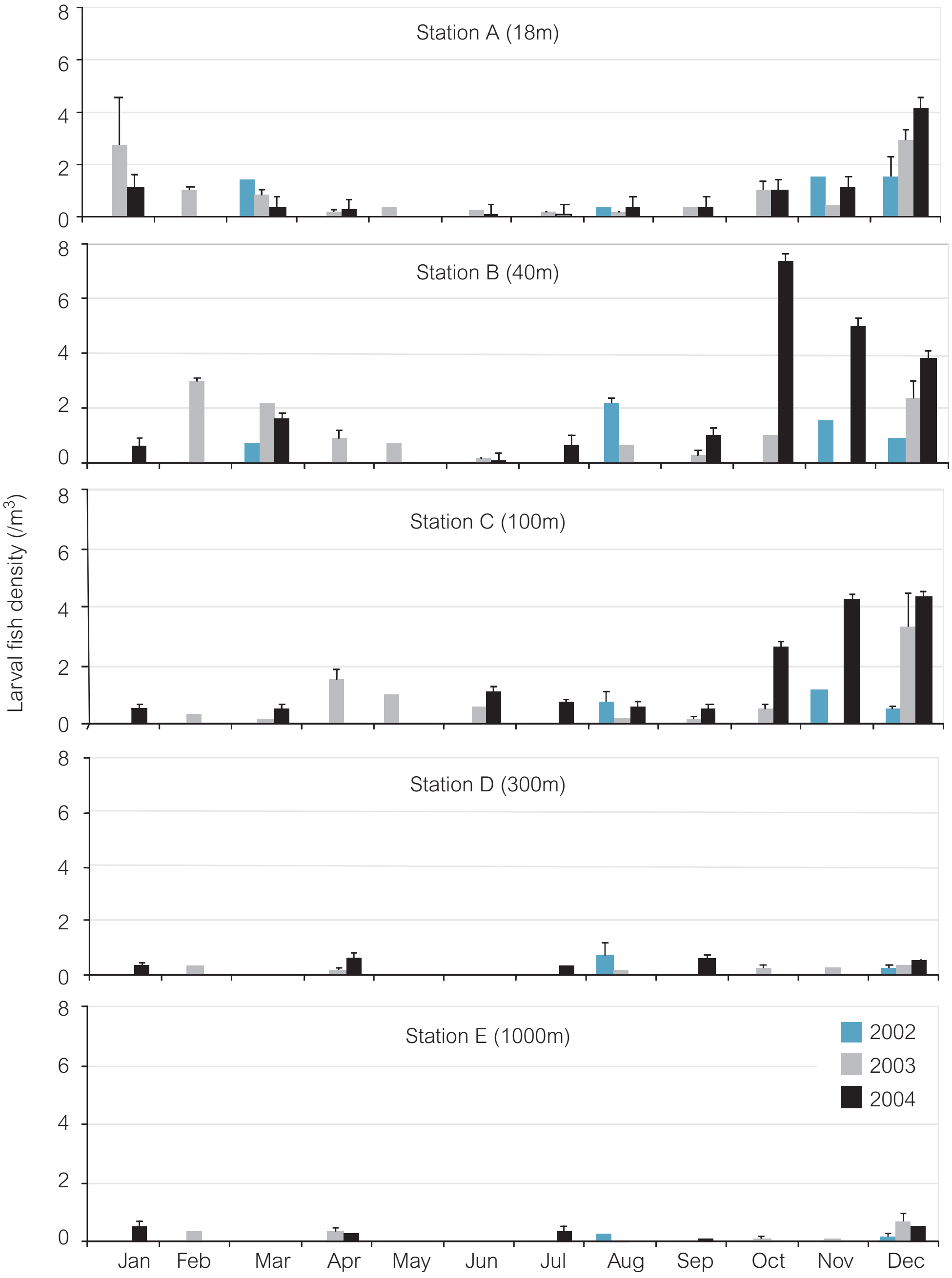

Figure 2.34: Density /m^3 of larval fish at stations A to E, August 2002 to December 2004.

BIOENV analysis was completed on all larval fish assemblage data, and then on various subsets of the data, to elucidate those environmental variables best correlated with assemblages within and between stations and seasons. Results from analyses within all winter samples, and within all summer samples, are displayed using PCA (Figure 2.35). When samples from winter were compared, the clear separation of samples from station A was evident. The water column where these samples were taken was colder at the chlorophyll maximum layer ("Temp. CM"), and belonged to a different water mass to samples from other stations (winter inshore as opposed to Leeuwin Current). Water depth was shown to structure the rest of the sampling stations, with microzooplankton cell density (microzoo. surf.) at the surface, and salinity at the CM also separating samples along approximately the same axis as water depth. Larval fish assemblages were shown to reflect these environmental characteristics, with station A assemblages distinct, and a less defined gradient existing from stations B to E. Summer larval fish assemblages were shown to be well matched to physical parameters, with samples clearly structured along a gradient of water depth. There was further separation along PC2 by mixing (mean for 5 days previous to sampling: "mixing avg. 5"), with surface salinity showing only a slight influence. Larval fish assemblages were well aligned with the water depth gradient from left to right, and also showed some weak affinity with the mixing gradient along PC2 (Figure 2.35).

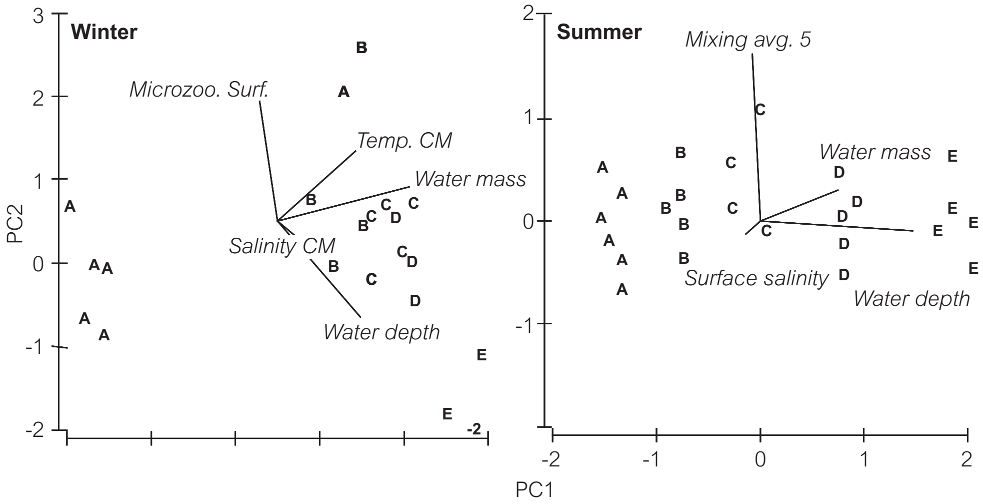

Figure 2.35: PCA ordination of season sub-groups of samples by selected environmental variables identified using the BIOENV procedure: winter and summer samples. Labels represent station at which sample was taken.

Discussion

Results from this study suggest that larval fish assemblage structure was spatially and temporally variable, in response to water depth, water mass, and season. Different family groups dominated the inshore, shelf and offshore sampling stations. Larvae of small reef fishes, from families such as the Gobiidae and Blenniidae, were abundant inshore, while larvae of pelagic species, such as those from the Clupeidae and Carangidae dominated shelf assemblages. Offshore assemblages were largely comprised of the larvae of oceanic species, such as those from the Myctophidae, Phosichthydae and Gonostomatidae. Larvae from the Clupeidae (*Sardinops sagax*, *Etrumeus teres*), Engraulidae (*Engraulis australis*) and Carangidae (*Pseudocaranx* spp., *Trachurus novazelandiae*) represented the only commercially significant species found in any significant numbers. Larvae of other commercially important inshore and reef fish (e.g., *Glaucosoma herbraicum*, *Pagrus auratus*; *Pomatomatus saltatrix*) were caught either in very low numbers or not at all. This suggests that the open shelf and offshore water sampled in this study may be more important for larvae of pelagic species than for larvae of reef species. Inshore assemblages were found to be the most seasonal, with offshore assemblages the least so. Assemblage structure tended to mirror the seasonal variation in the oceanographic conditions found during each season, with the distribution of species across the shelf and offshore apparently strongly influenced by the current regime at the time of sampling. Correlation of larval fish assemblages to environmental variables showed water mass and water depth to be strongly correlated to assemblages, with smaller scale biological and meteorological factors also shown to be potentially important. Comparison between results of this analysis within winter samples, and within summer samples highlighted the contrasting oceanographic conditions, and hence larval fish assemblages at the two different times of year. In winter, inshore larval fish assemblages were strongly distinct from those at stations B to E, which showed less clear separation. This corresponded to the lower water temperatures found at station A in winter, which may be several degrees cooler than stations B to E, in the Leeuwin Current (Pearce et al., this volume). In summer, larval fish assemblages were also well distinguished by water depth, but the added water mass of the Capes

Current appeared to further distinguish assemblages from the two shelf stations (B and C). The added influence of mean mixing rates in the five days prior to sampling suggests that meteorological influences on parameters such as stratification may further structure larval fish assemblages within broader water mass groups.

Acknowledgements

Thanks are extended to all other members of the SRFME Biophysical Oceanography project, in particular Nick Mortimer, Harriet Paterson and Alan Pearce, for their help with data analyses and interpretation.

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Muhling, BM, Beckley, LE and Koslow, JA, (2005) "*Ichthyoplankton assemblages off south-west Australia and the influence of regional and local oceanography*", oral presentation, 7th Indo-Pacific Fish Conference, Taipei, Taiwan.

Muhling, BM, Waite, AM, and Beckley, LE, (2005) "Effects of food web structure and productivity patterns on the ichthyoplankton of two meso-scale Leeuwin Current eddies", oral presentation, IOMEC Indian Ocean Conference, Perth, Western Australia.

Muhling, BM, and Beckley, LE (2004) "*Ichthyoplankton in two meso-scale Leeuwin Current eddies: Preliminary results*", oral presentation, AMSA national conference, Hobart, Tasmania.

Muhling, BM, Beckley, LE and Koslow, JA, (2004) "*Ichthyoplankton assemblage structure in coastal, shelf and slope waters off Western Australia*", oral presentation, AMSA national conference, Hobart, Tasmania.

Thesis submitted June 2006 and PhD subsequently awarded.

Publications to date

Muhling, B.A. and L.E. Beckley (submitted). Seasonal variation in horizontal and vertical structure of larval fish assemblages off south-western Australia, with implications for larval transport. (Submitted to *Journal of Plankton Research*)

Muhling, B.A, L.E. Beckley, J.A. Koslow and A.F. Pearce (in press). Larval fish assemblages and water mass structure off the oligotrophic south-western Australian coast. *Fisheries Oceanography.*

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Waite, A.M., P.A. Thompson, S. Pesant, M. Feng, L.E. Beckley, C. Domingues, D. Gaughan, C. Hanson, C. Holl, J.A. Koslow, M. Meuleners, J. Montoya, T. Moore, B.A. Muhling, H. Paterson, S. Rennie, J. Strzelecki and L. Twomey (submitted). The Leeuwin Current and its Eddies: An Introductory Overview. (Resubmitted after review to *Deep Sea Research II* - special issue)

Waite, A.M., B.M. Muhling, C. Holl, L.E. Beckley, J. Montoya, J. Strzelecki, P.A. Thompson and S. Pesant (submitted). Food web structure in two counter-rotating eddies based on d ^{15}N and d ^{13}C isotopic analyses. (Resubmitted after review to *Deep Sea Research II* - special issue)

2.2.9 Microzooplankton off south west Western Australia: Their spatial and temporal variations and impact of phytoplankton

Investigator / Institution

Harriet Paterson	The University of Western Australia.

Supervisors

Dr Tony Koslow	CSIRO
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Executive Summary

Seasonal and spatial variability in the microzooplankton assemblage off south western Western Australia was evident. The microzooplankton formed an important component of the planktonic food web in this region, consuming ~60% of the primary productivity. Their biomass was greatest in winter, responding to increases in prey availability. Their diversity was limited inshore, possibly due to the highly variable environment encountered. Diversity increased with distance offshore as physical and chemical properties in addition to prey availability and predation become more stable. Strictly heterotrophic cells were evenly distributed between inshore and offshore. Those organisms harbouring endosymbionts had a higher biomass offshore where basic metabolic costs are covered by photosynthesis during periods of low prey availability. Cells that are primarily photosynthetic, that may phagocytize particles were favoured inshore where they survived low nutrient environments more efficiently than do strictly autotrophic cells.

The grazing impact exerted by microzooplankton on phytoplankton was generally balanced in winter; however in summer phytoplankton growth rates tended to exceed grazing rates, effectively decoupling these rates. Inshore, the sporadic availability of diatoms caused this decoupling, as these phytoplankton are often too large to be consumed by microzooplankton. The mechanisms involved offshore in decoupling between phytoplankton growth and grazing losses during summer were more complex. Microzooplankton appeared to graze at reduced rates, effectively maintaining the low phytoplankton biomass just above threshold feeding levels.

Introduction

Microzooplankton has been studied since the mid 1980s when their important function in the planktonic food chain was identified. Since this time they have been studied extensively in the Atlantic, Pacific and Antarctic regions, as well as in other, well-studied water bodies. Microzooplankton repackage carbon from small pico (<2 µm) sized phytoplankton cells to micro (20 – 200 µm) sized particles which are available to larger consumers. Unravelling the microbial food web is fundamental to understanding how the system works.

The region off the west coast of Australia represents the only pole-wards flowing eastern boundary current in the world, resulting in an oligotrophic region with comparatively low productivity and a different food web compared to other eastern boundary currents (Pearce 1991). Studying microzooplankton in this region, allows clarification of the role of microzooplankton in a temperate, oligotrophic waters in a coastal environment.

Aims and objectives

The objectives of this study were to:

1 Characterize the microzooplankton assemblage off south western WA and their temporal and spatial variability.

2 Quantitatively assess the herbivory of microzooplankton on phytoplankton, and its temporal and spatial variability.

3 Examine the distribution of three functionally different groups of micro-zooplankton on the Two Rocks transect.

Methods

Microzooplankton biomass, abundance and species richness were analysed from 190 samples of ~850 mL of seawater fixed with Lugol's iodine. These were routinely collected from the Two Rocks transect (defined below), using the microscopy method of Utermöhl (1958). Cells were identified using the methods described in Marshall (1969), Thomas (1997) and Boltovskoy (1999). Each cell was classified into three functional groups, HETERO for strictly heterotrophic cells, ENDO for cells with endosymbionts and MIXO for primarily autotrophic cells that may phagocytize particles. The biomass for each group was compared between inshore (station A and B) and offshore (stations C, D and E). The grazing impact of microzooplankton on phytoplankton was evaluated using the dilution method (Landry and Hassett 1982) with changes in chlorophyll *a* and picoplankton measured by flow-cytometry to quantify changes to the phytoplankton community. The computer packages SPSS and PRIMER were used to analyse the data.

Study site

During this study, five sites along a transect running from 4 km south west of Two Rocks, Western Australia, to 85 km offshore (See Fig. 2.32), were sampled from February 2002 – December 2004 (31.5 - 31.8˚S, 115.6 – 114.9˚E). The sites represented the coastal lagoon (A, water depth 15 m), inner shelf (B, 40 m), outer shelf (C, 100 m), shelf break (D, 300 m) and offshore (E, 1000 m) habitats. Two sampling strategies were followed: inshore stations A, B and C were sampled monthly, weather permitting, using the 8 m *RV Mesocat*; stations A – E were sampled quarterly from larger vessels, *RV Naturaliste*, *RV Maritime Image* or the *RV Southern Surveyor*. Samples for microzooplankton were routinely collected from the surface and deep chlorophyll *a* maximum (DCM) using 10 L Niskin bottles. Water was collected from the surface only from station A, C and E during quarterly cruises for microzooplankton grazing experiments.

Results

There were 157 morphotypes of microzooplankton discriminated from 190 samples. The major groups were ciliates and heterotrophic dinoflagellates, although nauplii, acantharians, radiolarians and foraminiferans were also found. Of the ciliates, *Strombidium* sp. and *Strobilidium* sp. were the most dominant forms and 19 genera of tintinnids were found. *Protoperidinium* sp. and *Gyrodinium*/*Gymnodinium* sp. were the most abundant dinoflagellates, although *Ceratium furca* was an important contributor to dinoflagellate blooms inshore. The average abundance of microzooplankton in the surface was 2400 cells L^{-1} with a biomass of 2.9 µg C L^{-1}, and in the DCM the average abundance was 2100 cells L^{-1} and the average biomass was 2.1 µg C L^{-1} (Fig. 2.36). There was a significant increase in microzooplankton biomass in winter (p=0.002), but the peak biomass of 15 µg C L^{-1} was in autumn, and caused by a *C. furca* bloom.

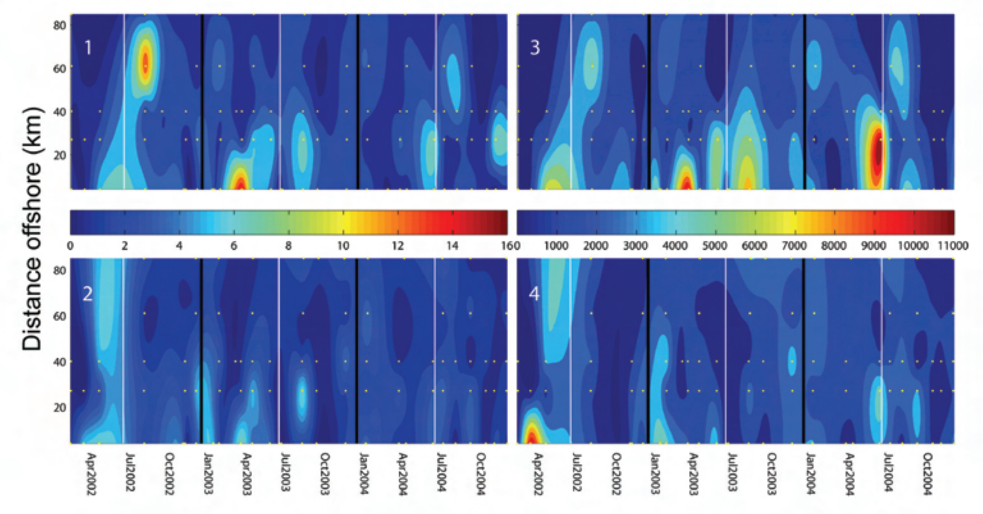

Figure 2.36: Biomass and abundance of microzooplankton from the Two Rocks (WA) transect, 2002-04. Panels 1 and 2 represent microzooplankton carbon µg C L^{-1}; surface (1), deep chlorophyll *a* maximum (2). Panels 3 and 4 represent microzooplankton cell abundance L^{-1}; surface (3), deep chlorophyll *a* maximum (4).

Species richness increased significantly with distance offshore ($F_{(4, 173)}$ =23, p=0.000), winter was significantly richer ($F_{(3, 173)}$ = 4 p=0.009) than in other seasons, across the transect; and samples from the DCM were richer than those from the surface ($F_{(1, 173)}$ =5.1 p=0.024). The variability between samples, as measured by the Multivariate Dispersion Index, for each site, decreased with distance offshore ($F_{(1, 4)}$ = 19, p=0.02) (Fig. 2.37A).

The three functional groups differed in their distribution between inshore and offshore. The HETERO group had no difference in distribution. The ENDO group had a significantly greater biomass offshore ($t_{(1, 173)}$ = -1.9, p=0.056), while the MIXO group had a significantly greater biomass inshore ($t_{(1,173)}$ =3.9, p<0.01).

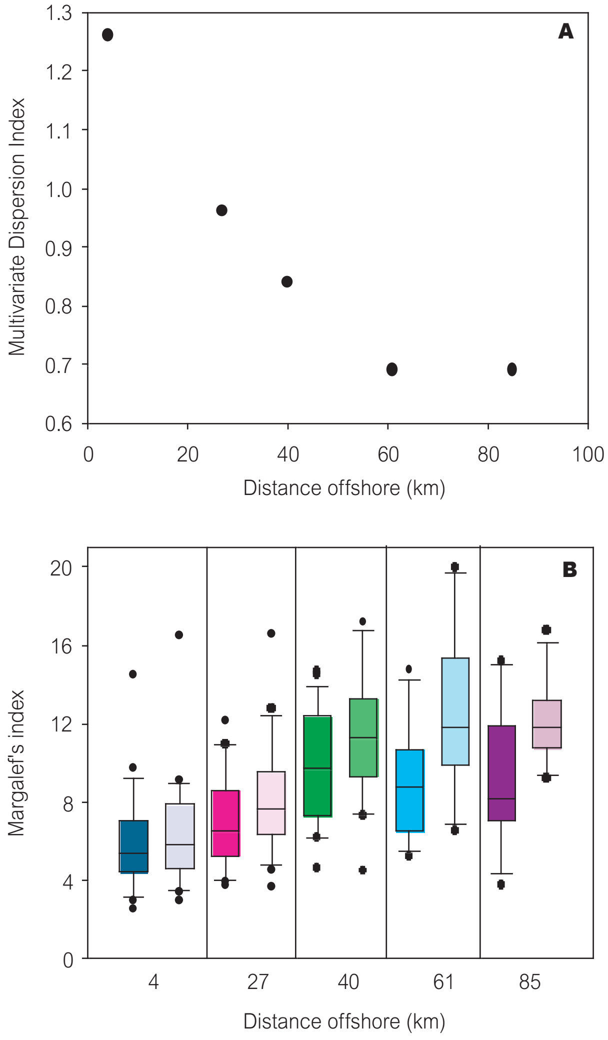

Figure 2.37: Species diversity: Panel A, Multivariate dispersion Index for microzooplankton, calculated from scatter of points from Non-metric multi dimension scaling plot of square root transformed microzooplankton biomass data. Panel B, Distribution of Margalef's index of species richness for each station, top and bottom of box represent the 75th and 25th percentiles, wiskers represent the 90th and 10th percentiles. Dark colour surface data, light colour deep chlorophyll *a* maxima data. From April 2003 to December 2004, from the Two Rocks transect Western Australia.

The relationship between phytoplankton growth and microzooplankton grazing differs between summer and other seasons (Fig. 2.38). During the summer the phytoplankton biomass was low, although its apparent growth rate was high. At the offshore station the grazing rate was also high during summer, effectively maintaining the low phytoplankton biomass. In the lagoon and outer shelf the grazing rate did not rise in accordance with the phytoplankton growth rate, resulting in decoupling. Most results showed linear grazing responses, however saturation feeding was seen in results from the outer shelf and offshore during summer, and threshold feeding was evident in some experiments during the year, mostly in the lagoon and outer shelf. There is also evidence of saturated feeding and a threshold response by microzooplankton throughout the year. Microzooplankton grazing on total phytoplankton production and standing stocks in the lagoon ranged from 33-55 and 69-89% in summer and 68-96% and 48-56% in winter, respectively, and at the two offshore stations 29 – 91% and 60 – 82% in summer and 26-85% and 39-55% in winter, respectively. Picoplankton growth was generally balanced by microzooplankton grazing (Fig. 2.38). Heterotrophic bacteria and *Prochlorococcus* spp. had the highest growth and grazing rates (2 – 2.5 d^{-1}) and cryptophyte 1 the lowest (0.5 – 1 d^{-1}). Rates on *Synechococcus* sp. and the pico-eukaryotes were varied, with grazing occasionally exceeding growth.

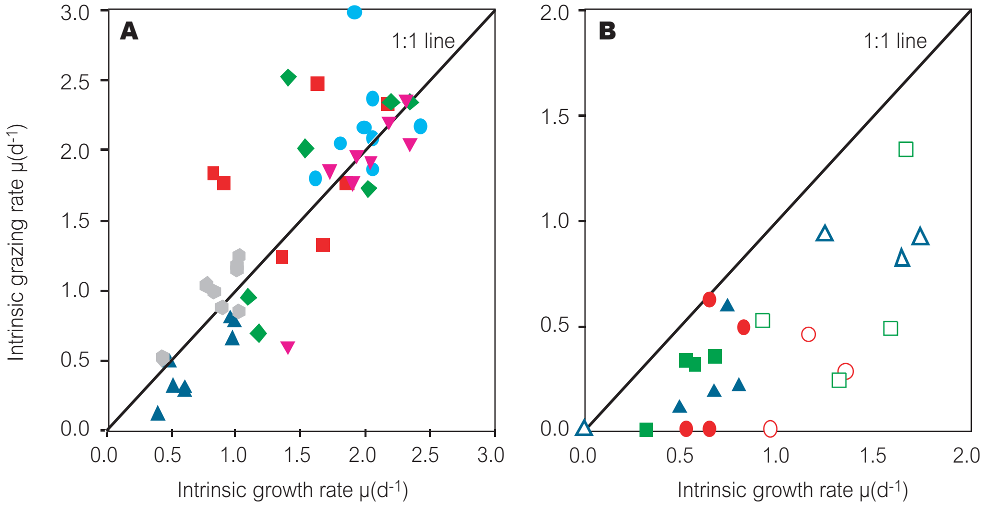

Figure 2.38: Relationship between intrinsic growth rates and mortality due to microzooplankton grazing. Line is the 1 to 1 relationship between growth and grazing.

Panel A: growth and grazing for six pico-phytoplankton populations;

- ● Prochlorococcus spp.
- ■ Synechococcus spp.
- ▲ Cryptophyte 1
- ⬢ Cryptophyte 2
- ◆ Pico-eukaryotes
- ▼ Heterotrophic bacteria

Panel B: growth and grazing determined from total chlorophyll *a*;

- ● Lagoon
- ■ outer shelf
- ▲ offshore

Open symbols summer (December – February), closed symbols all other seasons (March – November).

Discussion

The Two Rocks transect may be divided into 3 zones based on the abundance and biomass of microzooplankton data. The lagoon was influenced by near-shore processes; the inner shelf was influenced (to some degree) by near shore processes, the summer Capes Current and also periodically by the Leeuwin Current; and the outer shelf, shelf break and 1000 m stations were dominated by the Leeuwin Current, with some influence from the Capes Current during summer at the outer shelf; the offshore station was occasionally influenced by oceanic water. Increases in microzooplankton biomass during winter presumably represent responses to increases in phytoplankton biomass and productivity that result from new nutrient being introduced into the photic zone during autumn and winter when the mixed layer deepens.

The physical and chemical differences between the lagoon and offshore station explain some of the differences between these regions. In the lagoon, bottom-up forces of temperature and salinity changes, combined with episodic nutrient inputs, resulted in low species richness and highly variable abundance and biomass, and in rapid turnover of the dominant microzooplankton species. The offshore stations provide a comparatively stable environment where nutrient limitation caused consistent microzooplankton abundance and biomass, and where prey availability, niche diversification and selective grazing by predators resulted in a relatively diverse community.

The distribution of the three functional groups may be explained by the advantages gained by the different modes. The strictly heterotrophic organism gained no advantage inshore or offshore demonstrating their viability and diversity. The ENDO group may cover their metabolic costs by harvesting photosynthetic products directly from their endosymbionts. This gives them a competitive advantage during periods of low prey availability. The MIXO group are similar to strict autotrophs, hence their higher biomass inshore, however they have a greater advantage during periods of low nutrient availability as they may consume particles and assimilate nutrients directly.

The grazing impact of microzooplankton on total phytoplankton off south western Western Australia differs between summer and the rest of the year. High phytoplankton growth rates in the lagoon during summer were not coupled with grazing. Large diatoms, known to bloom sporadically in the lagoon during summer, may have been the cause as they are not preferentially grazed on by microzooplankton. Offshore, the likelihood of saturation feeding occurring during summer, when phytoplankton biomass is low, suggests that microzooplankton are capable of reducing feeding rates, which presumable prevent the phytoplankton biomass being grazed to threshold levels where microzooplankton cease to feed.

The impact of microzooplankton grazing on specific picoplankton populations is generally balanced between seasons. However, while growth and grazing of picoplankton is balanced, growth and grazing on total phytoplankton is not balanced. The larger phytoplankton cells that contribute to this imbalance are likely to be grazed by mesozooplankton, which are equipped to consume phytoplankton cell.

Microzooplankton constitute an important component of the planktonic assemblage off south western, Western Australia. Their impact on phytoplankton varies seasonally, and their diversity increases with distance offshore.

Acknowledgements

I acknowledge the help of P. Fearns, M. Harrison, N. Johnston, M. Mackie and N Mortimer in acquiring samples; also the skippers and crews of the *RV Maritime Image*, *RV Naturaliste* and *RV Southern Surveyor*; and B. Alexander, and A. Begrum for laboratory help and D Montagnes for help training in the identification of microzooplankton.

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Conference attendance and presentations

Award

SRFME Student Symposium 2003, Best abstract
SRFME Student Symposium 2004, 2nd presentation

Symposium

Third International Symposium on Zooplankton, Spain, May 2003
SRFME Student Symposium 2003
SRFME Student Symposium 2004
AMSA 2004
SRFME Student Symposium 2005
CMM seminar series 2005

PhD awarded in December 2006

Publications

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2.2.10 Diurnal variations in physical processes & phytoplankton response

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Executive Summary

Oligotrophy, high irradiance and consistent diurnal cycles in water column stratification and mixing in the coastal waters offshore Perth, Western Australia presented an opportunity to study natural phytoplankton community responses to an interesting combination of physical processes. This research aimed to determine the phytoplankton response for varying strengths of water column stratification and irradiance at sites with different exposures. We estimated the phytoplankton community response through examination of vertical chlorophyll *a* concentration variability and distribution on an hourly timescale, in vivo fluorescence fluctuations, *in situ* primary production experiments and measurements of photosystem II efficiency (yield). A combination of air–sea heat fluxes and wind stress control the vertical stratification strength, measured through the potential energy anomaly. In general, the water column is well mixed in the morning because of night-time cooling and convection and stratifies during the day in response to solar heating. Our field study showed that chlorophyll *a* concentration and in vivo fluorescence (which were 48 % correlated) were both lowest in the surface (1-5 m) during prolonged (hours) periods of stratification when the irradiance experienced was highest and phytoplankton were retained in the surface layer due to an absence of vertical mixing (generally around midday). Short-term *in situ* primary production rates (measured through 1-hour carbon uptake incubations and normalised to chlorophyll *a*

concentration) showed a diurnal trend with the highest production at midday in the surface, even though instantaneous measures of photosystem II efficiency (through yield) and relative electron transport rate (rETR) were depressed at the surface during this time. Chlorophyll *a* concentration and in vivo fluorescence were both highest at the sea bed (10 m) in summer and highest near the middle of the water column (5 m) in winter, showing an increase from morning to late afternoon at all sites. At the more exposed sites, or when the water column was well-mixed and did not stratify as strongly, chlorophyll *a* concentration and in vivo fluorescence were more constant throughout the day. We propose that the increase in chlorophyll *a* concentration at depth (at the least exposed sites) was a result of favourable light conditions there and possibly in combination with nutrient enrichment from the sea bed. This research also aimed to characterise the effect on phytoplankton community response of the strong summer sea breeze regime, where wind mixing results in a breakdown of stratification in the early afternoon and likely exposes phytoplankton to a range of light levels.

Introduction

Vertical mixing effects on phytoplankton biomass and productivity have been studied extensively and modelled for at least two decades, generally in the ocean surface mixed layer of the open ocean (e.g. Cullen and Lewis, 1988, Denman and Marra, 1986). When the rate of vertical mixing is greater than that of photoadaptation, phytoplankton will experience a range of light levels and their productivity will be of an intermediate nature (Falkowski, 1983). If, however, the mixing rate is slower than photoadaptation, productivity will reflect the phytoplankton's immediate light history. Diurnal vertical mixing and stratification therefore impact on net primary productivity since the phytoplankton production will not be the same for a mixed regime as for a stratified water column, often due to the non-homogeneous nature of nutrient distributions. Also, if the water column is shallow or highly stratified and the irradiance that phytoplankton consequently experience is sufficiently great for sustained periods, photoinhibition can occur, resulting in reduced productivity and lower biomass (Neale and Richerson, 1987). Nutrient limitation enhances the effects of photoinhibition (Prézelin et al., 1986)—a situation commonly found in nutrient-depleted surface waters and oligotrophic waters. Prézelin (1982) showed how low light phytoplankton populations survived better than high light populations when subjected to nutrient-limited conditions. Unfortunately, there have been few field studies conducted in oligotrophic, high light coastal waters to support these laboratory experiments. To investigate the diurnal density cycle and irradiance effects on productivity and chlorophyll *a* concentration in an oligotrophic environment, sites along the south-western Australian coastline were chosen, where diurnal variations in chlorophyll *a* were almost of the same order as seasonal scale variations (0.1 – 1 mg/m^3).

Aims

Our research aims to test the hypotheses that the diurnal cycle of density stratification and irradiance is directly related to chlorophyll *a* concentration structure and *in vivo* fluorescence in the water column, and that a response to these physical processes on a short (hours) time-scale is also seen in photosystem II efficiency (yield) and *in situ* primary production. We propose that the supra optimal light conditions and nutrient-limitation stress when phytoplankton are retained for prolonged (hours) at the surface, favours chlorophyll *a* to be synthesized at depth relative to the surface. Possible enrichment of nutrients continuously released from the sediments and taken up by phytoplankton immediately upon stratification (and therefore retention) at depth may also additionally contribute to the enhanced chlorophyll *a* concentrations particularly by the late afternoon, at depth.

Methodology

Field experiments were conducted in the shallow oligotrophic coastal waters of the Indian Ocean's eastern boundary. The region exhibits a low tidal range (maximum of 0.8 m), and currents are predominantly wind-driven (Pattiaratchi *et al.*, 1997). During winter, the coast experiences onshore winds and frequent (about 30 a year) storm events, whilst during summer there are offshore winds and strong (up to 15 ms^{-1}) sea breezes, commencing at approximately noon and weakening during the night (Pattiaratchi *et al*., 1997). Study sites were chosen for their degree of exposure (in terms of exposure to wave climate as well as coastal currents), where Mangles Bay was the most enclosed of the three sites, Warnbro Sound was semi-exposed, and Two Rocks was the most exposed site.

A mooring was deployed at each site for six to ten days to measure small-scale temporal changes in water properties. The mooring consisted of an acoustic Doppler current profiler (ADCP), conductivity-temperature-depth and dissolved oxygen sensor (CTD-DO), *in situ* fluorometer, and integrating light sensor. While the mooring was deployed, sampling was conducted aboard a boat, adjacent to the mooring, during daylight hours for two consecutive days. A CTD and *in vivo* fluorometer were deployed to obtain vertical profiles every 20 minutes. Water samples for chlorophyll *a* extraction from the surface, 5, and 10 m depths were taken hourly and filtered on board—2 L through a Nitex filter to capture the size fraction greater than 5 μm and 1 L through a glass fiber filter (GF/F) for all size fractions greater than 0.7 μm. Nutrient samples (for nitrate + nitrite, silicate, orthophosphate and ammonium) were taken hourly from the surface, 2, 5, 7, and 10 m and frozen for later analysis. *In situ* carbon uptake experiments were conducted four times during the second day of sampling at each site. Samples from the surface, 5, and 10 m were inoculated with 1 ml (40 μCi) ^{14}C and duplicates, plus a shaded dark bottle, were incubated *in situ* at the depth from which they were obtained. Incubations were ended (with formalin) after one hour and stored in the dark until the end of the day when they were transported to the laboratory to be filtered and analysed. Light sensors were fastened to the rope onto which the bottles were clipped to record the ambient light at each depth. A pulse amplitude-modulated (PAM) fluorometer was used to estimate maximum photosystem II quantum yield (Φ_e or F_v/F_m) and this was used to calculate the relative electron transport rate (rETR) and to create rapid light curves for dark-adapted samples from the surface, 2, 5, 7, and 9 m depths each hour. The curve-fit of Platt *et al*. (1980) was used to find maximum rETR and α (the initial slope of the curve).

Results

Irradiance

Irradiance on the Western Australian coast often peaks around 1500 $\mu mol/m^2s$ during the day in summer and can reach 1000 $\mu mol/m^2s$ at the surface in winter. Typical summer and winter extinction coefficients (k) were $0.153 \pm 0.0145\ s^{-1}$ and $0.317 \pm 0.0590\ s^{-1}$, respectively. Irradiance for which photoinhibition is likely to start differs for various species of phytoplankton as a result of the variations in the size of light harvesting complexes associated with photosystem II (Juneau and Harrison, 2005). Primary production by natural populations of phytoplankton is reported to plateau around 200 $\mu mol/m^2s$ and some are photoinhibited at greater irradiances (Harris, 1978). The phytoplankton community found in this coastal environment is likely to be adapted and acclimated to these high light conditions and could be expected to have well developed capabilities for photoprotection with limited photoinhibition manifest during the most extreme exposures to supra optimal irradiances.

Stratification & mixing

Three distinct stratification phases may be identified from the field data during the diel summer cycle in Western Australia (Imberger, 1985, Pattiaratchi et al., 1997, Zaker *et al*., 2002): (1) a relatively calm (wind) period of solar heating from about 0800 to 1200; (2) a period of wind mixing, due to the afternoon sea breeze, from about 1200 to 2300; and, (3) a period of penetrative convection from about 2300 to 0800. Time series of the potential energy anomaly (Φ) demonstrate the effect of this wind and solar radiation cycle on the water column density structure (Figure 2.39). The water column's progressive stratification during the morning and the start of de-stratification due to wind mixing in the afternoon is illustrated in this figure. The degree of stratification was found to be negatively correlated to site exposure. Previous studies have shown the eroding of stratification continues until the sea breeze has completely subsided (about midnight). There was a distinct gradient in the potential energy anomaly, from lower values (0.2) at the more exposed site (TR) to higher values (6.1) at the enclosed site (MB). Sampling at all sites was undertaken on calm days during winter. Again, a progressive stratification was observed at sites that experienced no wind mixing during the day (data not shown). Values of Φ ranged from 0.1 to 2.6 in winter—much lower than the degree of summer stratification (0.2–6.1). Unlike summer, no significant trend existed between Φ and site exposure.

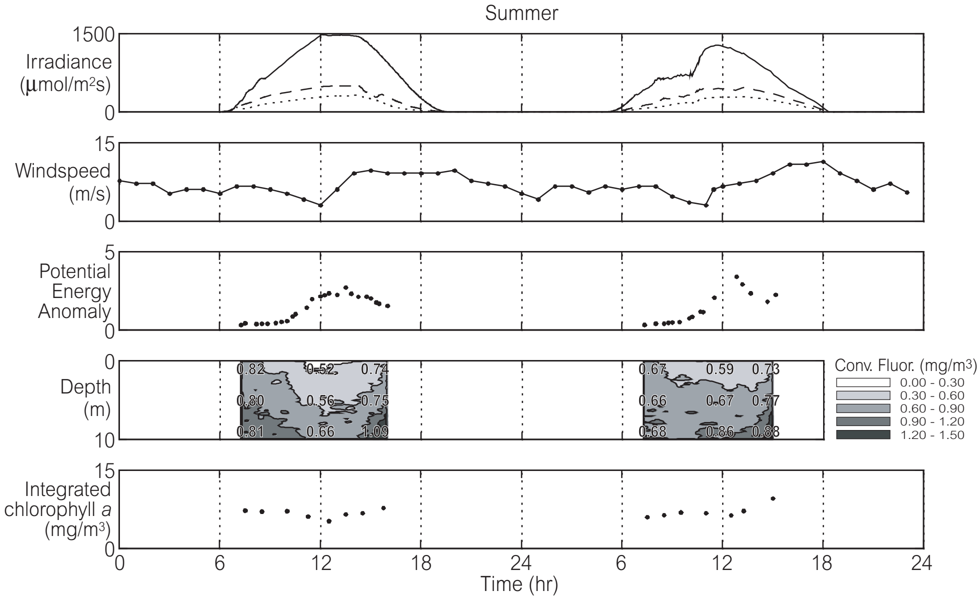

Figure 2.39: Summer (a) solar irradiance, (b) wind speed, and (c) potential energy anomaly, (d) chlorophyll *a* distribution with depth and (e) integrated chlorophyll *a*.

Chlorophyll *a* concentration and in vivo fluorescence

Chlorophyll *a* concentration (measured by filtering and extracting the pigments in samples) was used as an estimate (or proxy) of phytoplankton biomass. Although the chlorophyll *a* only explained 52 % of the variation in in vivo fluorescence, the latter was used to give an indication of how fluorescence fluctuated during the diurnal cycle with depth, and how this related to the chlorophyll *a* concentration variations. In summer, three stages of development of vertical chlorophyll *a* concentration structure and in vivo fluorescence signal were observed in concurrence with the diurnal stratification and the mixing cycle previously described (1) Overnight when the water column was vertically mixed, the chlorophyll *a* concentration was also homogenously distributed through the water column and in vivo fluorescence was constant throughout (Figure 2.39d). This feature was observed at all sites; (2) Progressive stratification of the water column through solar radiation was also common to all sites and during this time (morning to mid-afternoon) the chlorophyll *a* concentration gradually depleted vertically throughout and the in vivo fluorescence signal was very low, particularly in the surface waters, and this is clearly demonstrated in Figure 2.39e. The extent to which the integrated chlorophyll *a* concentration was depleted was directly related to the degree of stratification due to the intensity and quantity of light phytoplankton experienced at particular depths in the water column; and (3) During sea breeze events, experienced at only some sampling periods, the chlorophyll *a* was mixed through the water column, with the depth of mixing depending on the strength of the sea breeze. At sites that did not experience a sea breeze, the chlorophyll *a* concentration near the seabed continued to increase, and the water column showed vertical differences in chlorophyll *a* concentration and in vivo fluorescence by late afternoon. Sites that had a higher potential energy anomaly during the early part of the day had a higher integrated chlorophyll *a* concentration by late afternoon.

Winter chlorophyll *a* concentration was approximately double that of summer at all sites, as reported in other work (Lourey et al., 2006, Thompson and Waite, 2003). This is in response to the higher nutrient status in winter (Lourey et al., 2006). Spatial and temporal chlorophyll *a* and in vivo fluorescence trends were weaker than during summer, yet still showed definite periods that correlated to the diurnal stratification and mixing regime (data not shown). Overnight, the water column chlorophyll *a* concentration was homogenously mixed; resulting in a high integrated biomass and the in vivo fluorescence signal was also constant with depth. As the water column stratified (more weakly than in summer) from early morning to late afternoon, the same trends were observed as in summer, where chlorophyll *a* concentration was depleted in the surface waters, but stayed constant at the seabed and the in vivo fluorescence signal showed low values in the surface and higher values at depth. Generally, there was no mixing period during the afternoon due to the absence of a sea breeze. As was observed in summer, winter chlorophyll *a* concentration also increased in the water column by early afternoon and continued developing well into the night. The distribution of chlorophyll *a* concentration in the afternoon was not as localised near the seabed as in summer, but was higher near the middle of the water column.

Primary production and photosystem II quantum yield

Two techniques were employed to investigate photosynthesis rates and efficiency (1) *in situ* carbon uptake rate experiments through 1 hour incubations and (2) pulse amplitude-modulated (PAM) fluorometry. The former is a measure of the rate that carbon is taken up into the cell whilst the latter measures how well photosystem II transports electrons through the electron transport chain. Summer results showed that primary production (carbon uptake) that had been normalised to chlorophyll *a* concentration was highest at midday in the surface samples for the least exposed sites (Figure 2.40) and the trend was less pronounced at the most exposed site. Results from the PAM however showed yield was depressed around midday, especially at the surface. Maximum electron transport rate ($rETR_{max}$) was seen to be homogenous in the morning, highest at the sea bed around noon (and lowest at the surface) and increases at all depths to homogeneity by the end of the day (Figure 2.41). During winter, carbon uptake per unit chlorophyll *a* was highest in the surface and mid-water for the least exposed sites and again showed no clear trend at the most exposed site. Trends in winter for the PAM measurements mirrored those of summer but due to the lower irradiances, the depression in yield was only observed in the surface waters, and maximum yield was seen around mid-water rather than near the sea bed (winter data not shown). In summary, although the short-term measurements from the PAM showed a depression in yield when irradiance was highest and phytoplankton were retained at their respective light levels, production experiments revealed that carbon uptake per unit chlorophyll *a* was still greatest at the surface around midday. When the water column was well mixed in the morning, yield was vertically homogenous and was relatively high. As the water column progressively stratified and irradiance increased, yield decreased and was higher at depth relative to the surface. In the afternoon, when the irradiance again decreased and there was a sea breeze, the yield increased to a vertically homogenous high value.

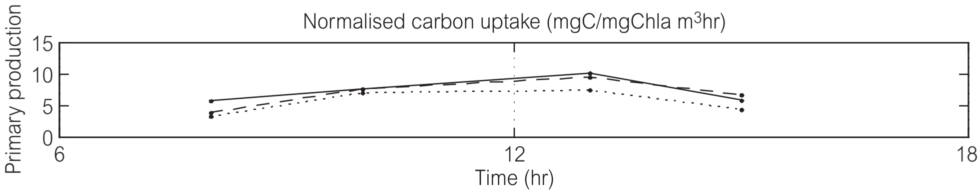

Figure 2.40: Summer carbon uptake per unit chlorophyll *a* (mgC/mgCha m^3hr) for surface 0 m (solid line), mid-water 5 m (dashed line) and sea bed 10 m (dotted line).

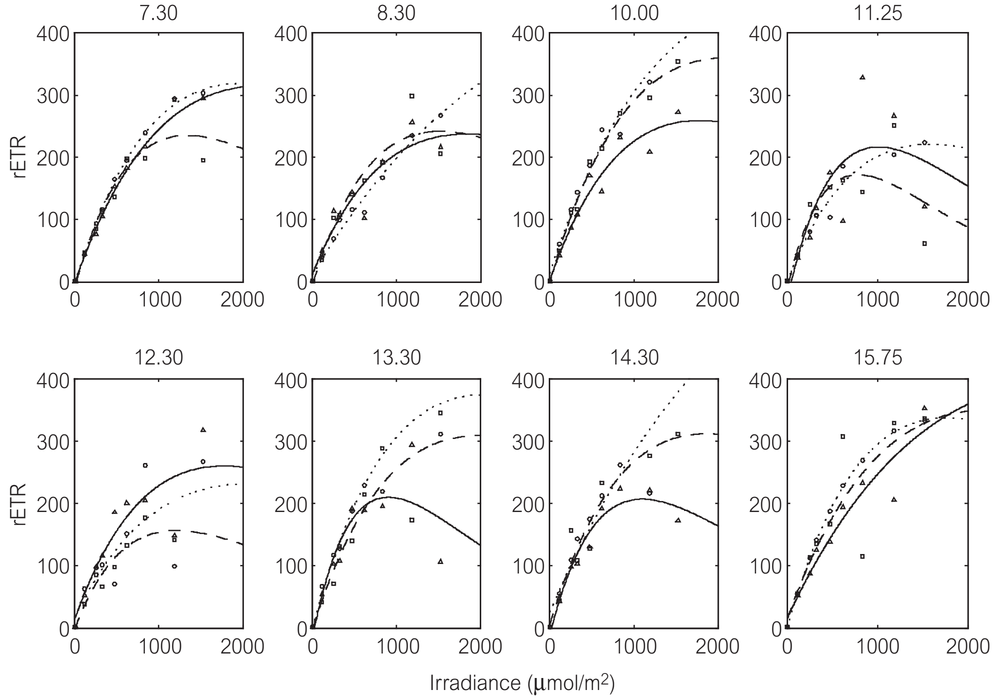

Figure 2.41: Summer relative electron transport rate (rETR) with irradiance for consecutive samples at surface 0 m (solid line), mid-water 5 m (dashed line) and sea bed 10 m (dotted line).

Nutrients

The nutrient analyser was not sensitive enough to measure the low nutrient concentrations, therefore we generally could not detect whether there were any significant relationships between nutrient concentrations and chlorophyll *a* concentration (especially in summer when concentrations were lowest). Our inability to measure these fluctuations did not mean that the concentrations that were present did not affect phytoplankton growth and variability; most likely the phytoplankton community that are present in this environment are well-adjusted to low nutrient availability and nanomolar concentrations are more likely the most significant scale to this community. For concentrations that were within the instrument measurement range (winter Si, PO_4, NO_x & NH_4; summer NO_x & NH_4 only), we performed ANOVA two-tailed t-tests between sampling depths (0 & 10 m, 0 & 5 m and 5 & 10 m) and between morning and afternoon samples to test for significant trends. Significant ($p < 0.05$) linear decreases were found in winter from morning to afternoon in integrated water column NO_x and NH_4 concentrations at the two least exposed sites. In summer, only at the least exposed site, surface NH_4 concentration was significantly ($p = 0.03$) higher at the surface relative to the sea bed. All other t-tests for comparisons between depths and times of day were found to be insignificant ($p > 0.05$). Although we could not measure higher concentrations of nutrients that may have been emanating from the sea bed, recent research has shown that there is a discharge here that may be of importance (Forehead 2006, PhD thesis).

Discussion

In this research we studied the temporal response of the phytoplankton community in a system dominated by diurnal physical processes. Limited research has been conducted in coastal regions such as this that exhibit extreme irradiances and oligotrophy. The results we have presented indicate that significant variations in chlorophyll *a* concentration and in vivo fluorescence both in the vertical and temporal scales are driven by diurnal cycles of irradiance, stratification and mixing, and possibly nutrient enrichment at the sea bed. Although no significant correlation was found between nutrient concentration fluctuations and short term chlorophyll *a* variation, nanomolar scale nutrients may be of importance to phytoplankton here, a scale of measurement that we could not capture with our instrumentation. Our results also provided evidence that photosystem II quantum yield and carbon uptake rate was directly correlated to the diurnal physical processes. Differences existed in the outcomes of this biophysical 'model' according to site exposure, degree of mixing and stratification, season, and possibly the phytoplankton community structure, but the underlying mechanisms remained constant. Although the most enclosed sites during summer generally experienced the highest degree of stratification and the most exposed sites during winter generally experienced the highest degree of mixing, there were atypical cases where stratification was observed at the more exposed site in winter and mixing occurred at the more enclosed site all day in summer. In these cases, where the typical seasonal conditions did not prevail, the biological response to the physical driving processes was more complex to define, but still followed the same general rules as the base case situations.

An interesting observation was the decrease of chlorophyll *a* concentration and lower in vivo fluorescence in the top part of the water column at most sites during the middle of the day, especially the most enclosed site during summer. It was realised the light intensity the surface phytoplankton must have experienced during these midday times was extremely high (often greater than 1500 μmol/m^{2}s) and prolonged for several hours as they were retained in the surface layer whilst the water column was stratified. Experiments conducted in freshwater Lake Titicaca (Peru/Bolivia) by Neale and Richerson (1987) revealed similar patterns in diurnal density stratification and mixing, high irradiances (surface ~ 2000 μmol/m^{2}s) and a depressed midday fluorescence response. After examining our PAM results, which showed depressed photosynthesis through lower yield and lower rETR$_{max}$, and considering the low background concentration of nutrients in the water column, it was deduced that, overall, the phytoplankton may have been photo-protecting themselves during these times. Primary production results (through carbon uptake experiments) however showed that during the highest light and most stratified times, phytoplankton from the surface were taking up the greatest carbon per unit chlorophyll *a* relative to the rest of the water column. This may mean that on a short-term (minutes) timescale, the community was contesting the high light through photo-protecting mechanisms (as seen in the PAM data) but on the longer (hourly) timescale they were not actually photo-damaged. Natural populations of phytoplankton are generally photoinhibited around 200 μmol/m^{2}s (Harris, 1978) but these studies are often from higher latitudes that have an overall lower irradiance profile.

Chlorophyll *a* concentration and in vivo fluorescence were greater near the seabed where there was more moderate light and possibly nutrient enrichment from the sea bed and there was a relative increase in chlorophyll *a* concentration and fluorescence towards the afternoon at most sites. This enhanced chlorophyll appeared to originate near the sea bed and increase progressively throughout the day, to then be distributed throughout the water column when there was a sea breeze. On days that did not exhibit a sea breeze, the higher chlorophyll *a* was retained at the depth of synthesis. Our study has shown the importance for phytoplankton community response of daily physical processes such as the irradiance and density cycle in retaining and mixing phytoplankton throughout the water column in shallow coastal waters.

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Conference attendance & presentations

Indian Ocean Marine Environmental Conference (IOMEC) 2005

Biotechnological and Environmental Applications of Microalgae (BEAM) 2005

Date planned to submit thesis: March 2007

Publications

Verspecht, F. and C. Pattiaratchi (submitted). Diel variations in physical processes and the phytoplankton response. (*Submitted to Continental Shelf Research*)

2.2.11 Comparisons between benthic macroinvertebrate assemblages in estuarine and nearshore marine habitats

Investigators / Institutions

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Introduction

The nearshore marine and estuarine environments of south-western Australia comprise a range of different habitats, which can be distinguished on the basis of a suite of environmental characteristics. Differences among such habitats are thus likely to be reflected in differences in the compositions of their benthic macroinvertebrate assemblages. A thorough exploration of the ways in which these assemblages vary amongst habitats and the rigorous statistical analyses of faunal-habitat relationships depend firstly on the habitats having been distinguished on the basis of sound quantitative data and then on the ability to match statistically those data with quantitative data on species composition.

Components of study completed and in progress

Aim: To compare benthic macroinvertebrate assemblages in different nearshore marine habitats on the lower west coast of Australia.

Benthic macroinvertebrates were sampled seasonally in 2000 in the subtidal and upper and lower swash zones at two sites in each of six nearshore habitat types on the lower west coast of Australia. Five randomly located sediment cores were collected from each zone at each habitat type in each season in waters >1 m deep. The collection of samples from each site was staggered over a 2-3 week period in the middle of each season to reduce the chances of the resultant data being unduly affected by an atypical sample. The cylindrical corer, which was 11 cm in diameter and had a surface area of 96 cm^2, was sampled to a depth of 15 cm. The sediment samples were preserved in 5% formalin buffered in sea water and subsequently wet sieved through a 500 µm mesh.

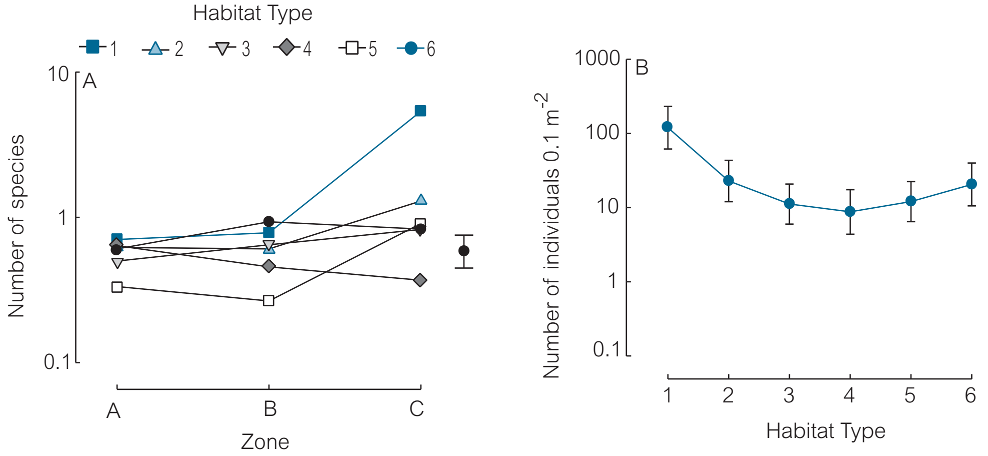


Figure 2.42: Mean (± 95% CI) (A) number of species in Zones A, B and C at habitat types 1-6 and (B) densities of benthic macroinvertebrates at habitat types 1-6, derived from samples collected in all seasons during 2000. For clarity, the overall mean ± 95% CI is provided for (A).

The habitat types, which differed mainly in the extent of their exposure to wave activity and whether sea grass and/or nearshore reefs were present, had been distinguished quantitatively using values for a suite of seven statistically selected enduring environmental characteristics (Valesini et al. 2003).

The core samples yielded 121 species representing eight phyla, among which the Polychaeta, Malacostraca and Bivalvia were the most speciose classes, contributing ~ 38, 23 and 10%, respectively, to the total number of individuals. The mean number of species and mean density of macroinvertebrates were far greater in zone 3 at habitat type 1 than at any other habitat type (Fig. 2.42).

Habitat type influenced species composition to a greater extent than either zone or season. Furthermore, the extents of the differences among the species compositions of the six habitat types statistically matched the extents of the differences among the values for the suite of enduring environmental characteristics that distinguished each of those habitat types. Overall, the species composition at habitat type 1 was the most distinct (Fig. 2.43A) and was characterised by five abundant species of polychaetes that were adapted to deposit-feeding in calm waters with high levels of organic material and which were rare in all other habitat types. In contrast, the fauna at the most exposed habitat type was characterized by four crustacean species and a species of bivalve and polychaete, whose mobility and tough external surface facilitated their survival and feeding in turbulent waters. The differences in faunal compositions among habitat types were greatest in the case of the subtidal zone (C) (compare Figs. 2.43B and 2.43C). The faunal compositions differed among zones and seasons only at the most protected habitat type.

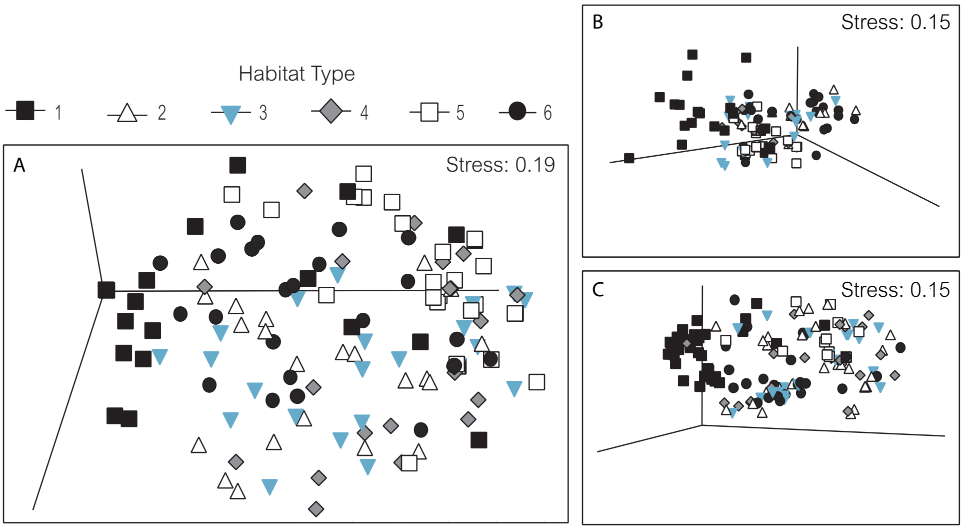


Figure 2.43: Three-dimensional MDS ordination of the densities of benthic macroinvertebrate species in samples collected at habitat types 1-6 during the summer, autumn, winter and spring of 2000 in (A) Zones A, B and C, (B) Zone B and (C) Zone C. Each sample is coded for habitat type.

Aim: To classify nearshore habitats in the Swan-Canning Estuary.

Environmental data (e.g. depth data and aerial photographs) were sourced and used to generate information on 18 different variables for one hundred sites in the lower, middle and upper regions of the Swan-Canning estuary. These variables characterised each site in terms of three broad scale parameters:

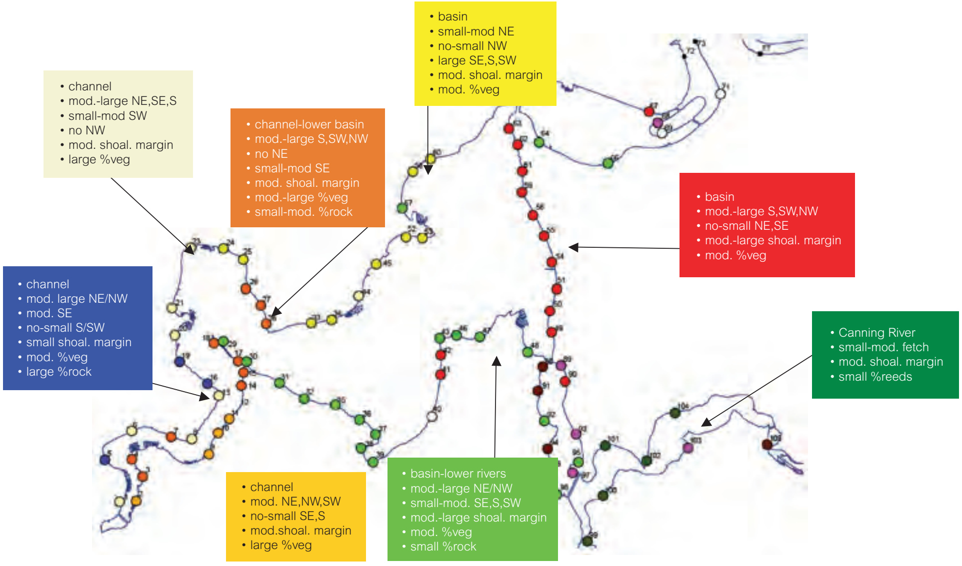
1) Its location within the estuary- distance from estuary mouth.

2) The extent of its exposure to wave action - modified effective fetch distances in 9 different directions, distance to the two-meter depth contour and the average slope.

3) The type of substrate present - percentage contributions of sand, vegetation (seagrass and macroalgae), rock, snags, reeds and bivalve beds to the substrate located within a 100m arc from the center point on the shore at each site.

The GIS package ArcGIS 9 was used to generate information on the variables reflecting location and exposure to wave action. In order to determine the contributions of the various types of substrate at each of the sites, aerial photographs were classified using the GIS program Idrisi Kilimanjaro v14.

A subset of these 18 variables was selected using the BVSTEP procedure in the PRIMER v 6 statistical package as those that accounted for most of the variation among the sites. The data for the subset of variables was then used to classify the one hundred sites into different habitat types with the use of the SIMPROF module in the PRIMER v 6 statistical package. Ten habitat types were distinguished in the Swan-Canning Estuary, eight of which are described in Fig. 2.44.



- basin
- small-mod NE
- no-small NW
- large SE,S,SW
- mod. shoal. margin
- mod. %veg

- channel
- mod.-large NE,SE,S
- small-mod SW
- no NW
- mod. shoal. margin
- large %veg

- channel-lower basin
- mod.-large S,SW,NW
- no NE
- small-mod SE
- mod. shoal. margin
- mod.-large %veg
- small-mod. %rock

- basin
- mod.-large S,SW,NW
- no-small NE,SE
- mod.-large shoal. margin
- mod. %veg

- channel
- mod. large NE/NW
- mod. SE
- no-small S/SW
- small shoal. margin
- mod. %veg
- large %rock

- Canning River
- small-mod. fetch
- mod. shoal. margin
- small %reeds

- channel
- mod. NE,NW,SW
- no-small SE,S
- mod.shoal. margin
- large %veg

- basin-lower rivers
- mod.-large NE/NW
- small-mod. SE,S,SW
- mod.-large shoal. margin
- mod. %veg
- small %rock

Figure 2.44: Main habitat types in the Swan Canning Estuary distinguished on the basis of a range of enduring environmental variables. Lists of defining characteristics are provided.

Aim: To compare benthic macroinvertebrate assemblages in different nearshore habitats in the Swan-Canning Estuary.

Sampling of benthic macroinvertebrates in the shallow subtidal regions at pairs of sites representing six of the habitats that were classified in the Swan estuary was carried out during summer and winter 2005. The same methods as those used in the marine component of the study were used. The subsequent data will be used to investigate the extents to which the benthic macroinvertebrate fauna differ among habitat types and seasons in the Swan-Canning estuary and whether any such differences match those in the environmental variables that that were used to distinguish those habitat types.

Aim: To compare recent and historical data on benthic macroinvertebrate assemblages in the basins of the Swan-Canning and Peel Harvey estuaries.

Seasonal sampling of benthic macroinvertebrates was carried out at eight sites in the Swan-Canning and Peel-Harvey estuaries between winter of 2003 and winter of 2004 in order to make direct comparisons with data collected during a study carried out by Rose (1994) at the same sites between winter 1986 and winter 1987. The sites were originally chosen by Rose to represent a wide range of habitats found throughout the basins of each estuary and the Swan Estuary was used as a reference against which to compare the highly eutrophic Peel-Harvey Estuary. Since the completion of that study the construction of an artificial entrance channel between the ocean and the estuary at Dawesville has facilitated flushing of the Peel-Harvey Estuary with marine water and has ameliorated those extreme conditions. The aim of this study was to examine the ways in which such anthropogenic interactions can affect benthic macroinvertebrate fauna.

Five randomly located sediment cores were collected from each of the eight sites in waters >1 m deep during the day in each season between the winter of 2003 and winter of 2004. The collection of samples from each site was staggered over a 2-3 week period in the middle of each season to reduce the chances of the resultant data being unduly affected by an atypical sample. The cylindrical corer, which was 11 cm in diameter and had a surface area of 96 cm^2, was sampled to a depth of 15 cm. The sediment samples were preserved in 5% formalin buffered in sea water and subsequently wet sieved through a 500 µm mesh.

Swan-Canning Estuary

The results generated from the 2003/2004 data were consistent with that recorded by Rose (1994) in 1986/1987, *i.e.* 43 vs 39 species and 11718 vs 11822 individuals, respectively, which correspond to totals of 122062.54 vs 123145.87 individuals, when the number in each sample is adjusted to that in 0.1 m^{-2} and summed.

Overall the mean number of species differed significantly between time periods (9.62 ± 0.41 vs 8.75 ± 0.41, respectively). However, there were significant interactions between time periods, seasons and sites (Fig. 2.45).

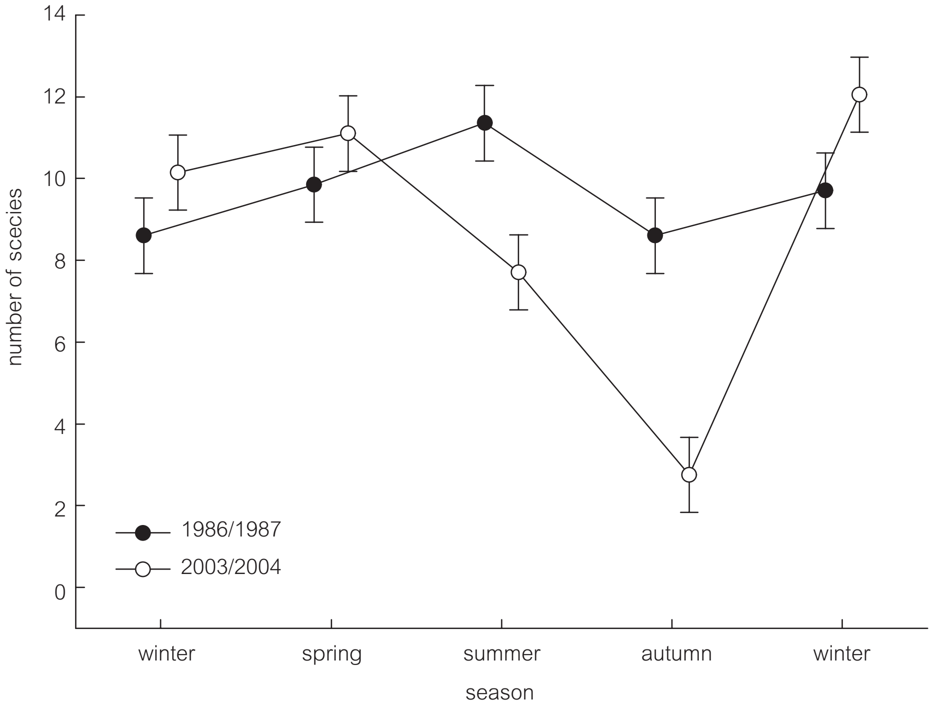


Fig. 2.45: Mean (+/- 95% CI) for the number of species recorded at four sites in five seasons during 1986/1987 and 2003/2004 in the Swan-Canning Estuary.

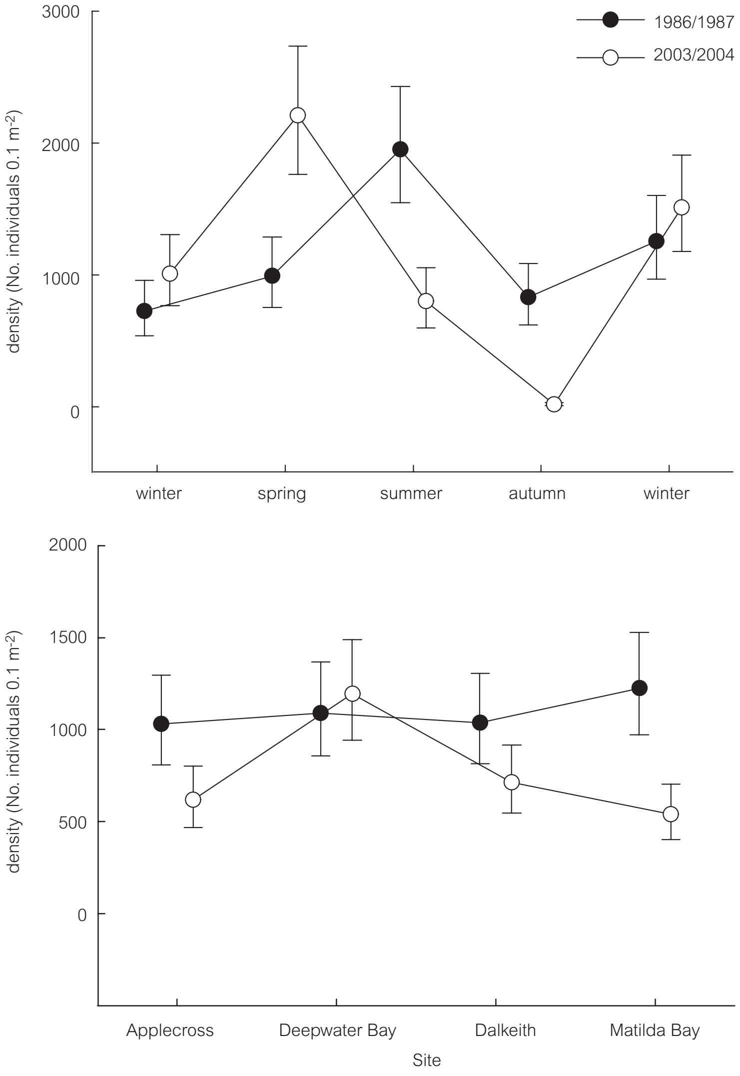


Fig. 2.46: Mean (+/- 95%CI) for the densities of benthic macroinvertebrates recorded during 1986/1987 and 2003/2004 in the Swan-Canning Estuary A) in five seasons and B) at four sites.

The mean density of benthic macroinvertebrates was significantly greater in 1986/1987 than in 2003/2004 (1094.94 ± 122.38 *vs* 737.87 ± 90.64, respectively). There were also significant three-way interactions between time periods, seasons and sites (Fig. 2.46).

The compositions of the benthic macroinvertebrate fauna in the Swan-Canning Estuary were influenced to a far greater extent by time period than by any other factor and were less variable in 1986/1987 than in 2003/2004 (Fig. 2.48A). Greater densities of the crustaceans *Grandidierella propodenta*, and *Tanais dulongii*, the bivalve *Arthritica semen* and the polychaetes *Boccardiella limnicola* and *Ceratonereis aquisetis* in 1986/1987 and greater densities of the bivalve *Sanguinolaria biradiata*, the polychaetes *Capitella* spp. and *Pseudopolydora* sp. 2 and the amphipod *Corophium minor* in 2003/2004 distinguished the species compositions between these two time periods.

Peel-Harvey Estuary

The total number of individuals recorded by Rose (1994) in the Peel Harvey Estuary in 1986/1987 (30669) was ~ three times greater than that recorded during 2003/2004 (9233), which correspond to totals of 319468.85 *vs* 96177.11 individuals, when the number in each sample is adjusted to that in 0.1 m^{-2} and summed. In contrast, the number of species recorded by Rose (1994) was ~ half of that recorded in 2003/2004 (28 *vs* 65).

Overall the mean number of species did not differ significantly between time periods, however there were significant interactions between time periods, seasons and sites. The mean density of benthic macroinvertebrates was significantly greater in 1986/1987 than in 2003/2004 (2862.12 ± 276.94 vs 679.12± 92.62, respectively). There were also significant three-way interactions between time periods, seasons and sites (Fig. 2.47).

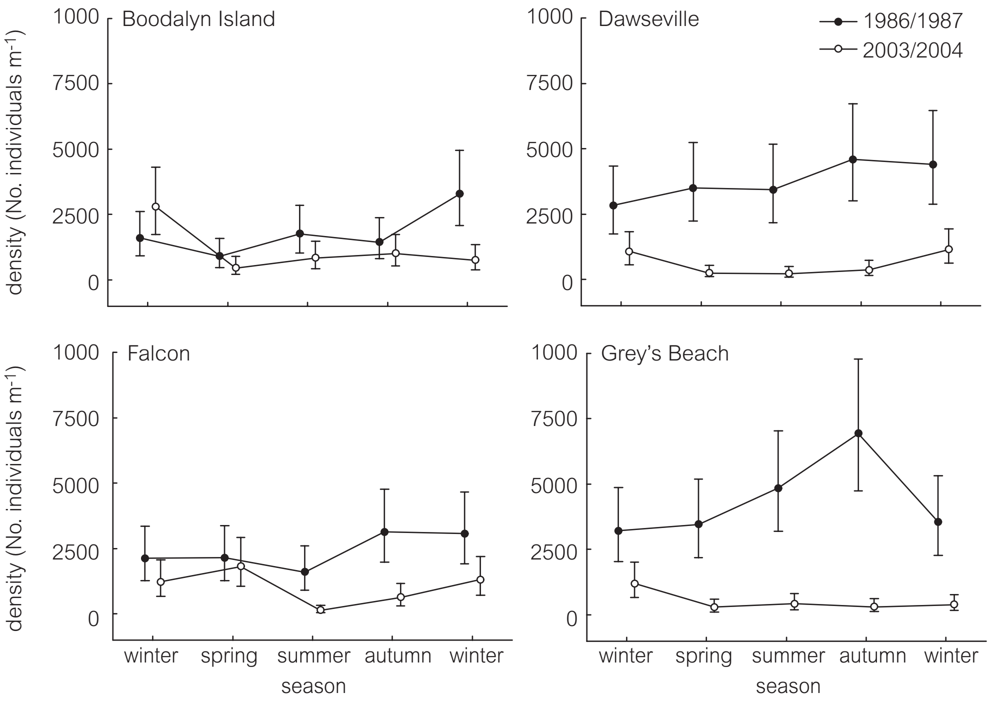


Fig. 2.47: Mean (+/- 95% CI) for the densities of benthic macroinvertebrates recorded during 1986/1987 and 2003/2004 in the Peel-Harvey Estuary in five seasons at A) Boodalyn Island, B) Dawesville, C) Falcon and D) Grey's Beach.

The compositions of the benthic macroinvertebrate fauna in the Peel-Harvey Estuary were also influenced more by time period than by any other factor and were far less variable in 1986/1987 than in 2003/2004 (Fig. 2.48B). Greater densities of the crustaceans *Grandidierella propodenta*, Corophium minor and *Tanais dulongii*, the bivalve *Arthritica semen* and the polychaetes *Capitella* spp., *Boccardiella limnicola* and *Ceratonereis aquisetis* characterised the species composition in 1986/1987, while greater densities of the bivalve *Sanguinolaria biradiata*, the polychaetes *Pseudopolydora* sp. 2, *Australonereis elhersii, Caraziella* sp., *Prionospio cirrifera* and *Leitoscoloplos normalis* characterised the species compositions in 2003/2004.

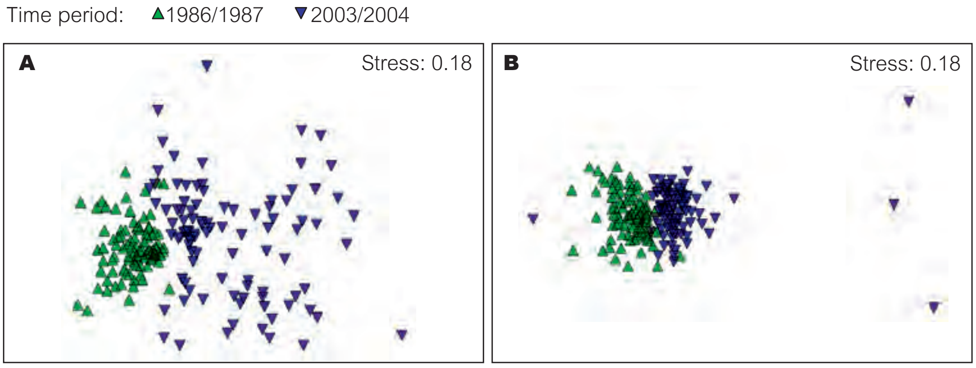


Figure 2.48: MDS ordination of the densities of benthic macroinvertebrates recorded at four sites in five seasons in 1986/1987 and 2003/2004 in A) the Swan-Canning and B) Peel-Harvey estuaries and coded for time period.

These preliminary results suggest that improved conditions in the Peel-Harvey Estuary since the opening of the Dawesville channel have facilitated a more diverse benthic macroinvertebrate fauna. Many of the new species recorded in this estuary in 2003/2004 were marine polychaetes, e.g. *Pseudopolydora* sp., *Prionospio cirrifera, Nephtys graverii* and were likely to have utilized the estuarine environment since the intrusion of marine water further upstream with the opening of the channel. Processing of environmental data including sedimentary organic content, sediment grain size is to be completed by May 2006 and will enable further discussion and conclusions regarding these results.

Summary and Conclusions

The marine component of my study has been completed and published in an international journal. Classification and sampling of the habitats in the Swan Estuary has also been completed and a first draft of this component of the study will be completed by July 2006. A draft of the chapter on comparisons between current and historical data on the benthic macrofaunal assembles in the basins of the Swan and Peel-Harvey estuaries is in progress and will be completed by May 2006.

Intended date for thesis submission: January 2007.

Conference attended: Annual Meeting of the North American Benthological Society, Vancouver 2004 (presented marine component of my work).

Publication

Wildsmith, M.D., Potter, I.C., Valesini, F.J. and Platell, M.E. (2005). Do the assemblages of benthic macroinvertebrates in nearshore waters of Western Australia vary among habitat types, zones and seasons? *Journal of the Marine Biological Association of the United Kingdom*, 85, 4787/1-16.

2.2.12 The ecology and biogeochemistry of sandy sediments in the warm temperate coastal waters of Western Australia

Investigator

Hugh Forehead	University of Western Australia

Supervisors

Dr Peter Thompson	CSIRO Marine and Atmospheric Research
Dr Gary Kendrick and Dr Anya Waite	University of Western Australia

Executive Summary

Benthic microalgae (BMA) are a major source of primary production in shallow coastal waters and play an important role in the cycling of organic matter. The biomass and functioning of the communities of BMA and associated organisms can be affected by wave and current disturbance. This thesis tested a conceptual model that proposed that 1: the biomass of BMA was inversely proportional to the level of disturbance by waves and currents and 2: the increased BMA biomass would increase the capacity for uptake of inorganic nutrients. A suite of pigment and lipid biomarkers and other sediment properties were used to characterise the sediment organic matter and communities of BMA and other microbes. Fluxes of oxygen, N_2 fixation, denitrification and inorganic nutrients were measured in ex-situ incubations to document how these processes respond to changes in the physical and chemical environment.

The effect of depth was measured at 1.5m, 4m, 8m and 14m along triplicate transects.

The 1.5m sediments were markedly different from the other depths; there was frequent wave disturbance and BMA biomass was around 50% of the other depths. The bacterial fraction of the community was significantly less than the other depths. Inorganic nutrients were released in the light and taken up in the dark; around half of the dark uptake at 1.5m could be attributed to diatoms. The net fluxes of inorganic nutrients were not significantly different to the other depths. The deeper depths were strongly autotrophic, biomass was around 88 $mg.m^{-2}$ chlorophyll a and net primary production (NPP) was 2.4 mmol O_2. $m^{-2}.h^{-1}$.

The extensive shallow coastal waters of Western Australia (WA) are oligotrophic, warm (16° to 24°C) and subject to a seasonal pattern of greatest swell activity in winter and mainly smaller, wind-generated waves in summer. There is also a wide spectrum of exposure to swells along the coastline which varies from being open to the Indian Ocean to fringed by reefs and islands. A survey was made of sediments at paired sites, exposed and sheltered by sea walls, at 3 times of year. NPP ranged from -0.39 to 2.51 mmol $O_2.m^{-2}.h^{-1}$. Shelter resulted in increased biomass and elevated rates of NPP and community respiration (CR); though there were no consistent differences in the fluxes of inorganic nutrients. CR increased between cool and warm times of the year by around 100%. N_2 fixation was an order of magnitude smaller than DIN (NH_4+NO_x) fluxes and could only be detected in warm months. Denitrification was of a similar magnitude to N_2 fixation, measurable on all 3 occasions and 6 locations.

Experiments were conducted to examine the effects of shelter and of nutrient enrichment of the water column. After ten days, BMA biomass had increased by around 30% due to shelter, but enrichment had no additional effect. Bacteria and microheterotrophs also increased as a fraction of the community in response to shelter and to enrichment. Sheltered plots had elevated photosynthesis: respiration (P:R) ratios, enrichment resulted in larger ratios. Neither shelter nor the decrease in the N:P ratio stimulated N_2 fixation; there were no significant changes in fluxes of inorganic nutrients.

The resuspension of sediments by waves was simulated by raking. There was a loss of biomass in response to raking, and an increase in the ratio of heterotroph to autotroph biomarkers, suggesting that bacteria were more susceptible to removal and damage by resuspension than were BMA. Raking did not result in any significant changes in the sediment-water exchanges of inorganic nutrients.

Only the first part of the proposed conceptual model proved to be correct in these sediments. Disturbance by waves was responsible for removing biomass; but changes in BMA biomass resulted in little or no significant change to sediment-water exchanges of inorganic nutrients. The balance between autotrophic and heterotrophic components of the microbial biomass changed with disturbance, optimising the use of resources in these oligotrophic waters.

Changes in the sediment microbial community and nutrient cycling along a depth gradient in oligotrophic warm temperate waters

The microbial communities of coastal sandy sediments are often highly productive, sometimes containing more biomass than the water column. The composition of benthic microalgae (BMA) and bacteria in sediment communities become less autotrophic with water depth. As depth increases, the 2 gradients of decreasing levels of light and hydrodynamic energy have opposing effects on autotrophic biomass and sediment ecology. Many studies of sediment biogeochemistry and ecology have been conducted in eutrophic cool temperate conditions. In clear, warm temperate waters, the depth-related gradients of energy operate over very different spatial scales.

Three replicate transects were sampled at 4 depths down a subtidal sandbank in Cockburn Sound, Western Australia (WA); at its shallowest, 1.5m, then 4m, 8m and on the flat at its base at 14m. Sediment cores were collected for ex-situ incubations to measure fluorescence, fluxes of oxygen and inorganic nutrients, N_2 fixation and denitrification. Sediments were analysed for granulometry, pigments, fatty acids, neutral lipids, and organic C and total N. The sediments could be classified into 2 functional zones based on depth: 1.5~<4, and ≥4m. At 1.5m there was a chl *a* concentration of 42.3mg.m^{-2}, wave disturbance was the dominant influence on the sediment biota, and on nutrient processing. The 1.5m sediments were net heterotrophic, with bacterial activity apparently fuelled by BMA photosynthates; there were effluxes of inorganic nutrients in the light and uptake in the dark. The ratio of bacterial: BMA biomass increased with depth, but the P:R ratio was around 2 for all the other depths. The 2 intermediate depths had greater amounts of BMA biomass, 88.4 mg.m^{-2} and 87.6 mg.m^{-2} respectively and greater primary productivity of up to 2.38 mmol O_2. m^{-2}.h^{-1}. The BMA at 4m and 8m also supported a conspicuously large biomass of herbivores (sand dollars). The 14m sites were on a depositional flat at the base of the bank, where chl *a* concentration was slightly lower at 74.7 mg.m^{-2}, and sediments were still net autotrophic, though the greatest bacterial biomass was recorded at this depth.

Fluxes of inorganic nutrients were dominated by NH_4, with a large uptake at 4m (539µmol.m^{-2}.d^{-1}, se 207 n=6) and efflux at 8m (1044µmol.m^{-2}.d^{-1}, se 753 n=6). Around half of the uptake in the dark could be attributed to diatoms. There was no N_2 fixation detected, and denitrification was only measured twice, at one site at 8m and at 14m; rates were less than 0.1µmol N_2.m^{-2}.h^{-1}.

The BMA community was dominated by diatoms at all depths, with around 10% cyanophytes and chlorophytes. The strong PAR climate and clear waters resulted in an important contribution by BMA to primary production beyond 14m. The discontinuity in most parameters at 1.5m suggested that wave disturbance of these sediments resulted in a dramatic shift in their ecology; biogeochemical modelling should not assume linear gradients of biomass and nutrient cycling in these shallow coastal sediments. Compared with areas with shallow euphotic zones, the sediments of Cockburn Sound showed shifts in community composition and ecology over large distances and depth ranges. Wave disturbance in the shallows significantly controlled biomass; there were high levels of biomass and productivity at deeper depths due to organic matter accumulation.

Benthic microalgae in subtidal sandy sediments: effects of seasons and exposure to ocean swells on microbial communities and nutrient cycling

The benthic microalgae (BMA) in subtidal sediments play an important role in nutrient cycling in coastal waters. Physical disturbance of the sediments by waves and currents reduces BMA biomass. On the West Australian coast, sediments are subject to a range of hydrodynamic conditions, due to a coastline that can be open or fringed by reefs and islands. There is also a strong temporal difference between frequent disturbance of sediments by large waves in winter and more stable conditions in summer. This study examines the effects of high and low levels of hydrodynamic energy on the sediment ecology at 3 times of year: August and December 2002 and March 2003. A suite of pigment and lipid biomarkers and other sediment properties were used to characterise sediment communities. A range of different fluxes: oxygen, N_2 fixation, denitrification and inorganic nutrients, were measured in ex-situ incubations. Sediment organic matter was mainly composed of benthic microalgae and bacteria, though relative proportions varied. Diatoms remained the dominant algae in all locations and at all times of year. Chlorophyll a (chl *a*) concentrations in the top 0.5cm of the sediment surface ranged from 5.43 (se 0.61, n=4) to 20.25 (se 15.76 n=4) $mg.m^{-2}$. The BMA contained between 2.4 to 14.5 times the chlorophyll a (chl *a*) of water column phytoplankton per square m. Chl *a* concentrations were always less at exposed sites than at the paired sheltered sites; the reduction was proportional to levels of hydrodynamic energy and ranged from 96% to 14%. Net primary production (NPP) ranged from -0.39 (se 0.27, n=4) to 2.51 (se 0.40, n=4) $mmol.m^{-2}.h^{-1}$, its magnitude was greater at sheltered than at exposed sites. Rates of NPP were comparable to sandy sediments elsewhere in the world, and fixed C contributed 175mg $C.m^{-2}.d^{-1}$ to the ecosystem. Despite this level of productivity, net (24 hour) nutrient fluxes between the sediments and water column were small, the largest inorganic nutrient flux was an uptake of 1.45 (se 1.22) mmol dissolved inorganic nitrogen $(DIN).m^{-2}.d^{-1}$.

Denitrification and N_2 fixation were minor fluxes of N, around 2 orders of magnitude less than DIN. No N_2 fixation was detected in August, which was the coolest sampling period. Sediments were usually a sink for DIN, a source for Si, the direction of P fluxes varied at different times of year. Different conditions of hydrodynamics, temperature and light resulted in large variations in the sediment metabolism and biomass, and the ratio of heterotrophs to BMA, particularly between winter and spring. The resulting fluxes of nutrients across the sediment-water interface changed relatively little. Across a range of conditions, the sediment community acted to minimise the loss of nutrients to the water column. Mainly via increases in the standing stock of BMA, the sheltering of subtidal sediments of coastal Western Australia increases the sequestering of nutrients into BMA and increases the supply of resources available to the food web.

The effects of shelter and enrichment on the ecology of subtidal carbonate sediments in the warm temperate waters of Cockburn Sound, Western Australia

Sheltered sediments often have greater biomass of benthic microalgae (BMA) than those that are exposed to waves and currents. Nutrient enrichment of the water column can also increase biomass in the sediments; and if the enrichment results in N limitation, then N_2 fixation can be expected to increase. Increased water column stability and enrichment are conditions likely to co-exist in sheltered coastal waters, or in prolonged periods of calm waters. The coastline of Western Australia borders the Indian Ocean, and a series of islands, rocky reefs and subtidal sand bars provide sediments with variable degrees of shelter from swells. Summer in these waters is characterised by extended periods with small swells. An experiment was designed to test whether the sediments in oligotrophic waters of Western Australia would respond to decreased physical disturbance by increasing biomass, changing community composition; and whether decreasing the N:P ratio of the water column would stimulate N_2 fixation. Enclosures with 500 micron plankton mesh tops were used to examine the effects of shelter and enrichment on subtidal (7m deep) sediments in Cockburn Sound, Western Australia over a ten day period. Control plots were just marked with stakes (C), treated plots were either only enclosed (E), or enclosed and enriched with slow release N+P fertiliser (E+E). Concentrations of fatty acids, neutral lipids and pigments in the sediment were measured, and intact sediment cores were incubated to measure fluxes of oxygen, inorganic nutrients and N_2 fixation, at the start and end of the experiment. In-situ concentrations of inorganic nutrients were elevated in all enclosures, with greatest concentrations and the lowest N:P ratio, 4.46 (se 1.69), in the E+E treatments. Shelter resulted in a 30% increase in the biomass of BMA, and there was no evidence of an effect of enrichment on biomass. There was an increase in diatoms as a fraction of the BMA community, but only a very small increase of cyanophytes; the shift in the N:P ratio did not increase N_2 fixation over the 10 day period. The remaining biomass, bacteria and other heterotrophs, also increased in response to enrichment and shelter. Levels of net primary production (NPP) were high for oligotrophic sediments, up to 3.67mmol.m^{-2}.h^{-1} and community respiration (CR) ranged up to 3.06 mmolO_2.m^{-2}.h^{-1}. There was a correlation between NPP and the water column nutrient concentration; but accounting for CR, gross primary production increased by similar amounts in both enclosure treatments. Lipid biomarkers suggested that macrofaunal grazers that were excluded from the enclosures, such as sand dollars, were replaced by microheterotrophs. There were small changes in hourly rates of sediment-water fluxes of PO_4 and Si in response to shelter, but there was no net difference over 24 hours. Reducing bottom stress on these sediments caused an accumulation of labile organic carbon and little change to inorganic nutrient cycling. Sheltered sediments are likely to have an increased capacity for supporting grazers, including invertebrates and fish. With increased hydrodynamic energy, resuspension of previously sheltered sediments would be likely to result in a significant increase in water column biomass.

Scratching the surface: resuspension of subtidal sediments in Western Australia, effects on sediment ecology and nutrient cycling

The biomass of benthic microalgae (BMA) is reduced by the disturbance of sediments by waves, causing resuspension and cell damage. BMA can modify sediment-water fluxes of oxygen and nutrients in a number of ways. In a conceptual model of the sediments in Cockburn Sound, it was proposed that physical disturbance decreased BMA biomass and reduced the sediment uptake of inorganic nutrients. To investigate the effects of physical disturbance on the sediment community, a resuspension event was simulated by raking subtidal sediments. Concentrations of sediment pigments, fatty acids, neutral lipids, organic carbon and nitrogen were used to characterise the sediment community before and after the disturbance. Fluxes of oxygen, inorganic nutrients, denitrification and N_2 fixing capacity were measured by intact core incubations. The sediment community was dominated by BMA and there were strong correlations between the biomass of BMA and bacteria. Following the disturbance, concentrations of degradation products were similar to those found following a winter storm in nearby sediments. Raking resulted in a 41.5% reduction in chlorophyll a (chl *a*) concentration; lost by removal of, and damage to, BMA. Diatoms remained dominant, but a decrease in the fucoxanthin: chl *a* ratio, and in sediment sterol ratios suggested a possible change at the species level. The ratio of bacteria to BMA was decreased in raked relative to control plots, suggesting that bacteria were more susceptible to removal or damage. Net primary production (NPP) differed significantly from the start to the end of the experiment for unraked controls, but changed little in control plots. Rates of N_2 fixation were around 2 orders of magnitude less than DIN fluxes, and were reduced by raking. Raking resulted in greater uptake of Si relative to controls, most likely due to a reduction in sediment reserves. NH_4 uptake, the majority DIN flux by an order of magnitude, did not change. The resuspension associated with raking suspended sufficient chl *a* to raise the concentration of the 7m deep water column by 2.44µg.L^{-1} (171%), or 148µg.L^{-1} organic carbon. The study demonstrated that resuspension events were important in increasing water column productivity. Resuspension decreased benthic biomass, and controlled sediment microbial community composition in these coastal subtidal sediments in south west Australia. Apart from increasing the uptake of Si, a result contrary to the original proposition, resuspension did not significantly alter sediment-water fluxes of inorganic nutrients.

Acknowledgements

My heartfelt thanks to the people who have given me help and encouragement over the course of this PhD. To those I've missed in the following, I apologise. My parents Mary and David, sister Jane and brother Ralph, for unconditional support and encouragement; My wife, Vikki for support and keeping my life full; My supervisors: Peter Thompson, Gary Kendrick and Anya Waite, for their financial support, guidance and ideas; great minds, great people. Peter especially, for generosity with his time and resources, he was usually the first port of call. Gary for making things that I needed happen in Perth, boundless energy and encouragement. Anya for great facilities at CWR. Di Walker, who convinced people that I could do this project from 3500 km away; For valuable discussions and sharing their knowledge: Andy Revill, John Volkman, Peter Nichols, Anne Brearley, Marion Cambridge, Paul Lavery, Karen Hillman, Perran Cook, for a large role in getting me started, generously passing on techniques, advice, and knowledge; while finishing his own PhD. Lesley Clementson and Pru Bonham for time spent teaching me pigment analysis by HPLC, follow-up advice and logistic help. Thanks to Pru Bonham for doing pigment extractions in April 2003 and March 2004.

For use of his lab and equipment in Hobart, Ed Butler. For advice with lab work and assistance with equipment and instruments: at CSIRO- Kate Berry, Stephane Armand, Rebecca Esmay, Danny Holdsworth, Ian Jameson, Cathy Johnston. UWA- Liza Tunnell, Greg Cawthray, Jamie McLaughlin, Bridget Alexander, Siew Hong Wade, Greg Attwater, Lidia Bednarek, Hai Ngo. For getting me started in ammonium analysis: Ros Watson. For doing my other nutrient analyses: Val Latham, Neale Johnston, Dave Terhell. For making equipment that was better than I could have bought, the workshop crews: in Hobart- Bob Driscoll, Dave Kube, Christian Blood, Neal McQueen, Dave Cherry, Dean Medwin. In electronics: Matt Sherlock, Erik Madsen, Jeff Cordell. UWA- Leon Hodgson. For help in the field, special thanks to Simon Grove, also to Anne Brearley, Marion Cambridge, Julia Phillips, Nicole Murphy, Jamie McLaughlin, Dave Gull, Paul Dean and fellow students: Alicia Loveless, Kieryn Kilminster, Nisse Goldberg, Ben Toohey. For collecting seagrass samples, and sending them to Hobart: Marion Cambridge, Renae Hovae, Oceanica Consulting Pty. Ltd., Perth for generously sharing environmental data; Kwinana Industry Council funded the collection of much of the Cockburn Sound environmental data from reports that were cited in this thesis; For CSIRO Marine Research and UWA (SRFME) for financial support, including UWA student travel grant. The Phycological Society of America for a student travel award.

Conferences/workshop attended

2005	Oral paper given at American Society of Limnology and Oceanography summer meeting
2004	Oral paper given at Australian Marine Sciences Association annual meeting
2003	Seminar paper at University of Hawaii
2003	Presented paper at Phycological Society of America Annual Meeting
2002	Attended "Sediment biogeochemistry workshop" at Southern Cross University

Thesis submitted, March 2006, Degree conferred July 2006.

CHAPTER 3

3. COLLABORATIVE LINKAGES PROGRAM: COLLABORATIVE PROJECTS

3.1 SRFME Collaborative Projects

The objective of this SRFME Collaborative Linkages program is to deliver strategic research outcomes, capacity building and new and/or strengthened research collaboration among CSIRO, Universities, other research providers and government agencies. A total of $1.99 million has been committed to the funding of eight collaborative projects within SRFME, to universities and institutions including the University of Western Australia, Edith Cowan University, Murdoch University, and the WA Museum.

Two SRFME collaborative projects symposia were held at the Floreat Centre for Environment and Life Sciences of CSIRO, in June 2004 and March 2006. Some of these projects are still ongoing and will finish in 2007, so their reports are preliminary.

3.2 SRFME Collaborative Projects, PI's, and Affiliations

Project Title	Principal	Principal Investigators	Co-Invesigators
Interaction of Coastal Currents, Phytoplankton Dynamics and Trophic Transfer in the Coastal Waters of Western Australia	Dr Anya Waite – UWA	Dr Anya Waite – UWA Dr Peter Thompson – CSIRO Dr Luke Twomey – UWA Dr Dan Gaughan – WA Fisheries	Dr Michael Borowitzka – Murdoch A Prof Mervyn Lynch – Curtin
Spatial Patterns in Sessile Benthic Sponge and Ascidian Communities of the Recherche Archilpelago	Dr Gary Kendrick – UWA	Dr Gary Kendrick – UWA Dr Jane Fromont – WA Museum Dr Justin McDonald – UWA	Dr Euan Harvey – UWA Dr Chris Simpson – CALM
Understanding the Natural Variability of Currents Along the Western Australian coastline	Prof Charitha Pattiaratchi – UWA	Prof Charitha Pattiaratchi – UWA Dr Yun Li – CSIRO Dr Ming Feng – CSIRO	Dr Gary Meyers – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: Trophodynamics	Dr Glenn Hyndes – ECU	Dr Glenn Hyndes – ECU	Dr Mat Vanderklift – CSIRO Dr Russ Babcock – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster	Dr Glenn Hyndes – ECU	Dr Glenn Hyndes –ECU	Dr Russ Babcock – CSIRO Dr Mat Vanderklift – CSIRO
Ecophysiology of Benthic Primary Producers	Dr Paul Lavery – ECU	Dr Paul Lavery – ECU	Dr Russ Babcock – CSIRO
Biodiversity of Marine Fauna on the Central West Coast	Dr Jane Fromont, Dr Fred Wells – WA Museum	Dr Jane Fromont, Dr Fred Wells – WA Museum	Dr Russ Babcock – CSIRO
Ecological Interactions in Coastal Marine Ecosystems: The Fish Communities and Main Fish Populations of the Jurien Bay Marine Park	Professor Ian Potter – Murdoch University	Professor Ian Potter David Fairclough – Murdoch University	Dr Russ Babcock – CSIRO

3.3 Collaborative Project Reports

3.3.1 Interaction of coastal currents, phytoplankton dynamics and trophic transfer in the coastal waters of Western Australia

September 2003 – March 2006

Dr. Anya M. Waite[1], Dr. Peter A. Thompson[2], Dr. Luke Twomey[1], Dr. Dan Gaughan[3]

1. School of Environmental Systems Engineering, University of Western Australia, 35 Stirling Highway, Crawley WA 6009

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3. Research Division, Department of Fisheries, Government of Western Australia P.O. Box 20, North Beach, WA 6920

Executive Summary

This project aimed to elucidate connections between fisheries production and the influx of upwelled nutrients, particularly nitrate, into surface waters off Western Australia. We hypothesized that the primary controls of this flux were 1) wind-driven upwelling and 2) pumping of nutrients within the active mesoscale eddy field of the Leeuwin Current. We therefore needed to determine both whether this upwelling occurred and whether it enhanced ecosystem production when active. Using a series of cross-shelf transects off Albany, we made some of the first measurements of upwelling off the south coast coupled with enhanced uptake of nitrate, and enhanced distribution of chlorophyll in near-shore and surface waters. Production overall was dominated by the picoplankton (< 5 μm fraction) but with important occasional peaks in the microplankton (> 5 μm fraction). We also showed that the likely diet of the South Coast sardine is the >100 mm fraction of zooplankton (primarily small copepods, but also likely including microheterotrophs) which utilize ~70% nitrate-driven production. We also found unusually high F-ratios (nitrate uptake as a fraction of total N uptake) in coastal waters off SW Western Australia in regions where surface concentrations of nitrate were frequently at or below our detection limit of 50 Nmol L^{-1} , highlighting the possible importance of sporadic upwelling events in driving coastal production. Finally, our research has demonstrated that warm-core (WC) eddies off WA are unusually productive, and may be important features moving nutrient-rich and/ or phytoplankton-rich water from the shelf and shelf break into the open ocean off WA. In contrast, the cold-core eddies were not active upwelling systems as originally expected.

Overall, our work highlights the importance of nitrate-driven both primary and secondary production in a number of regions of WA waters (the Southwest, the South Coast, and WC eddies of the Leeuwin Current) where nitrate is at concentrations so low that they are not analytically detectable, and the importance of measuring uptake rates rather than static variables in the analysis of production patterns off our coast.

Project Aims

1. To determine the extent to which new upwelled nitrate associated with the interaction between nearshore and continental-shelf currents in coastal waters near Esperance fuels phytoplankton productivity and trophic transfer to finfish and shellfish larvae.

2. To determine whether N-fixation occurs in the Esperance region, and if so, to estimate its possible contribution to the growth of larval fish and shellfish

3. To develop an understanding of the link between primary productivity and the spatial and/or temporal distribution of larval *Sardinops sargax* in coastal waters between Albany and Esperance.

4. In a comparative study, to map the larval abundance & health, and ecosystem structure of two eddies off the west coast of WA: a downwelling ("death-trap") eddy, possibly dominated by N-fixation, and an upwelling ("nursery") eddy, possibly dominated by upwelled nitrate.

Expected Outcomes

1. Detailed understanding of the links between upwelling, phytoplankton nutrient requirements, and ecosystem structure off Esperance and in the eddy system off WA's west coast.
2. Enhanced understanding of the links between primary productivity and fish population dynamics.
3. Enhanced understanding of regional dynamics impacting the fisheries resources of WA.
4. Improved ability to manage future commercial/industrial development.
5. Estimate of the possible contribution to fish production made by N-fixing cyanobacteria, essentially short-circuiting the need for upwelled nutrients during non-upwelling periods.

Project Summary

The SRFME collaborative project (henceforth SCP) was funded in September 2003. Since initiation we have completed 2 major offshore voyages, 1) the October 2003 Eddy Research Voyage on the R/V *Southern Surveyor* led by Waite et al., and 2) the coastal survey voyage led by Pattiaratchi in September-November 2003. We completed 4 collaborative field trips with Fisheries WA which have sampled the waters between Albany and Hopetoun, Esperance and Albany, Cape Naturaliste and Perth, and a repeat of Albany and Hopetoun.

We have also completed three summer field sampling programmes (2003 – 04, 2004 – 05 and 2005 - 06) off the coast of Albany to investigate coastal upwelling associated with Albany trench. During the cruises we measured phytoplankton biomass, primary production, nitrogen uptake, nitrogen fixation and isotopic signatures, and directly addressed all four stated aims of the SCP (above).

In October 2004 we organized a very successful Special Session on the Leeuwin Current at the Australian Marine Sciences Association annual meeting, including an invited talk and informal review of our project by Dr. Robert Bidigare (Univ. of Hawaii). Since then we have negotiated a Special Issue of Deep-Sea Research II on the Leeuwin Current and its Eddies in 2006. Many key scientific outcomes are now being finalized.

Finally, to ensure we maximize outcomes for the final year of the Waite SRFME Collaborative Project, we successfully bid for two final allocations of ship time in 2006 1) to investigate further the role of mesoscale eddies in the Leeuwin Current in mediating cross-shelf transport (Chief Scientist: Waite) and 2) to survey production off the south coast of WA (Ship time awarded to Pattiaratchi, Waite, Thompson; Chief Scientist: Pattiaratchi).

The work initiated in this project has formed the springboard for a successful ARC Discovery Grant awarded to Chief Investigator Waite 2006 – 2008 (See Appendix 2).

Field Sampling –Summary

Fisheries Sampling:

9th July – 17th July 2003 (Albany to Hopetoun)

1st – 15th March 2004 (Hopetoun to Esperance)

11th – 17th July 2004 (Cape Naturaliste to Perth)

13th – 20th July 2005 (Hopetoun to Albany)

Southern Surveyor

Eddy Research Voyage

1 October – 22 October 2003

Southern Surveyor

SW Survey Voyage

Geraldton – Cape Leeuwin

24th September – 9th November 2003

Albany Field Sampling

13 transects completed (2003-2006):

Albany Trench Day Trip 1, February 2004

Albany Trench Day Trip 2, September 2004

Albany Trench Day Trip 3, October 2004

Albany Trench Day Trip 4, November 2004

Albany Trench Day Trip 5, December 2004

Albany Trench Day Trip 6, January 2005

Albany Trench Day Trip 7, February 2005

Albany Trench Day Trip 8, May 2005

Albany Trench Day Trip 9, July 2005

Albany Trench Day Trip 10, September 2005

Albany Trench Day Trip 11, October 2005

Albany Trench Day Trip 12, December 2005

Albany Trench Day Trip 13, January 2006

Southern Surveyor

South Coast Survey – April 2006

Southern Surveyor

Eddies II – May 2006

Staffing Summary

Post-doctoral Research Associate:

Luke Twomey continued his 0.5 appointment as the project manager. His duties include project design, managing the field research and collection and collation of data.

Field Technician:

Geoff Bastyan: field consultant based in Albany, employed on a contractual basis to assist in field research.

Field / Laboratory Technician:

Kim Brooks continued a 0.5 appointment as the project field and laboratory technician.

Student Involvement

Final Year Students

There were two final year students who completed honours projects associated with the research project in 2003 – 04, and one in 2004 – 05.

1. Tim Malseed: investigating the isotopic signatures of fish gut content to link primary productivity and trophic transfer through the food chain. (Superv. by A. Waite, PI, and Dr. Daniel Gaughan, Fisheries WA) (Compl. October 2004)
2. Vanessa Pez: examining spatial and temporal nitrogen uptake dynamics of phytoplankton on the SW Survey Voyage (SS09/03). (Superv. by A. Waite, PI; Compl. December 2004)
3. Elis Smedley: Investigating trophic transfer of nutrients through the marine food web in Albany Harbour and the adjacent coastal waters. (Superv. by L. Twomey and A. Waite, Completed Dec 2005)

Australian Postgraduate Students

1. Florence Verspecht : As part of her SRFME PhD project, Florence executed primary production measurements on the SW Survey Voyage (SS09/03) (Supervised by A. Waite, PI and C. Pattiaratchi, CWR)
2. Harriet Paterson: Harriet was involved with analysis of microzooplankton diversity and abundance on the Eddies Cruise in 2003 (Supervised by A. Waite, B. Knott, UWA and T. Koslow, CSIRO)

International Postgraduate Students

1. Carrie Holl, Georgia Tech, USA: Measurements of Nitrogen Fixation on the Eddies Cruise 2003 (Supervised by J. Montoya, Georgia Tech)
2. Jason Landrum, Georgia Tech, USA: Measurements of Nitrogen Fixation on the Eddies II: Cross-shelf Transport cruise in 2006. (Supervised by J. Montoya, Georgia Tech)
3. Moira Llabres CSIC, Spain: Measurement of phytoplankton cell lysis, UV effects and atmospheric N deposition on the Eddies II: Cross-shelf Transport cruise in 2006 (Supervised by S. Agusti and C. Duarte, Spain)

Scientific Outcomes

The Waite, Thompson and Twomey SRFME Collaborative Project is still ongoing (until September 2006) and has two more major research cruises planned for April and May 2006 respectively. However we offer a brief summary of the scientific outcomes of the study to date, including the Coastal Surveys, the South Coast, and the Eddies studies. We plan a review paper synthesizing the last 5-6 years of production estimates along the WA coast and highlighting novel aspects of lagoon and shelf ecosystem function based the SCP and other related work.

Coastal Survey: A coastal survey consisting of a series of transects off southwestern WA (Sept 2003) was the first study executed as part of the SCP, and the results of that study provided the first broad-scale regional characterisation of the phytoplankton-nitrogen (N) dynamics across the continental shelf between the Abrolhos Islands and Cape Leeuwin, Western Australia. We demonstrated key features of phytoplankton nutrient-uptake including nitrate and ammonium uptake and N fixation, across the dominant current systems of the west coast of Australia during a 2-week period in spring-summer. The surface waters of the region were N impoverished with low phytoplankton biomass. Nitrate and ammonium uptake rates were among the lowest recorded, but surprisingly, *f*-ratios were high compared to other oligotrophic systems (*f*-ratio ~ 0.5 throughout) indicating an equal preference for nitrate and ammonium uptake. This suggests the much greater importance of upwelling in regional production in this area than in regions north of the Abrolhos. Areas of high phytoplankton biomass were most likely fuelled by nitrate transported into the euphotic zone during temporally short bursts of upwelling on ~weekly, rather than monthly, time scales, based on the time scales of phytoplankton enzymatic response to the presence of nitrate. When upwelling had relaxed, phytoplankton productivity was largely maintained by microbial regeneration (ammonium production) in the euphotic zone. A large proportion (20-60%) of the phytoplankton biomass was comprised of picoplankton and nanoplankton diazotrophs. However, rates of N_2 fixation were 2 orders of magnitude lower than dissolved inorganic N uptake, indicating that N_2-fixation did not significantly contribute to phytoplankton productivity during the study.

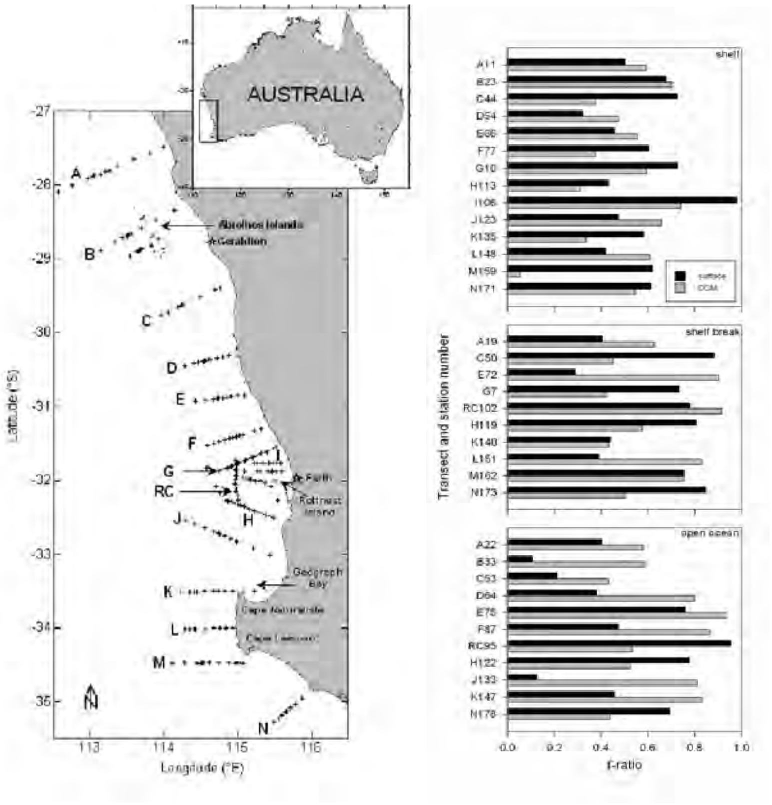


Figure 3.1: Map of Coastal Survey Voyage (L) and the dominance of nitrate as an N source to phytoplankton (R) given as the f-ratio. A ratio of > 0.5 indicates that nitrate probably dominates the N nutrition of the algae. The primary source of nitrate to this system is the upwelling of deep nitrate from off the shelf (from Twomey *et al.*, submitted).

Throughout this survey, nitrogen uptake from Nitrogen Fixation was negligible (Table 3.1).

Table 3.1. Summary of N uptake measurements at the deep chlorophyll maximum (DCM) for the Coastal Survey (above). Note similarity in uptake rates of ammonium and nitrate (leading to an f-ratio of ~0.5 or greater, while N-fixation is 2 orders of magnitude lower.

Nitrogen Uptake (nmol L^{-1} h^{-1})	Depth	Continental Shelf	Shelf break	Open Ocean
NO_3	SFC	2.0 (0.36)	2.0 (0.72)	1.3 (0.25)
	DCM	2.0 (0.53)	12.6 (6.1)	5.8 (2.9)
NH_4	SFC	1.4 (0.26)	1.2 (0.32)	2.1 (0.38)
	DCM	1.8 (0.32)	2.5 (0.56)	1.5 (0.26)
N_2 (gas)	SFC	0.017 (0.006)	0.007 (0.006)	0.003 (0.003)
	DCM	0.003 (0.002)	0.001 (0.001)	0.004 (0.003)

South Coast Program: Under the supervision of Dr Luke Twomey, the team executed a series of 1-day transects across the continental shelf seaward from Albany; these were punctuated with 4 regional plankton surveys in collaboration with Fisheries WA.

Scientific Objectives

- To examine the vertical structure of salinity, temperature and fluorescence across the continental shelf break adjacent to the Albany trench.
- To measure phytoplankton biomass, productivity and nitrogen uptake relative to nutrient availability.
- To collect particulate organic matter (POM) at various size fractions to examine the isotopic signatures various trophic levels.

Personnel: Kim Brooks, Geoff Bastyan (SESE technician)+ 2 charter boat crew

Methods

- The charter boat sampled 7 sites, including 3 major sites for biological sample collection. The boat was taken across the continental shelf break to an area where the depth exceeded 500m.
- The CSIRO Seabird CTD was used to collect depth profiles of salinity, temperature, depth and fluorescence at sites.
- Surface and chlorophyll maximum water samples were collected for phytoplankton biomass, productivity, nitrogen uptake and taxonomic analyses at 3 major sites on each transect.
- Planktonic samples were collected and size fractionated for POM analysis at 3 major sites on each transect.

Day Trip Summary

The day trips were highly successful despite the inhospitable conditions encountered in the coastal waters off the Albany coastline. All of the major objectives have been fulfilled and the full complement of physical, chemical and biological sampling are now complete. Kim Brooks and Geoff Bastyan were extremely competent and efficient field technicians. The charter boat operators were enthusiastic in their approach to the project. February and March day trips were cancelled due to poor conditions on the south coast. Currently data are being processed for the preparation of manuscripts from the study. We are awaiting nutrient concentration data and the mass spectrometry data. Preparation of the first manuscript is underway and there are data to produce at least one other. We envisage submission of these manuscripts to leading peer-reviewed journals by August 2006.

The results from the Albany day trips will be presented at the Australian Marine Science Association Conference in Cairns, July 2006.

One of the most interesting aspects of the South Coast research program was the direct linkage to aspects of the Pilchard Fishery. The South Coast program included both day trips across the shelf to the Albany canyon, and > 1 week efforts in collaboration with Fisheries WA. Two honours students executed food web assessment based on isotope analyses, including dissection of local Pilchard guts (see Trophodynamics section below). The food web maps suggested the pilchards were supported by production significantly enriched in nitrate; this would have been driven by periodic upwelling along the south coast. Clear upwelling off Albany was observed at a number of sampling dates (e.g., October 2005, February 2004) following significant easterly winds, bringing cool, nutrient-rich water directly on shore (Figs 3.2, 3.3 and 3.4). While the small boat work certainly had its logistical limitations, it has allowed us to test key hypotheses about the function of the south coast ecosystems.

Analysis of production and nutrient uptake experiments are still in progress, but preliminary results (Figures 3.2-3.4) indicate that at times of strong upwelling, such as that seen during sampling October 2005, nitrate uptake rates are significantly enhanced, primarily in the Deep Chlorophyll Maximum (DCM) on the shelf and slope. This key result indicates for the first time that wind–driven upwelling results in an increase in nitrogen uptake into the plankton off the South coast of Western Australia. This is especially relevant given that the pilchard diet seems to be significantly enriched in parts of the food web feeding primarily on nitrate (see below).

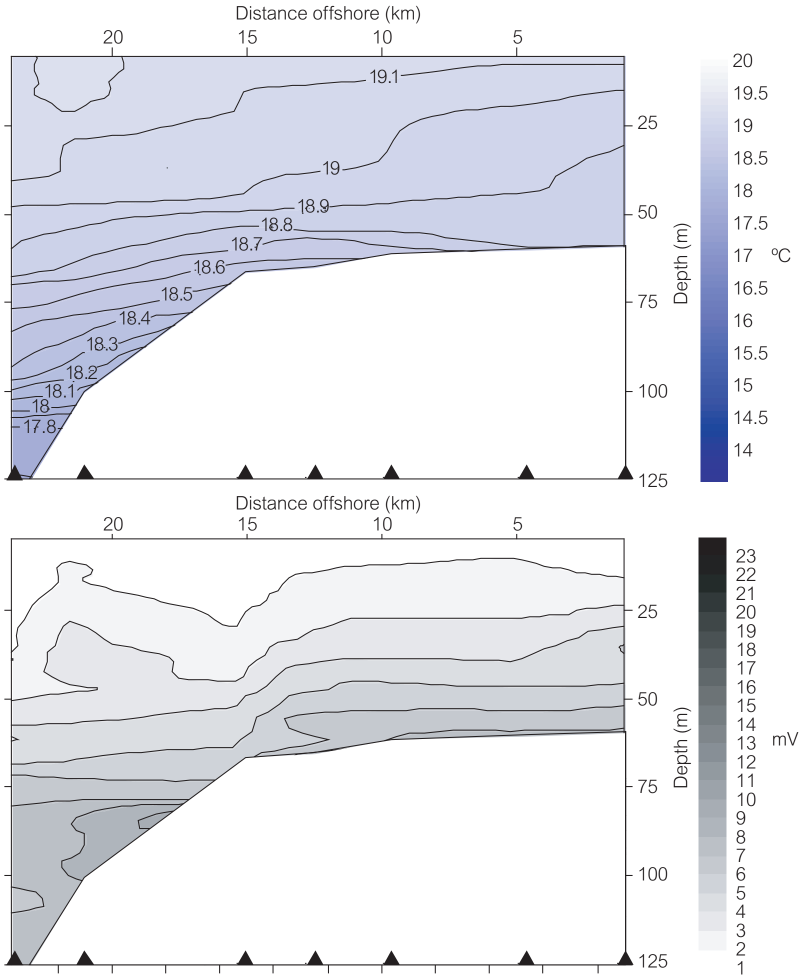


Figure 3.2: (i) Temperature and (ii) Fluorescence profile for February 2004 off Albany showing gentle upwelling (upward tilting of density clines) after a period of easterly winds (see Fig 3.5 for wind rose).

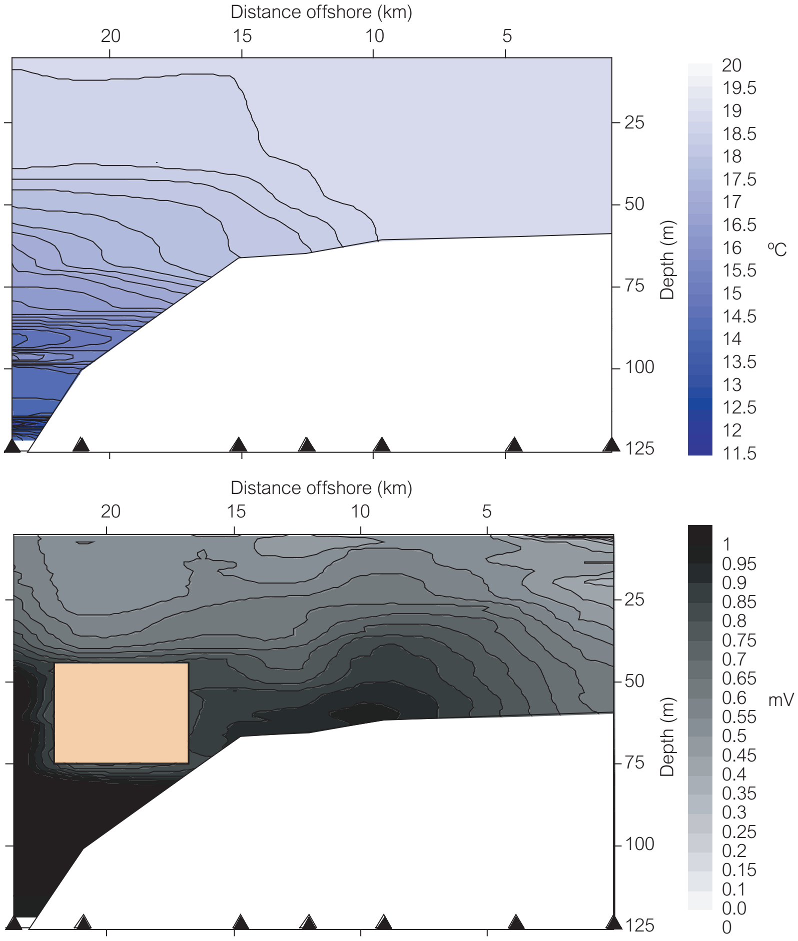


Figure 3.3: (i) Temperature and (ii) Fluorescence profile off Albany for December 2004 showing a non-upwelling situation with pycnoclines tilted in a downwelling direction. Note typical deep chlorophyll maximum near the bottom on the continental shelf. Tan area denotes poor data.

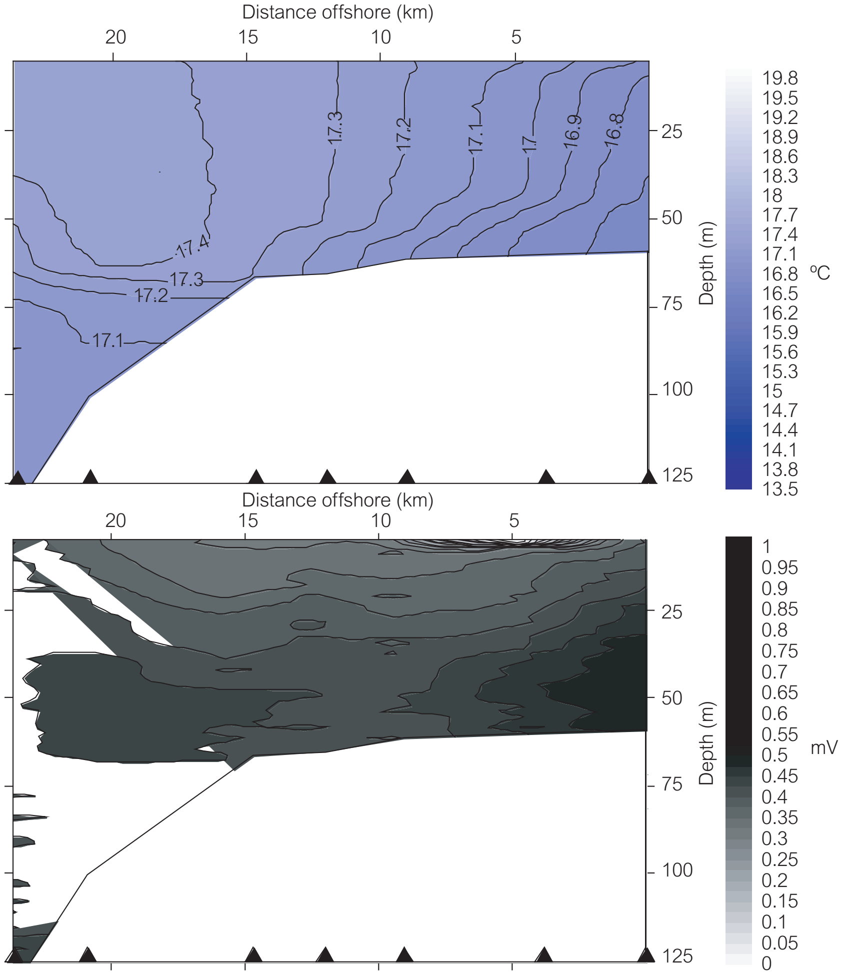


Figure 3.4: (i) Temperature and (ii) Fluorescence profile off Albany for October 2005 showing a very strong upwelling signature. Note that the wind rose shows a mixture of wind directions; however the easterly wind is likely to have dominated for a significant period.

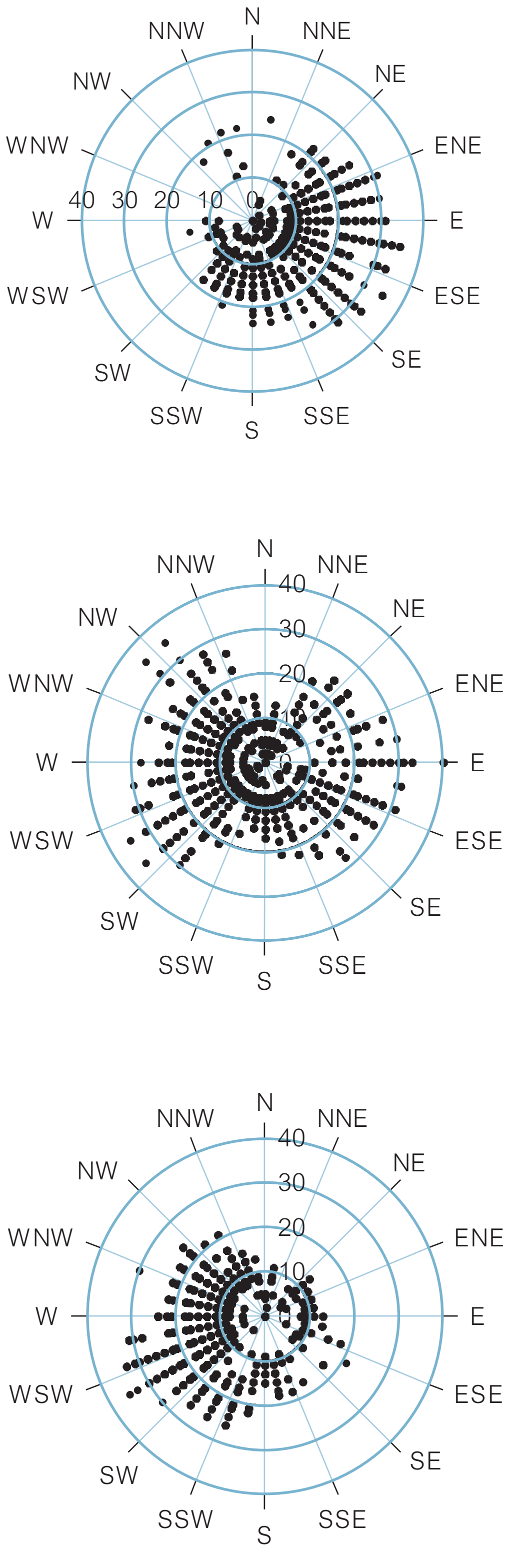


Figure 3.5: Wind roses showing hourly wind speeds for the 2 weeks previous to the Albany day cruises on February 2004, December 2005 and October 2005 respectively. Note the strong easterlies in October, which must have been sustained enough to generate significant amounts of upwelling.

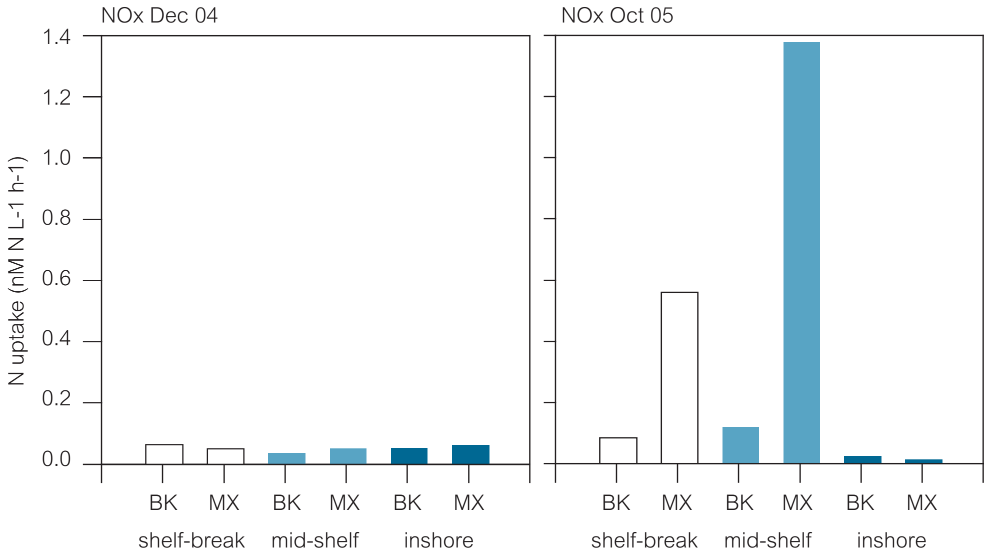
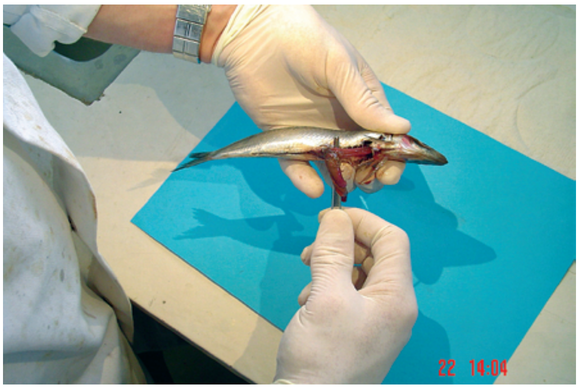


Figure 3.6: Nitrogen uptake (not normalized) per liter measured as uptake of $^{15}NO_3$ at the surface (Bucket, or BK) and at the deep chlorophyll maximum (MX) under non-upwelling conditions (top figure; December 2004) and under strong upwelling conditions (bottom figure; October 2005). Note the increase in N uptake at depth as nitrogen becomes more available during upwelling; Surface values are also increased but not as greatly.

Trophodynamics Analysis: Food Web Maps

Esperance Feb-March 2004.

In the coastal waters off the coast of Esperance, a study by T. Malseed (BE 2004) in 2004 investigated the food sources of the sardine *Sardinops sagax*. During the 2004 autumn Fisheries WA survey, Malseed surveyed the abundance and composition of plankton on the continental shelf off Esperance, and using nitrogen isotopic composition, estimated the fraction of nitrate-driven production that supported the sardine. He found that even the photosynthetic picoplankton (< 5 µm) , which often grow primarily on ammonium, were acquiring a large fraction of their DIN with a similar signal to deep water nitrate. Sardine white muscle tissue had a signal which represented a mixture of food sources from the large phytoplankton and zooplankton, dominated by small copepods (see Fig. 3.7). This was confirmed by analysis of the gut content. The signal suggested that primary food sources of sardines in Esperance were derived from large diatoms (20 µm) small zooplankton (100 µm), which were largely acquiring DIN in the form of nitrate with a similar signal to deep water nitrate, a transfer to the sardine of ~70% nitrate-based production. This was similar to planktonic and sardine analysis off Albany (Fig. 3.8).



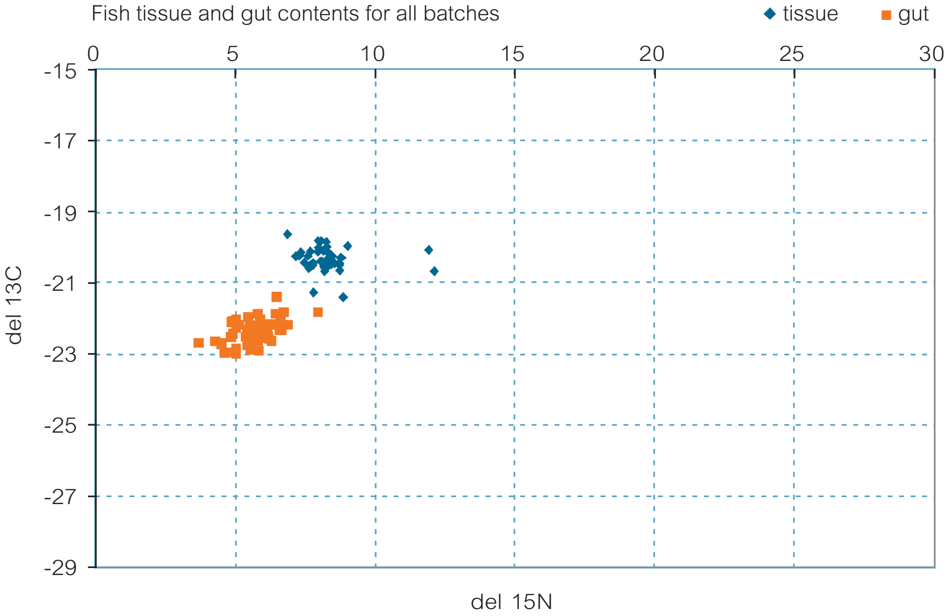


Figure 3.7: A study by T. Malseed off Esperance involved dissection of the sardine *Sardinops sagax* to measure the isotopic composition of its muscle tissue and assess the composition of its gut contents (top). The mean differences, or fractionation, in $\delta^{15}N$ and $\delta^{13}C$ signature between the tissue (blue symbols) and its gut contents (pink symbols) were 2.67 +/- 0.20 and 1.97 +/- 0.07 for N and C respectively. This signature was then matched with the isotopic composition of various measured plankton fractions to estimate the likely prey. In this case the prey were estimated to be > 75% 100 μm zooplankton (small copepods).

Albany June 2005

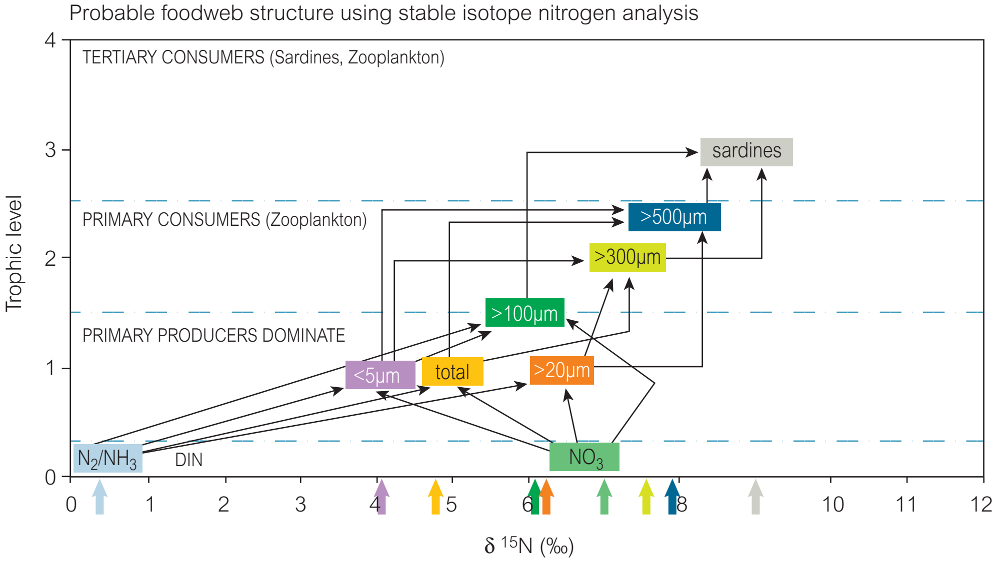


Figure 3.8: The planktonic community of the nearshore waters of Albany was dominated by diatoms and flagellates. These groups were generally of a small size, with a large number of nanoplankton observed from these groups. Although the picoplankton size fraction was too small to be detected using x 20 magnification, it is likely that there would have been a large number of organisms in this fraction and it is likely that the majority of these would have been either cyanobacteria or flagellates. There were also a significant number of larger (>20 µm) primary producers observed. These were predominantly diatoms and dinoflagellates. However, as most of the dinoflagellates in Western Australian waters are heterotrophic (Wood, 1954), it is unclear how much contribution the dinoflagellates make to the autotrophy versus heterotrophy.

A study by E. Smedley (BE 2005) indicated a remarkable similarity between the Esperance and Albany plankton and sardine isotopic composition. As was seen off Esperance, the sardine diet seemed dominated by the >100 µm size fraction, which contained a roughly even number of zooplankton, dinoflagellates and diatoms, however zooplankton dominated the biomass. This group was made up predominantly of copepods, nauplii and fish eggs. Evidence from the sardine gut analysis confirmed that these groups were the primary diet of the sampled sardines. The other significant contributors were heterotrophic and autotrophic dinoflagellates, and large diatom species. Although present in large numbers, there was no evidence that the smaller primary producers were grazed by *S. sagax*. However, these groups were important in the diet of zooplankton and heterotrophic dinoflagellates, which are in turn fed upon by *S. sagax* aged two to three years age in the Albany region.

Previous studies undertaken have shown that the main food source for *S. sagax* are larger zooplankton with a size fraction of less than 1,200µm, and a modal size of around 300 µm (e.g., Bode et al., 2003). However, the studies were all undertaken in nutrient rich, upwelling regions or in laboratory conditions replicating these conditions. It is significant that sardines from different regions throughout the world, and in vastly different oceanographic conditions display remarkably similar diets.

Here we can show that, similar to the results off Esperance (Figure 3.7) ~70% of the sardine diet off Albany was driven by nitrate-based production.

Previous studies into the south coast population of *S. sagax* attributed the negative correlation between Leeuwin Current strength and sardine recruitment to larvae dispersion through advection and a decrease in sardine spawning due to an increase in water temperature (Caputi *et al*. 1996). Given the importance of upwelling in the productivity of the sardine population in the Albany region, it can be concluded that the Leeuwin Current influences productivity in more ways than those previously attributed. The suppression of upwelling by the Leeuwin Current greatly reduces the nitrogen available for primary production, which in turn decreases the productivity of zooplankton available for *S. sagax* to graze upon. The evidence from this study suggests that upwelling on the south coast of Western Australia plays a much greater role in the regional ecology than perhaps previously thought.

Eddies Study: The Leeuwin Current (LC) dynamics include the formation of a dynamic mesoscale eddy field possibly important to regional fisheries such as the Western Rock Lobster, *Panulirus cygnus*. In 2003 we launched an initiative to investigate the impact of eddies on regional productivity.

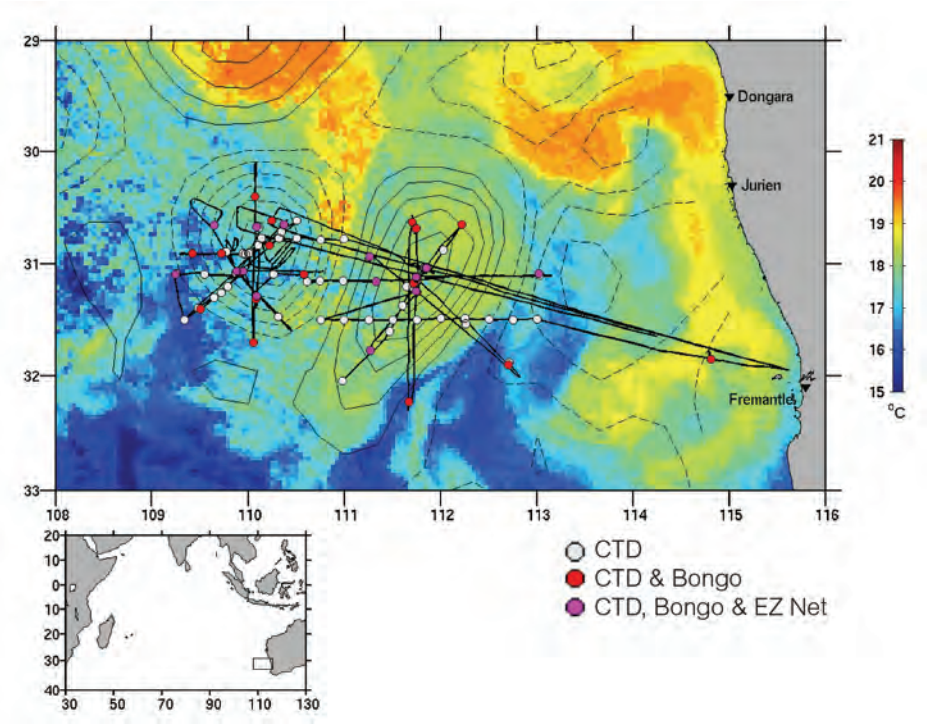


Figure 3.9: Cruise track of the Eddies Voyage 2003 showing all stations sampled within two counter-rotating eddies. The eddies had been formed off Fremantle in May 2003 and were stable, mature features at the time of sampling.

Satellite altimetry indicates that though the eddies studied in our 2003 field program were dynamically typical of LC eddies, the actual warm-core (WC) eddy studied in 2003 was relatively large and long-lived. The WC eddy contained relatively elevated chlorophyll *a* concentrations thought to originate at least in part from the continental shelf / shelf break region and to have been incorporated during eddy formation; nutrient fluxes across WC eddy boundaries may also be important in supporting the observed plankton populations.

During the Eddies ’03 voyage, a more detailed study comparing the WC and cold-core (CC) eddies illuminated more mechanistic details of the dynamics and ecology of the eddies. Nitrogen fixation was measured almost entirely in the picoplankton, but N_2 fluxes were not large enough to support large fractions of the observed primary production. Deep, rapid mixing of a large diatom population within the WC eddy, kept average light levels low and quantum efficiency high in the WC eddy; these diatoms were targeted by (among other predators) heterotrophic dinoflagellates with high grazing rates. Of particular interest in the CC eddy was the measurement of extremely high dark carbon uptake rates suggesting the possibility of chemosynthetic bacteria making a significant contribution to the carbon flux.

Larval fish populations were largely sourced from surrounding open-ocean waters in both eddies. However, food web analysis suggested that the WC eddy had an enhanced "classic" food web, with more concentrated mesozooplankton and large diatom populations than in the CC eddy. Implications for fisheries management were complex – while the WC eddy was clearly less productive than shelf waters, it was significantly more productive than surrounding ocean. However it was clear that a more mechanistic understanding of the interaction between the dynamics of the LC and fish populations on the continental shelf would be of immediate importance in clarifying possible impacts.

It was therefore clear that another research voyage targeting specific cross-shelf transport processes driven by the LC would be the natural next step in determining the nature of the LC interactions with shelf plankton and fish larval populations. To this end we will investigate in detail filament-driven transport of primary production and larvae across the shelf in May 2006 during a 26-day voyage on the Southern Surveyor headed by Waite (See Appendix 2).

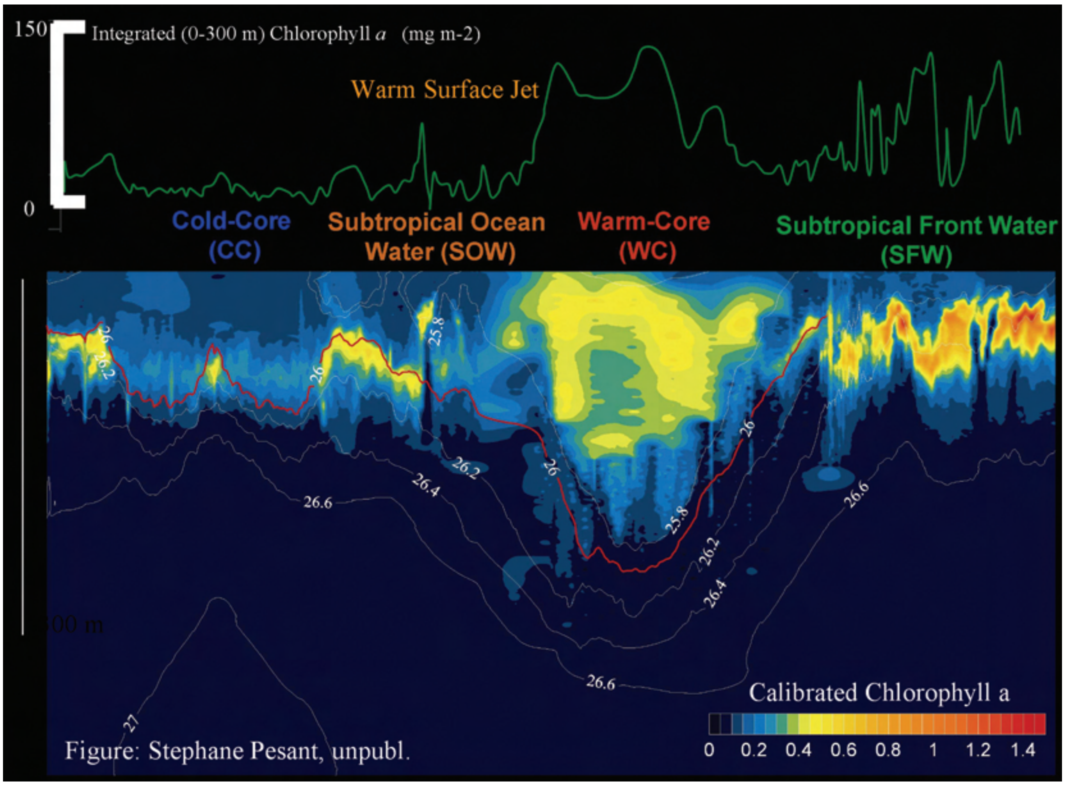


Figure: Stephane Pesant, unpubl.

Figure 3.10: A compilation of chlorophyll *a* data and temperature data from 4 SeaSoar transects off WA, covering four major water masses (L t o R) the Cold-core eddy, the inter-eddy jet (comprised of Subtropical waters from north of the eddies), the Warm-core eddy, and a body of Subtropical Front Water coming up from the south adjacent to the WC eddy. Both the Jet and the SFW may have contributed injections of nutrients to the WC eddy.

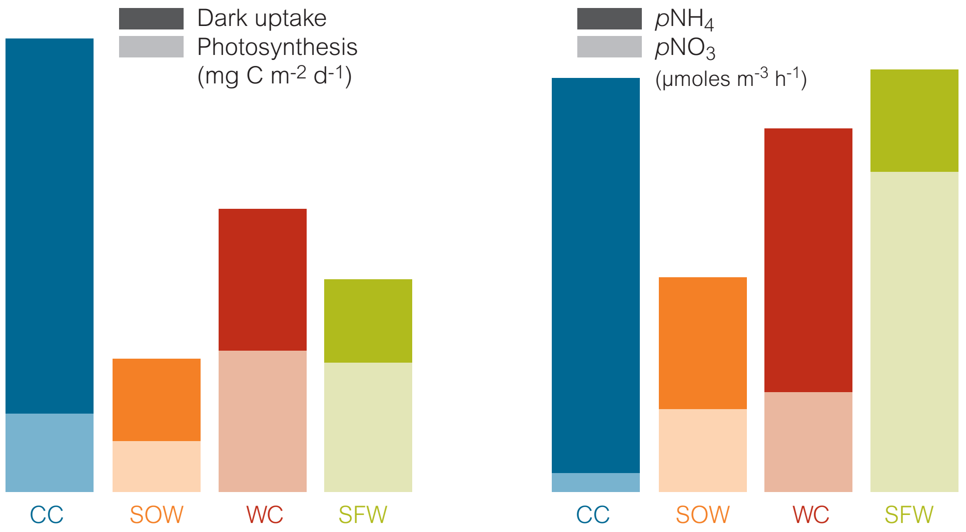


Figure 3.11: Summary of primary production (L) and nutrient uptake data across the four regions studied. Total primary production (photosynthesis + "dark" uptake) was higher in **CC** and **WC** compared to **SOW** and **SFW**. "Dark" uptake (full colour) contributed ~40% of total primary production in all systems, except in **CC** where it contributed ~80% Photosynthesis (light colour) was significantly lower in **CC** and **SOW** compared to **WC** and **SFW**. Total measured uptake of DIN in the Deep Chl *a* Maximum (DCM) was ~1.5 times lower in **SOW** compared to other systems, whose DIN uptake rates were not significantly different among themselves. Uptake of NEW nutrients dominated in the **SFW** system only, whereas REGENERATED production dominated in other systems. N2 fixation was insignificant compared to uptake of macronutrients (C. Holl)

Data from Pesant *et al.*, unpublished.

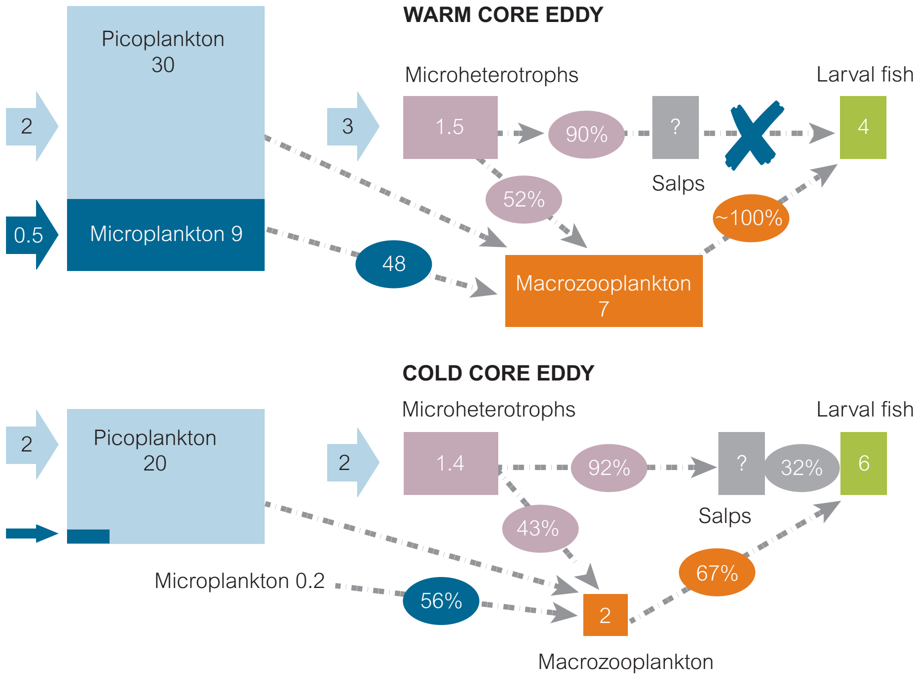


Figure 3.12: Food web maps of the two eddies based on carbon inventories (boxes), measured carbon fluxes (arrows) and isotopic composition of ^{14}N and ^{15}N in the various particulate fractions (ovals). Based on this analysis, the diatom → macrozooplankton → fish pathway, known as the "classic" food web, is significantly more important in the WC eddy than the CC eddy.

SRFME Collaborative Project Summary of Scientific Outcomes

- We documented upwelling off the south coast coupled with enhanced uptake of nitrate, and chlorophyll in near-shore and surface waters.
- The principal diet of the South Coast sardine are small copepods (>100 mm) which utilize ~70% nitrate-driven production.
- Unusually high F-ratios (>0.5) (nitrate uptake / total N uptake) in waters where surface concentrations of nitrate were below detection limit, highlighting the possible importance of sporadic cryptic upwelling events in driving coastal production.
- Nitrogen Fixation was not a major source of N to any system.
- Warm-core (WC) eddies off WA are unusually productive, and may be important features moving nutrient-rich and/ or phytoplankton-rich water from the shelf, while the cold-core eddies were not active upwelling systems as originally expected.
- Our work highlights the importance of nitrate-driven primary and secondary production where nitrate is not detectable and the importance of measuring uptake rates rather than static variables in the analysis of production patterns off our coast.

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Leeuwin Current Eddies Special Issue in Deep Sea Research II

In late 2004, Chief Scientist Waite approached the editors of Deep Sea Research II suggesting a special issue of the journal dedicated to the outcomes of the Waite et al. SRFME Collaborative Project, including the Eddies Cruise (SS08/2003) and any related research of equivalent scope (e.g., the SW Coastal Survey SS09/2003. The editors were interested in principle, and agreed that the general topic for the Special Issue was to be The Leeuwin Current and its Eddies, to be submitted 2005.

Summary of Scope and Contents of Deep-Sea Research II Special Issue: The recent Eddies Cruise and related papers provide a unique first glimpse into the interactions between physical, chemical and biological oceanography within the dynamic Leeuwin Current including its mesoscale eddy field. Dr. Anya M. Waite is principal Guest Editor of the Special Issue, assisted by Drs. Peter A. Thompson (CSIRO Hobart) and Lynnath Beckley (Murdoch University), who have agreed to act as co-Guest Editors. Below we summarize the current list of papers proposed for the issue. A strong interest in this issue has meant that the number of submitted papers has increased from 12 to 22, and the scope broadened to include a wide range of research on the Leeuwin Current and its Eddies (see Appendix 1).

Conference Attendance and Presentations

Australian Marine Science Association (AMSA), Hobart 2004

In Hobart, July 2004, Drs Anya Waite and Stéphane Pesant organised a special session on the Leeuwin Current, including Biological and physical oceanography off Western Australia and Mesoscale Eddies off Western Australia: Deserts and oases in an oligotrophic ocean. The session was organised to present the results from the Eddies Cruise (SS08/03) and the South Coast Survey (SS09/03) and to encourage discussion amongst our colleagues and peers. A highlight of the special session was the plenary presentation by Dr. R. Bidigare, biological oceanographer from the University of Hawaii. Dr. Bidigare also reviewed our project and participated in a workshop with key investigators discussing the preliminary outcomes of our work in the global context. Dr. Bidigare was highly complimentary of the project as a whole, and commended especially the excellent broad coverage of numerous important aspects of biological oceanography under the constraints of a modest budget. A list of the presentations that were directly associated with the current project are below:

Pattiaratchi et al. – Physical Oceanography off WA, Twomey et al. – Nutrient Limitation off WA., Pesant et al. – A size-fractionated approach to pelagic ecosystems off WA., Bidigare – Overview of mesoscale eddy features globally., Waite – Eddy Cruise Overview., Feng et al. – Physics of the Eddies., Pesant et al. – Phytoplankton component: DIC & DIN uptake., Thompson et al. – Phytoplankton component: HPLC & PAM, Holl et al. – Phytoplankton component: N-fixation., Paterson et al. – Microzooplankton component., Muhling et al. – Fish Larvae component : Ichthyoplankton in two meso-scale Leeuwin Current eddies: preliminary results., Waite et al. – Reconstructing the food webs: Isotopic signature approach., Pesant – SeaSoar Transects., Patterson et al. – Microplankton abundance., Pesant et al. – Pvs.I experiments Centre Station Eddy B., Thompson et al. – PAM experiments Centre Station Eddy B., Holl et al. – N-uptake experiments Centre Station Eddy B.

Indian Ocean Marine Environmental Conference (IOMEC) Linking Science, Engineering and Management 14 - 18 February 2005 – Perth, Western Australia

Lynnath E. Beckley, Barbara A. Muhling and Anya M. Waite. Primary production and fish larvae in two eddies.

Southern African Marine Science Symposium - Durban, July 2005 – Invited plenary

Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite

Leeuwin Current meso-scale eddies: death traps or saviours in the oligotrophic eastern Indian Ocean?

Indo-Pacific Fish Conference – Taipei May 2005

Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite

Meso-scale Leeuwin Current eddies: oceanographic history and ichthyoplankton assemblages

International larval fish conference – Barcelona July 2005

Lynnath E. Beckley, Barbara A. Muhling and Anya M.Waite

Ichthyoplankton assemblages and primary production in meso-scale eddies associated with the Leeuwin Current, eastern Indian Ocean.

American Society for Limnology and Oceanography- Hawaii, February 2006

Carrie Holl, Anya M. Waite, Peter A. Thompson and Stephane Pesant. Nitrogen Fixation in two counter-rotating eddies of the Leeuwin Current.

Stephane Pesant, Anya M. Waite, Carrie Holl, Peter A. Thompson. Primary production and nitrogen fluxes in eddies of the Leeuwin Current, Western Australia.

Appendix 1. Papers submitted to Deep Sea Research II as part of Special Issue on the Leeuwin Current and its Eddies

Characteristics of two counter-rotating eddies in the Leeuwin Current system off the Western Australian coast. Ming Feng, C. B. Fandry, Leon Majewski, Anya M. Waite.

Systematics of a rare radiolarian - *Coelodiceras spinosum* Haecker (Sarcodina: Actinopoda: Phaeodaria: Coelodendridae). H. L. Paterson, S. Pesant, P. Clode, B. Knott, A. Waite.

Ichthyoplankton assemblage structure in two meso-scale Leeuwin Current eddies. B. A. Muhling, L. E. Beckley, M. P. Olivar.

Unicellular Diazotrophy as a Source of Nitrogen to Leeuwin Current Coastal Eddies Carolyn M. Holl, Anya M. Waite, Joe Montoya, Stephane Pesant, Peter Thompson.

Phytoplankton variability off the Western Australian Coast: Mesoscale eddies and their role in cross-shelf exchange. Thomas S. Moore II, Richard J. Matear, John Marra, & Lesley Clementson

Variability in nitrogen uptake and fixation in the oligotrophic waters off the south west coast of Australia. Twomey, L. J., Waite, A. M., Pez, V. and Pattiaratchi, C. B.

The Leeuwin Current and its Eddies: an Overview. A. M. Waite, D. A.Griffin, S. Pesant, M. Feng, P.A. Thompson, L. Beckley , C. Domingues, D. Gaughan , C. Hanson, C. Holl, T. Koslow, M. Meuleners, J. Montoya, T. Moore, B. Muhling, H. Paterson, S. Rennie, J. Strezelecki, L. Twomey.

Food web structure in two counter-rotating eddies based on δ^{15}N and δ^{13}C isotopic analyses. Anya M. Waite, Barbara Muhling, Carrie Holl, Lynnath Beckley, Joe Montoya, Joanna Strzelecki, Peter Thompson, Stephane Pesant

Contrasting the vertical differences in the phytoplankton biology of a dipole pair of eddies in the south-eastern Indian Ocean. Peter Thompson, Stephane Pesant, Anya Waite.

Comparison of mesozooplankton communities of a paired warm and cold core eddy off the coast of Western Australia. J. Strzelecki, J. A. Koslow, A. Waite.

Microzooplankton community structure, and herbivory on phytoplankton, in an eddy pair in the Indian Ocean off Western Australia. Harriet L. Paterson, Brenton Knott, Anya Waite.

Management implications of the Leeuwin Current eddy system for teleosts of the Western Australian continental shelf. Daniel J Gaughan.

Dynamics of the surface and sub-surface currents off south-western Australia: a numerical study. Rennie, Susan J, Pattiaratchi, Charitha P, McCauley, Robert D.

A one-dimensional simulation of biological production in two contrasting mesoscale eddies in the south eastern Indian Ocean. J Greenwood, M Feng, A. Waite.

Vertical differences in the phytoplankton biology of a warm core eddy contrasted with a cold core eddy in the south-eastern Indian Ocean. Peter Thompson, Stephane Pesant, Anya Waite.

Food web structure in two counter-rotating eddies based on δ^{15}N and δ^{13}C isotopic analyses. Anya M. Waite, Barbara Muhling , Carrie Holl, Peter Thompson, Lynnath Beckley, Joe Montoya, Stephane Pesant, Joanna Strezelecki.

Phytoplankton community structure and nitrogen nutrition in Leeuwin Current and coastal waters off the Gascoyne region of Western Australia. C.E. Hanson, A.M. Waite, P.A. Thompson and C.B. Pattiaratchi.

Assessing the magnitude and significance of deep chlorophyll maxima of the coastal eastern Indian Ocean. Christine E. Hanson, Stéphane Pesant, Anya M. Waite, and Charitha B. Pattiaratchi.

Numerical modelling of the mean flow characteristics of the Leeuwin Current System.Michael J. Meuleners, Charitha B. Pattiaratchi and Gregory N. Ivey.

A numerical study of the eddying characteristics of the Leeuwin Current System. Michael J. Meuleners, Gregory N. Ivey and Charitha B. Pattiaratchi.

A Process-Oriented Numerical Study of Currents, Eddies and Meanders in the Leeuwin Current System. Mary L. Batteen and Richard A. Kennedy, Jr.

Flow Separation in the Leeuwin Current System off Cape Leeuwin. Henry A. Miller and Mary L. Batteen.

Simulated Lagrangian patterns of the large scale ocean circulation of the Leeuwin Current System off Western Australia. Catia M. Domingues, Mathew E. Maltrud, Susan E. Wijffels, Matthias Tomczak and John A. Church.

3.3.2 Spatial patterns in sessile benthic sponge and ascidian communities of the Recherche Archipelago

Investigators / Institutions

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Dr Jane Fromont	Department of Aquatic Zoology, Western Australian Museum, Kew Street, Welshpool, Western Australia

Introduction

The southwestern region of Western Australia is a relatively pristine environment of great diversity with high levels of endemism recognised in some groups of crustaceans and molluscs (Morgan & Wells, 1991). It is estimated that at least 60 percent of the Australian sponge fauna is undescribed, with the Demosponge fauna of temperate southwestern Western Australia being the most poorly known of all (Hooper & Lévi, 1994). Presently our knowledge of the sponge and ascidian fauna of the southwest is from a limited number of papers, most of which were published more than half a century ago (*e.g.* Lamarck, 1813-1814; Bowerbank, 1876; Lendenfeld, 1888). None of these early studies examined the fauna in the Esperance region and many of the publications only document fauna as far south as Albany. Indeed most of the historical collections were conducted in metropolitan waters (Cockburn Sound, Fremantle, Cottesloe and Rottnest Island). Poore (1995) has recorded high levels of endemic species in southern temperate regions of Australia and suggests that it is in the south that the majority of 'native' marine fauna resides. Yet for much of the temperate marine benthic fauna nothing is known of their distribution patterns or levels of endemism.

A recent 'biological survey of the major benthic habitats of the south coast' conducted by Colman (1997) in the Fitzgerald Biosphere Reserve identified 102 different sponges. Of this number, however, only one was identified to species level. The lack of taxonomic detail illustrates the importance of the present study in the Recherche Archipelago. There is an urgent need to correctly describe and quantify the sponge and ascidian communities. This study addresses the critical need for correct taxonomic identifications and statistically sound quantitative sampling of the sessile benthic communities from the Recherche Archipelago, and indeed the entire southwestern Australian region.

Aims/objectives

The primary goal of the proposed research is to provide a biological inventory of sessile benthic communities within the Recherche Archipelago and quantitatively identify the spatial patterns that exist within these communities. Within this goal there are three specific aims:

Study sites

In October 2002 fauna were collected from horizontal substrata at five islands: Black, Thomas, Woody, Figure of Eight, Mondrain Island. Habitats were sampled at sheltered and exposed sites, and at a range of depths: waters 0-10m, 10-20 m, and waters 20-25 m depth, with equal numbers of quadrats taken from each exposure and depth. As a result of the 2002 collections the sampling design was modified to capture habitats associated with vertical substrata in addition to the horizontal substrata. However, the addition of vertical substrata to the design effectively doubled the sampling and processing effort, and it was therefore decided that sampling would only occur at a single depth (between 10-20 m; generally 15 m). The 15 m depth was chosen as species diversity and numbers were greatest at this depth. This new sampling regime commenced at Figure of Eight and Mondrain Islands (Fig. 3.13). In October 2003 the final field trip sampled the more remote islands: Mart Group, Twin Peaks and Middle Island. These islands were sampled at sheltered and exposed sites, the single depth of 15m but sampled horizontal and vertical substrata.

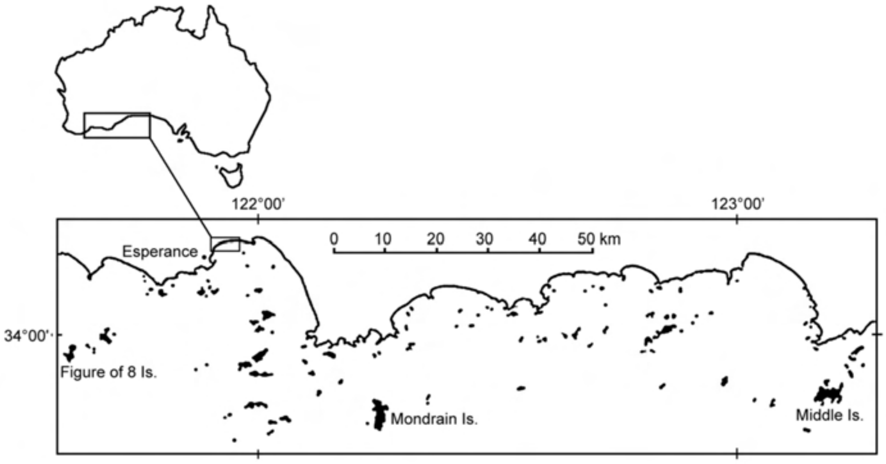

Figure 3.13: Map of the Recherche Archipelago study sites.

Aim 1. Describe the distribution and abundance of the sponge and ascidian dominated communities from the Recherche Archipelago

Major findings of aim 1:

Of the six phyla examined in this study, the sponges were the dominant taxa. Sponges represented approximately 72% of all fauna collected, bryozoans 10%, ascidians and sea-stars 7%, and hydroids and corals both 2%.

A total of 644 individual Demosponges were collected, representing 11 of the 15 orders of Demospongiae currently recognised. Demosponge orders were dominated by the Poecilosclerida and the Dictyoceratida, which in combination made up approximately 60% of the sponges identified to date. Sponges were consistently the most abundant organisms recorded for each island. No patterns in sponge community composition (using a full assemblage at order level) were associated with any of the factors tested (exposure, depth or substrata orientation). There were no significant differences in the number of sponges collected among exposures, depths or substratum orientation for the Chondrosidae, Dictyoceratida, Hadromerida or the Halichondrida. The Astrophorida had significantly more individuals in exposed sites and significantly more on vertical substrata (Figure 3.14). The Dendroceratida also had significantly more individuals on vertical than on horizontal substrata. The Haplosclerida showed significant differences associated with increasing depth, with significantly more individuals at 20^{+} m depth. The Poecilosclerida had significantly fewer individuals with increasing depth, with more individuals in <10 m depth (Figure 3.15). The Poecilosclerida also had had significantly more individuals in exposed than sheltered sites.

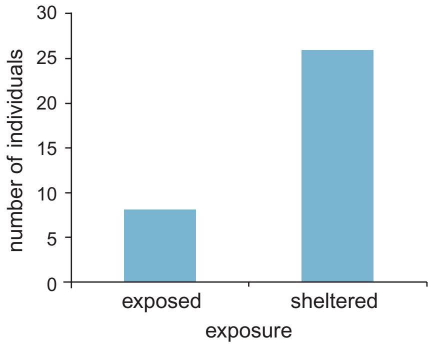

Figure 3.14: Number of Astrophorida individuals recorded from (a) exposed and sheltered sites (all islands (n=310 quadrats).

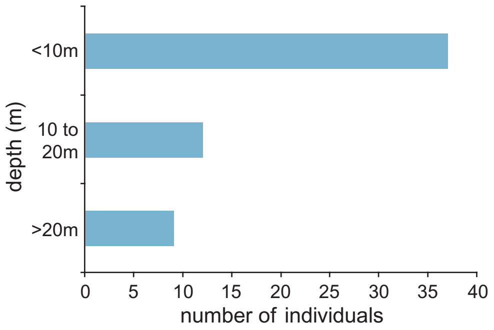

Figure 3.15: Decrease in the number of Poecilosclerid sponges with increasing depth.

Ascidian faunal structure differed at the island (kilometre scale; ANOSIM global R value: 0.32) (Figure 3.16) and regional scales (10-100 km; ANOSIM global R: 0.167).

There was no pattern in benthic assemblages associated with exposure (sheltered/ exposed)(global R value: -0.014) nor with substratum orientation (horizontal/ vertical)(global R value: 0.063).

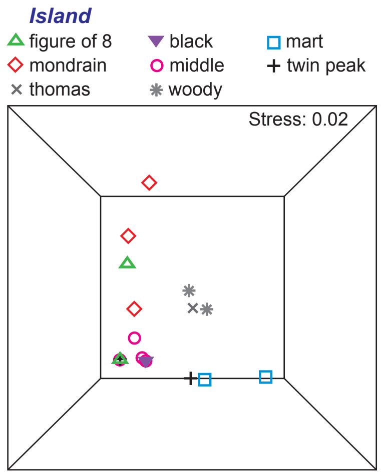

Figure 3.16: A two dimensional nMDS plot showing the pattern in ascidian assemblage across islands (100's m - km).

Ascidians were present in all three depth regimes sampled, however only one species, *Pyura gibbosa,* was recorded in all three depths. Ascidian fauna was numerically dominated by representatives of *Clavelina ostrearium* and *Herdmaina grandis*, which in combination made up approximately 69% of the ascidians recorded. *Herdmania grandis* showed a significant change with depth, individuals were completely absent at depths greater than 20 m (chi^2 10.7; chi^2 critical 5.99). *Clavelina ostrearium* and *Pyura spinifera* had the converse pattern no individuals present in shallow waters <10 m deep (chi^2 7.42 and 7 respectively; chi^2 critical 5.99).

The undescribed ascidian fauna consists mainly of colonial species, the majority of which are Didemnid species. The introduced pest *Ciona intestinalis* was recorded in Bandy Creek Harbour but was not observed at any of the sites targeted in this study.

Aim 2. Compile a taxonomic database of specimens collected during this study.

Major findings of aim 2:

A web-site has been constructed as part of the FRDC Recherché project and can be accessed from the http address below. This site has a page on the sponge and ascidian communities of the Recherche Archipelago.

http://www.marine.uwa.edu.au/recherche/

A web-based site specifically on the SRFME based research is currently under development. The site will outline the nature of the research and its primary findings. A menu page will list the fauna available for further examination. Users will then be able to select a desired subject *e.g.* seastars, and will be transferred to a seastar menu where they can browse a collection of thumbnail images. They then select the thumbnail image they are interested in and are provided with taxonomic and ecological information pertinent to that species. The database will be incorporated in FaunaBase on the website of the Western Australian Museum (WAM) (www.museum.wa.gov.au/FaunaBase), and will be accessible *via* this public interface and using web links from the UWA website. Note that an enormous number of species were collected and cannot all be processed during the scope of this study. As such only the most abundant species from each group will be available to web users.

Aim 3. Provide a comprehensive voucher collection of sponge, ascidian and associated macro invertebrate species from the region

Major findings of aim 3:

A comprehensive collection of sponge and ascidians has been collected through this study. The collection is very extensive, with 409 species of sponge, 11 species of ascidian, 12 species of seastar, 16 species of hydroid and over 100 species of bryozoan. Once all data processing has finalised the material will be deposited at WAM.

Discussion

The objectives of the study were to investigate the sessile benthic sponge and ascidian communities of the Recherche Archipelago and determine if there were any patterns associated with islands, exposure, depth, or substratum orientation.

Sponges were the dominant fauna and were highly diverse recorded from every island, exposure, depth and substrata orientation. There was considerable variation in the numbers of animals and the species richness among islands with no significant relationship evident between these factors recorded at any island. This suggests a fragmented distribution of sponge orders across all sites sampled.

Sponge composition using order level data differed with islands examined. Thomas and Middle Islands had individuals from nine orders, while Black and Twin Peak had only five orders present. There was, however, no difference in sponge composition between exposures indicating that orders were not exposure specific and occurred at both sheltered and exposed sites. There was a significant difference in the number of sponges, but not assemblage structure, associated with horizontal and vertical substrata.

The lack of differences in sponge assemblage structure among exposures, depths or orientation of substrata indicated that the distribution of sponge orders were not specific to these categories. This was evident in orders such as the Poecilosclerida, which occurred at every island, exposure, depth and orientation. The absence of pattern may, however, be related to the use of high taxonomic (order) level data masking any lower taxonomic variation present at family or genus levels. For groups such as sponges which require considerable time and effort in processing for identification, it may be that lower taxonomic level species data would be required to identify any assemblage level patterns that may exist.

Univariate examination of individual orders revealed that the sponges were dominated by the orders Poecilosclerida and the Dictyoceratida, which combined made up approximately 60% of the sponges identified to date. The Poecilosclerida are one of the most species rich orders in the Demospongiae (akin to the Phaeophyta in the algal realm) and consequently it is not surprising that they were recorded in every island, exposure, depth and orientation, dominating the sponge fauna of the Recherche Archipelago. Despite the cosmopolitan nature of the Poecilosclerida, they exhibited distinct preferences for exposure and depth, with significantly more individuals recorded from exposed sites and shallow depths (< 10 m). Several other sponge orders such as the Astrophorida, Haplosclerida and Dendroceratida showed significant differences in abundance associated with exposure, depth or substratum orientation, indicating a distinct preference in these orders for a particular habitat.

The ascidian fauna identified to date was dominated by six species of solitary ascidia belonging to three families, the Cionidae, the Clavelinidae and the Pyuridae. Many samples are still to be identified and consist mainly of colonial ascidians belonging to the family Didemnidae. The species described in this study are common throughout much of Australia's southern temperate waters. See McDonald 2004 in References for more details of this group.

Ascidian faunal structure differed at the island scale. These differences in assemblage structure require further investigation, however they are likely to be linked to differences in an environment variables such as nutrient content of the surrounding water column. As with the sponge assemblages there was no pattern in ascidian assemblages associated with exposure nor with substratum orientation. Indicating that these animals are more influenced by larger landscape scale environmental factors such as nutrient availability than smaller habitat specific attributes.

Ascidians were present in all three depth regimes sampled, however only one species, *Pyura gibbosa,* was recorded in all three depths. Multivariate analysis divided the sites based upon their species compliment. The species *Clavelina ostrearium* were completely absent from shallow waters less than 10 m deep. This species has a soft gelatinous head situated upon a short flexible stalk. It is this soft structure that may restrict this species to the calmer waters greater than 10 m deep where they are less likely to be negatively influenced by wave action. The habitat and anatomy (thin test) of *C. ostrearium* may make it vulnerable to UV damage as with *Corella inflata*. The thicker test of *H. grandis* and the darker opaque tests of the Pyurid species may provide protection from UV damage.

Conclusions

The data in this report provides valuable baseline data on the distribution of benthic invertebrates within the Recherche Archipelago. Furthermore it provides data on the distribution patterns in these fauna and sponge morphologies across a range of spatial scales.

The results of this study raise several questions. Are the spatial patterns recorded in sponge and ascidian communities determined by larval behaviour and morphology, physically mediated patterns in recruitment or are their distinct physiologically parameters of each species that restrict them to depths? Larval behaviour is proposed to be one of the primary determinants of species distribution. Direct observations on the settlement and mortality of larvae would be the most accurate way to measure depth preference, however given the difficulties of such a study the approach used in this study of recording adult presence/absence indicates a distinct pattern of distribution that provides the basis for further investigation.

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Morgan, G.J. and Wells, F.E. (1991). Zoogeographic provinces of the Humboldt, Benguela and Leeuwin current systems. *Journal of the Royal Society of Western Australia.* 74: 59-69

Conferences attended, or presentations given

McDonald J.I. (2004). Sponge and ascidian communities of the Recherche Archipelago CSIRO Strategic Research Fund for the Marine Environment Symposium, Perth.

McDonald J.I. (2004). Sponge and ascidian communities of the Recherche Archipelago Department of Conservation & Land Management (Marine Division) Lecture series, Fremantle, Western Australia.

Publications and/or outcomes to date

McDonald J.I. (2004). The invasive pest species *Ciona intestinalis* (Linnaeus, 1767) reported in a harbour in southern Western Australia - Marine Pollution Bulletin 49: 868-870.

McDonald J.I. (2005). Solitary Ascidiacea from shallow waters of the Recherche Archipelago, Western Australia. In: FE Wells, DI Walker, GA Kendrick (eds), The Marine Flora and Fauna of Esperance, Western Australia. Western Australia Museum, Perth. pp. 451-461.

McDonald J.I. (2005). Asteroidea from shallow waters of the Recherche Archipelago, Western Australia. In: FE Wells, DI Walker, GA Kendrick (eds), The Marine Flora and Fauna of Esperance, Western Australia. Western Australia Museum, Perth. pp. 463-475.

Kendrick, G., Harvey, E., McDonald, J., Wells, F. & Walker, D. (2005). Introduction to the marine biology of the Archipelago of the Recherche Western Australia. In: FE Wells, DI Walker, GA Kendrick (eds), The Marine Flora and Fauna of Esperance, Western Australia. Western Australia Museum, Perth. pp. 1-9.

Popular science publications

Landscope. (2004). Vision Splendid (provided scientific information and photographic imagery)

Landscope. (2004). Researching the Recherche (provided scientific information and photographic imagery)

Ecos November-December. (2004). Treasure Islands - The Recherche Archipelago's underwater riches (provided scientific information and photographic imagery)

Threatened species of Western Australia. (2004). (provided scientific information and photographic imagery)

Tracks Magazine of the Western Australian Museum. (2004). Esperance marine life under the microscope (provided photographic imagery)

Helix magazine. (2005). article and educational poster (provided scientific information and photographic imagery)

Reports

Kendrick, G.K., Harvey, E.S., McDonald. J.I., *et al.*, (2004). *Characterising the fish habitats of the Recherche Archipelago: Final Research Report*. Report to Fisheries Research and Development Committee

McDonald. J.I., and Fromont, J. (2004). *Sponge and ascidian communities of the Recherche Archipelago 3.* Report to CSIRO Strategic Research Fund for the Marine Environment

McDonald. J.I., and Fromont, J. (2004). *Sponge and ascidian communities of the Recherche Archipelago 2.* Report to CSIRO Strategic Research Fund for the Marine Environment

McDonald. J.I., and Fromont, J. (2003). *Sponge and ascidian communities of the Recherche Archipelago 1.* Report to CSIRO Strategic Research Fund for the Marine Environment

3.3.3 Understanding the natural variability of currents along the Western Australian coastline: Inter-annual variability of the Leeuwin Current

Investigators / Institutions

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Dr Ming Feng and Dr Gary Meyers	CSIRO Marine and Atmospheric Research
Dr Yun Li	CSIRO Mathematical and Information Sciences

Executive Summary

The Leeuwin Current is a warm, lower salinity, poleward flowing current, which flows along the continental shelf break of Western Australia and plays an important role in the region's marine environment and climate. The Current is driven by an alongshore steric height gradient, due to the meridional ocean cooling and the inter-connection between the Indian and Pacific oceans through the Indonesian Throughflow. In this study, the Simple Ocean Data Assimilation (SODA 1.4.2) reanalysis data for the 44-year period from 1958 to 2001 were used to determine the latitudinal variability of the Leeuwin Current along the coast of Western Australia in response to inter-annual variability. Results showed the alongshore slope was generally stronger (i.e. steeper slope) during La Niña years and weaker during El Niño years. The slope presented a positive (negative) linear trend during the PDO cool phase (warm phase). Composite maps also suggested the effect of ENSO was manifested in the simulated Leeuwin Current in the May–July period preceding the peak of ENSO in the Pacific Ocean and the response decays at higher latitudes.

Introduction

The Leeuwin Current System consists of three major currents: the southward flowing Leeuwin Current (LC) at the surface; the northward flowing Leeuwin Undercurrent (LU) at the sub-surface; and the northward flowing Capes and Ningaloo Currents on the continental shelf during summer. Generally, there is downwelling along the coast and local coastal upwelling due to equatorward wind and associated coastal currents during the summer. The Leeuwin Current is a warmer, lower salinity current, which flows poleward along the continental shelf break against the prevailing southerly winds (Thompson 1984; Godfrey and Ridgway 1985; McCreary et al. 1986; Batteen and Rutherford 1990; Godfrey and Weaver 1991; Smith et al. 1991; Clarke et al.1994; Meyers et al. 1995; Pearce and Pattiaratchi 1999; Feng et al. 2003). It is generated by an alongshore steric height gradient due to the poleward sea surface cooling (Thompson 1984; McCreary et al. 1986) and the presence of warm waters near the North West Shelf (NWS) (owing to the inter-connection between the Indian and Pacific oceans through the Indonesian Throughflow, Godfrey and Weaver 1991). Warmer, lower salinity water flows through the Indonesian archipelago from the Pacific to the Indian Ocean. This results in lower density water being present between Australia and Indonesia, when compared with the cooler and more saline ocean waters off south-western Australia. This density difference produces a change in sea level, of about 0.5 m, along the WA coast. Interaction of the Leeuwin Current with changes in the bathymetry and offshore water of different density results in the generation of eddies transported offshore, in particular, off Shark Bay, Abrolhos Islands, Jurien Bay, Rottnest Island and Cape Leeuwin (Andrews 1977; Cresswell and Golding 1979; Pearce and Griffiths 1991; Batteen et al. 1992; Batteen and Butler 1998;, Feng et al. 2005).

The Leeuwin Current has seasonal and inter-annual variability: it is globally stronger, during winter and under La Niña conditions and weaker during summer and El Niño conditions (Smith et al. 1991; Feng et al. 2005). However, the Leeuwin Current System's inter-annual variability is not completely understood. The recently developed reanalysis ocean climate data provides an ideal tool to investigate the Leeuwin Current decadal and multidecadal variations. The Simple Ocean Data Assimilation (SODA 1.4.2) reanalysis of ocean climate for the 44-year period from 1958 to 2001 (Carton and Giese, 2005), was used to determine the latitudinal variability of the Leeuwin Current along the coast of Western Australia in response to inter-annual variability.

Aims and Objectives

This project aimed to quantify the natural variability of the oceanic circulation off Western Australia through the analysis of long-term data sets. Study results are directly relevant to managers charged with establishing a network of marine protected areas, management of fish stocks and environmental protection as well as other researchers in the marine environment handling field data and studying the physical and ecological systems. Knowledge of the physical environment's natural variability (in most cases, this variability is responsible for the pelagic and benthic ecological responses) is crucial for management.

This project's objectives are to develop:

- an enhanced understanding of the natural variability of the nearshore and continental shelf current systems off Western Australia
- advanced statistical methods to detect climate change signals
- regional climate change scenarios for circulation off Western Australia
- the results presented in this paper are addressing the first point

Data Sources

Simple Ocean Data Assimilation (SODA) reanalysis data, version 1.4.2 (Carton and Giese, 2005) was used in this study. The re-analysis covered the 44-year period from 1958 to 2001;

and was spanned by daily surface winds from the European Center for Medium Range Forecasts ERA-40 atmospheric reanalysis. The reanalysis used direct observations in order to improve the ocean simulations. Carton and Giese (2005) provided details of the SODA reanalysis and the assimilation methods used. The reanalysis is available in a monthly-averaged form on a 0.5^o x0.5^o horizontal resolution and 40 vertical levels, gradually increasing from a 10 m-layer thickness to 250 m for the deepest layer. In this study, only the first 300 m of the ocean were considered and an interpolation into a constant 10 m-layer-thickness grid was undertaken. The period from 1960 to 1990 was used to calculate the variable anomalies extracted from the SODA 1.4.2 reanalysis.

Carton and Giese (2005) showed that, to the north of Australia, the reanalysis of the warm water exchanges between the Pacific and Indian oceans through the Indonesian archipelago was similar to the observed estimates. When the seasonal cycle was removed, Carton and Giese (2005) indicated that the monthly reanalysis sea level and TOPEX/Poseidon altimetry were correlated in excess of $r = 0.7$. Additionally, in the present study, the SODA 1.4.2 reanalysis data were compared with real observations to demonstrate the data's validity for the investigation of the Leeuwin Current System's variability.

The transport calculated from SODA reanalysis was generally within an average of +/–12% accuracy with the transport Feng et al. (2003) and Meyers et al. (1995) calculated from their observations. The SODA Sea Surface Height (SSH) anomaly was compared with the Fremantle Sea Level anomaly. The SODA SSH anomaly standard deviation of 51.78 mm was smaller than the Fremantle sea level anomaly standard deviation of 70.31 mm; nevertheless, the datasets were correlated at 0.7.

SODA reanalysis temperature data were also compared with an eXpendable BathyThermograph (XBT) transect starting from Fremantle and extending north-westward as far as 100°E (Wijffels and Meyers, 2004). The correlation between the XBT temperature data and the interpolated reanalysis data for the same period (1983—1999) was generally high and up to 0.8 in the first 100 m below the surface and near the coast; from 100 to 400 m, correlation was only about 0.4–0.5. However, there was generally a strong correlation between the two datasets in the area that comprised the Leeuwin Current, which is the focus of this study.

ENSO years

In this study, the ENSO events that occurred from 1958 to 2001, the period of the SODA reanalysis data set, were isolated by considering the monthly SOI and monthly Niño3 for El Niño years and monthly SOI and monthly Niño3.4 for La Niña years (Table 3.2). El Niño years are defined when six consecutive months of Niño3 three-month average are above 0.5 units of standard deviation (STD) and four consecutive months of the three-month average SOI are below 0.5 STD.

Table 3.2. El Niño and La Niña years. : El Niño years are based on the monthly SOI and monthly Niño3, and La Niña years are based on the monthly SOI and monthly Niño 3.4.

El Niño	1963, 1965, 1969, 1972, 1982, 1976, 1987, 1991, 1997
La Niña	1964, 1970, 1971, 1973, 1974, 1975, 1988, 1989, 1998, 1999, 2000

Results

Eddy kinetic energy

The presence of mesoscale eddies have been identified on the Leeuwin Current's western side (Andrews 1977, Cresswell and Golding 1979; Pearce and Griffiths 1991). Batteen et al. (1992) showed the generation of these eddies resulted from a mixed barotropic and baroclinic instability and that eddies have timescales of months and grow on scales around 150 km. The current's offshoots and meanders tend to occur at preferred locations along the coast, such as: Shark Bay, Abrolhos Islands, Jurien Bay, Rottnest Island, and Cape Leeuwin. The highest values of Eddy Kinetic Energy (EKE) are found off Western Australia south of 30°S (Batteen and Butler 1998) and between 30°S and 32°S (Feng et al. 2005). Eddy energy is weak during austral summer and El Niño years and strong during austral winter, and La Niña years (Feng et al., 2005).

The eddy kinetic energy was calculated here using the SODA surface current velocities. The mean EKE over 1958–2001 had a maximum of 180 cm^2 s^{-2} situated at 28.75°S (Figure 3.17a). The location of the maximum was lower in latitude compared with the results from Feng et al. (2005); this could be due to the coarse SODA reanalysis grid and limited coastline resolution. On an annual cycle, the mean EKE maximum moved southward from summer to the following spring (Figure 3.17b), more precisely, it was located at 27°S in summer, 28°S in fall, 30°S in winter, and 32°S in early spring. The strongest eddies were generated at lower latitudes during summer; as the current strength increased from north to south and from the end of summer to its maximum in winter, eddies were gradually generated at higher latitudes.

Sea surface height slope and ENSO

The general consensus is that the Leeuwin Current's driving force is an alongshore steric height gradient, which overwhelms the opposing equatorward wind stress (Thompson et al. 1984; Godfrey and Ridgway 1985; McCreary et al. 1986). Godfrey and Ridgway (1985) suggested the high surface dynamic height field present north of Western Australia (set by the flow of low-density Pacific Ocean water into the Indian Ocean trough the Indonesian Throughflow) might remotely force the Leeuwin Current. Although McCreary et al. (1985) showed that thermohaline forcing due to the poleward increase of surface density in the ocean interior might be considered as the main forcing of the Leeuwin Current, they concluded that the remote forcing mechanism proposed by Godfrey and Ridgway (1985) may also contribute to the Leeuwin Current.

Although Leeuwin Current forcing may be a combination of several mechanisms, an interesting way of quantifying this forcing is to determine the slope along the WA coast. A transect along the location of the maximum southward transport, i.e. Leeuwin Current, is considered (Figure 3.18a). The slope anomaly was determined to isolate periods of steep and weak slope (Figure 3.18b). On the annual scale, the slope was steeper in winter and weaker in summer. Early in the year it exhibited a strong dependence on that of the previous year; thus the May-to-December average slope anomaly (bars) was considered here to represent the characteristics of a particular year and to determine the slope's interannual variability.

The May-to-December average slope anomaly is generally negative during El Niño (weaker slope) and positive during La Niña (i.e. steeper slope). Few El Niño years (i.e. 1972, 1991) presented a slightly positive slope anomaly, and few La Niña years (i.e. 1975, 1988, 1989) presented a slightly negative slope anomaly. However, the averaged sea surface height along the transect (Figure 3.18b) appeared significantly low during these particular El Niño years and high during these La Niña years. This was consistent with Feng et al.'s (2003, 2004) study showing the Fremantle sea level had a strong linear dependence with ENSO and could be used as an index for the Leeuwin Current's strength on annual and interannual timescales.

Overall, Leeuwin Current' forcing was responding to ENSO and appears to be weaker during El Niño and stronger during La Niña.

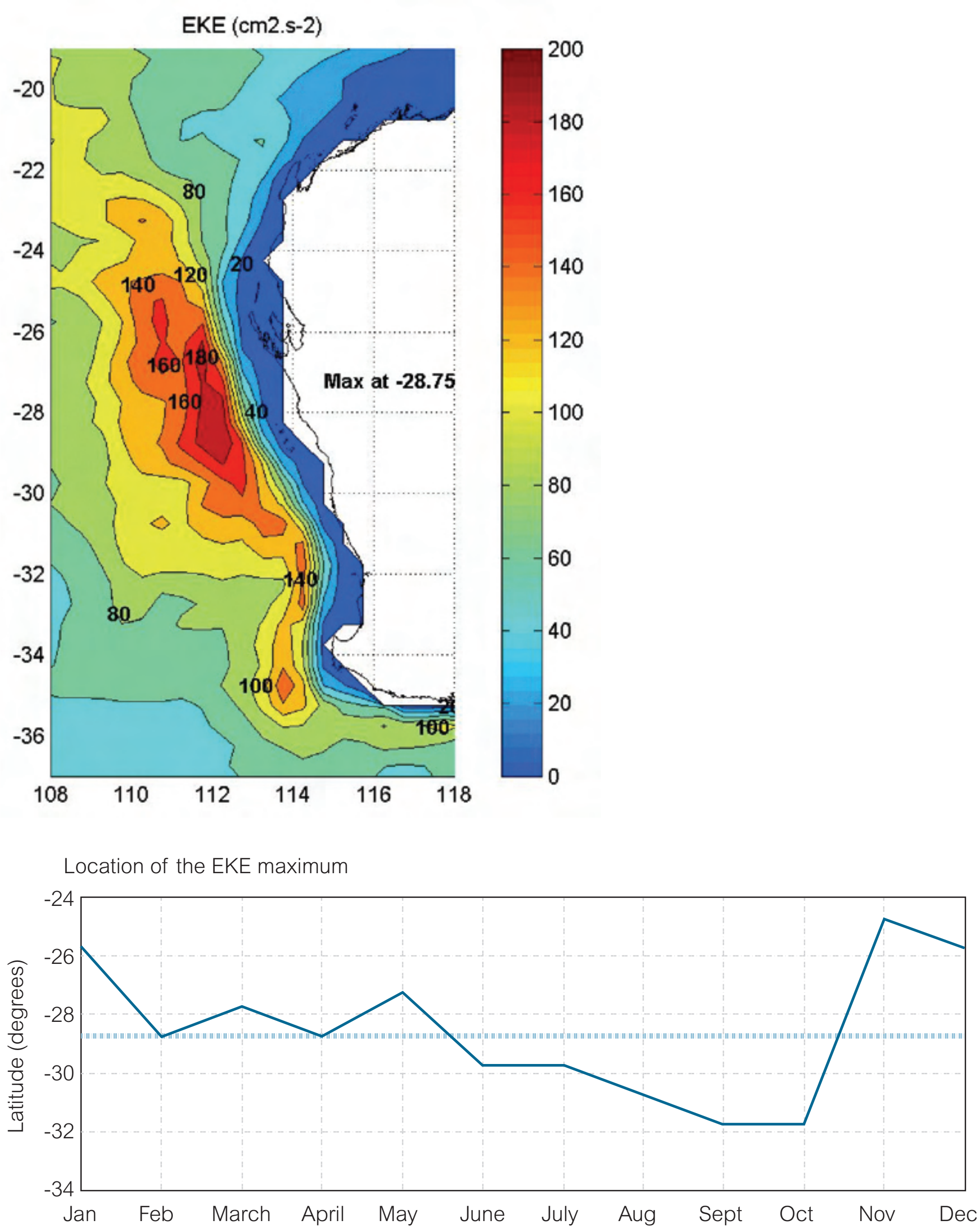

Figure 3.17: Eddy Kinetic Energy (EKE). a) mean EKE (in cm^2 s^{-2}); and b) location of the monthly mean EKE maximum over 1958–2001 calculated from SODA reanalysis surface velocity current data. The yearly mean EKE maximum is situated at 28.75°S.

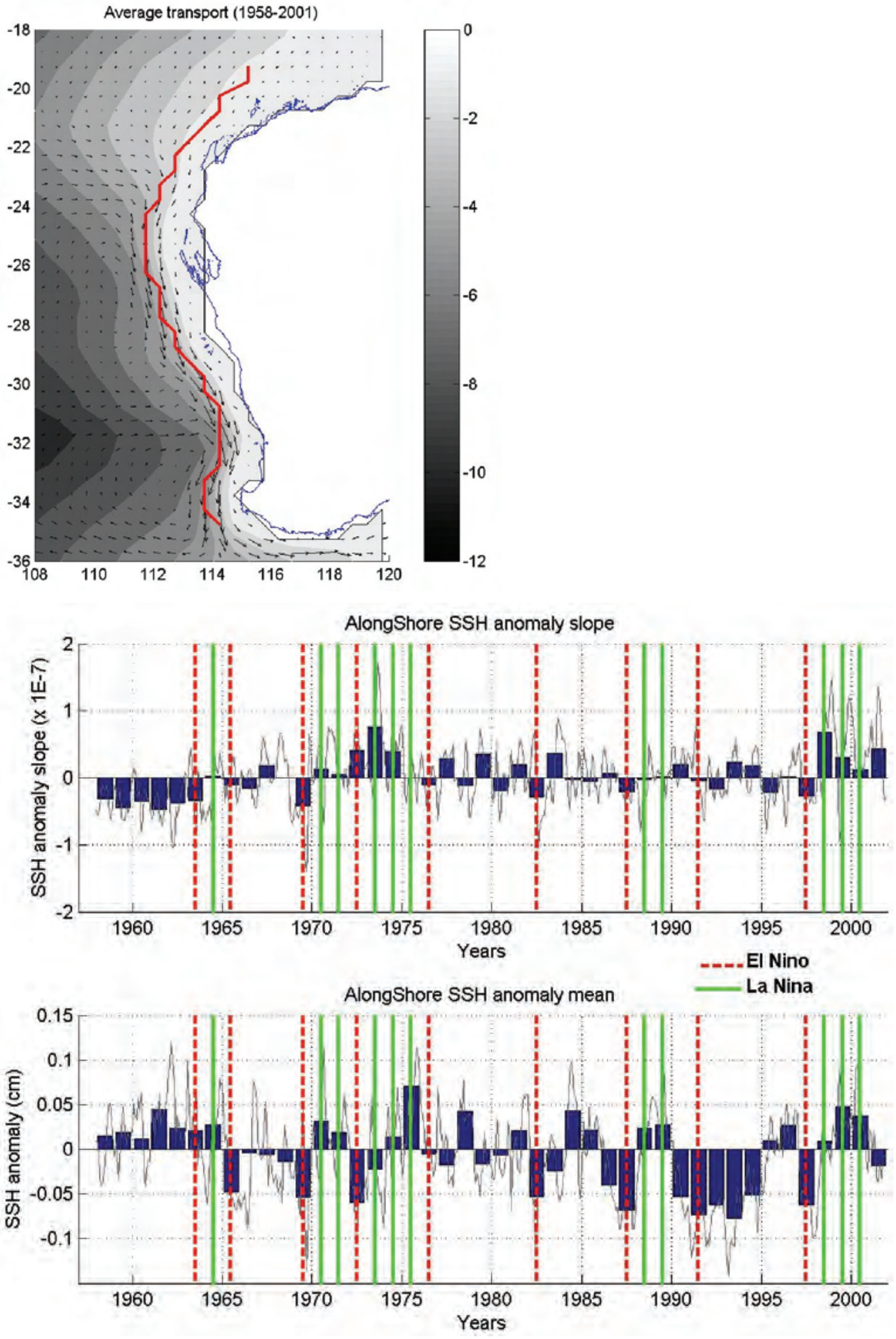

Figure 3.18: (a) Location of the maximum southward transport (red line). Arrows represent the 1958–2001 average transport, and contour plots represent the cumulated southward transport from the coast. (b) Sea surface height anomaly slope (top) and mean sea surface height anomaly (bottom), calculated along the location of the maximum southward transport (i.e. Leeuwin Current location). Bars represent the May-to-December average slope anomaly. Vertical, red, dashed lines (vertical, green line) represent El Niño (La Niña) years.

Sea surface height slope and Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is a long-term ocean fluctuation of the Pacific Ocean (Mantua et al. 1997; Zhang et al. 1997). A cool wedge of anomalously low sea-surface heights/ocean temperatures in the eastern equatorial Pacific and a warm pattern of higher than normal sea-surface heights connecting the north, west, and southern Pacific characterise the PDO cool phase. In the PDO warm phase, the west Pacific Ocean becomes cool and the wedge in the east warms. The SODA reanalysis data (1958–2001) covered two PDO cool phases 1960–1976 and 1998–200 and one PDO warm phase from 1977–1997.

The SSH anomaly slope along the Leeuwin Current presented a positive linear trend during the PDO cool phase and a weakly negative linear trend during the PDO warm phase (Figure 3.19). The SSH anomaly over the western Pacific (0–10°N 130–150°E box) showed a similar trend. During a PDO cool phase, a warm water/high sea surface height accumulation may develop in the Indonesian archipelago; the reverse (i.e. lower sea surface height) occurs during the PDO warm phase. During a PDO cool phase, the long-term accumulation of high sea surface height/ocean temperature in the western Pacific may be transmitted to the Indian Ocean, and more particularly to the north-west Western Australia, via the Indonesian Throughflow (Clarke and Liu 1994). Thus the slope in the sea surface height extending from the north-west to the south-west of Western Australia may increase. The reverse is expected during a PDO warm phase. The Leeuwin Current forcing therefore increases (decreases) during a PDO cool phase (warm phase).

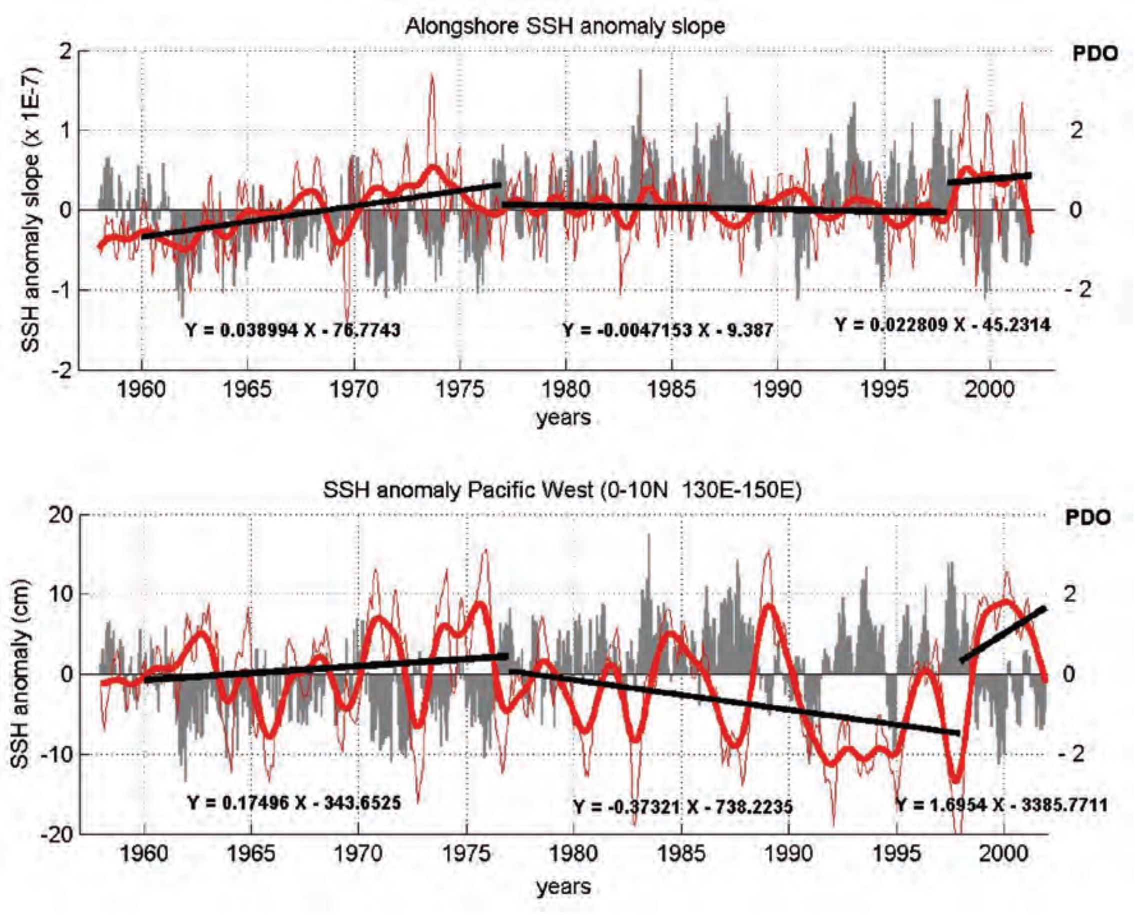

Figure 3.19: Pacific Decadal Oscillation (grey bars) and sea surface height slope anomaly (red line). The thick, red line represents the SSH anomalies filtered with a 19-year Hanning filter. Black lines represent positive (negative) linear trends during PDO cool (warm) phases.

Transport variability and ENSO

The Leeuwin Current flows southward along the continental shelf of Western Australia. Seven transects were extracted to determine the interannual variability's net transport along the coast (Figure 3.20). They extend to five degrees of longitude offshore (i.e. ~500 km) from the coast. Sensitivity tests were undertaken by considering transects of +/– 0.5 degrees of longitude (i.e. +/– 10% in length). Sensitivity of the transport calculation to the transect length was not considered significant at 95% confidence.

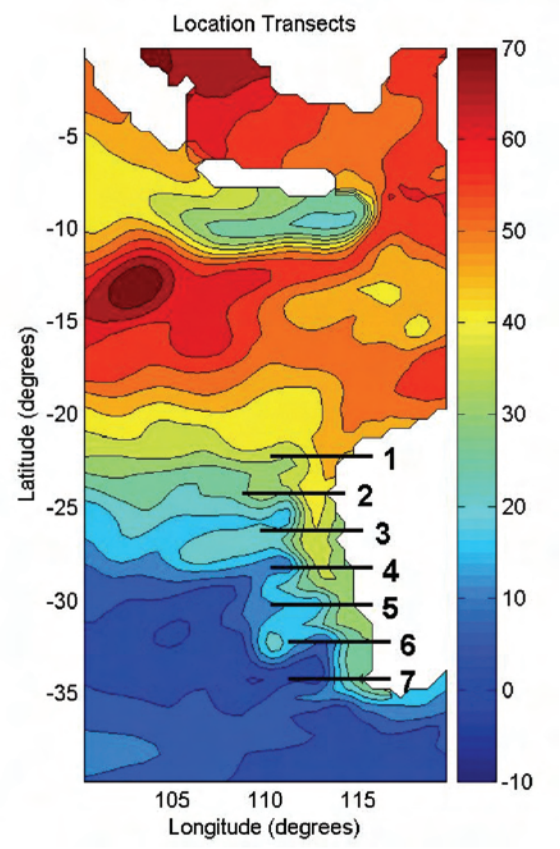

Figure 3.20: Location of the seven transects along the Western Australian coastline. Contours represent the mean sea surface height in cm (from SODA reanalysis) over 1958 to 2001.

From 24°S to 34°S, the mean net transport was southward of 3–4 Sv. Farther north at 22°S, the mean net transport was only 1.7 Sv southward. The weak southward transport at lower latitudes was due to the weak offshore geostrophic present at this latitude and also to the presence of the Ningaloo Current flowing northward near the coast during summer. Examination of the transport across all transects showed that a strong, yearly southward transport at lower latitudes might not remain as strong compared with the other years at higher latitudes, and vice versa. A measure of the Leeuwin Current transport at a particular point along the coast does not necessarily provide insight into the Leeuwin Current's overall strength along the coast.

During El Niño years (la Niña years), sea surface temperature cooling (warming) occurs in the western tropical Pacific and Java Sea as early as the austral autumn preceding the peak of ENSO in the tropical Pacific Ocean (SST composites not shown here) (Van Loon H. 1972a, 1972b). ENSO is 'felt' by the Leeuwin Current as early as during the May-July preceding the peak of ENSO in the Pacific in December. The composites map of the southward transport during the end of autumn/beginning of winter demonstrates the accumulated southward transport from the coast is much larger in the north of Western Australia during La Niña years (Figure 3.21).

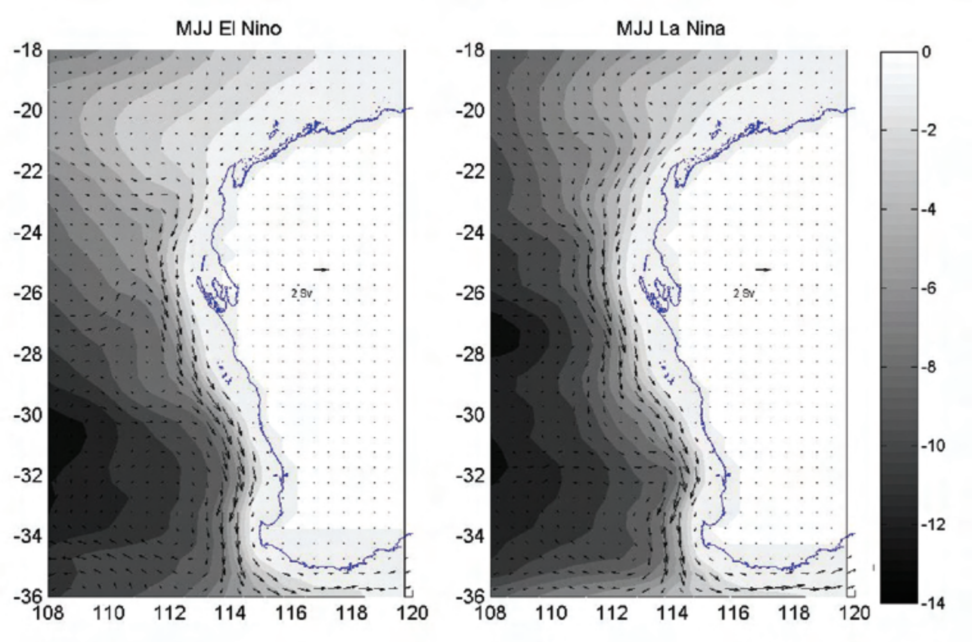

Figure 3.21: Composites map of the southward transport (Sv) during El Niño/La Niña events for May-June-July period.

The transport along the coast was further investigated by examining composites of the net transport across the seven transects presented in Figure 3.20. Generally, transects showed a maximum net southward transport near May–June and a minimum net southward transport in January–February as well as near September (Figure 3.22). As shown previously the location of the highest eddy kinetic energy (EKE) occurred offshore of the main current axis, around 28.75°S. The Leeuwin Current's response to ENSO appeared to be different between north and south of the EKE maximum.

Transects 1, 2, 3, and 4, situated north of the EKE maximum, presented a stronger net southward transport during most of the year for La Niña years than for El Niño years. Transects 5, 6, and 7, situated south of the EKE maximum, presented a net transport with different characteristics throughout the year. During autumn and winter, the net southward transport was equal or even weaker (transect 6), for La Niña years than for El Niño years. From the end of winter to summer the net southward transport was mostly stronger for la Niña years. In summer, when the Leeuwin Current was weak, no significant differences existed between El Niño and La Niña years.

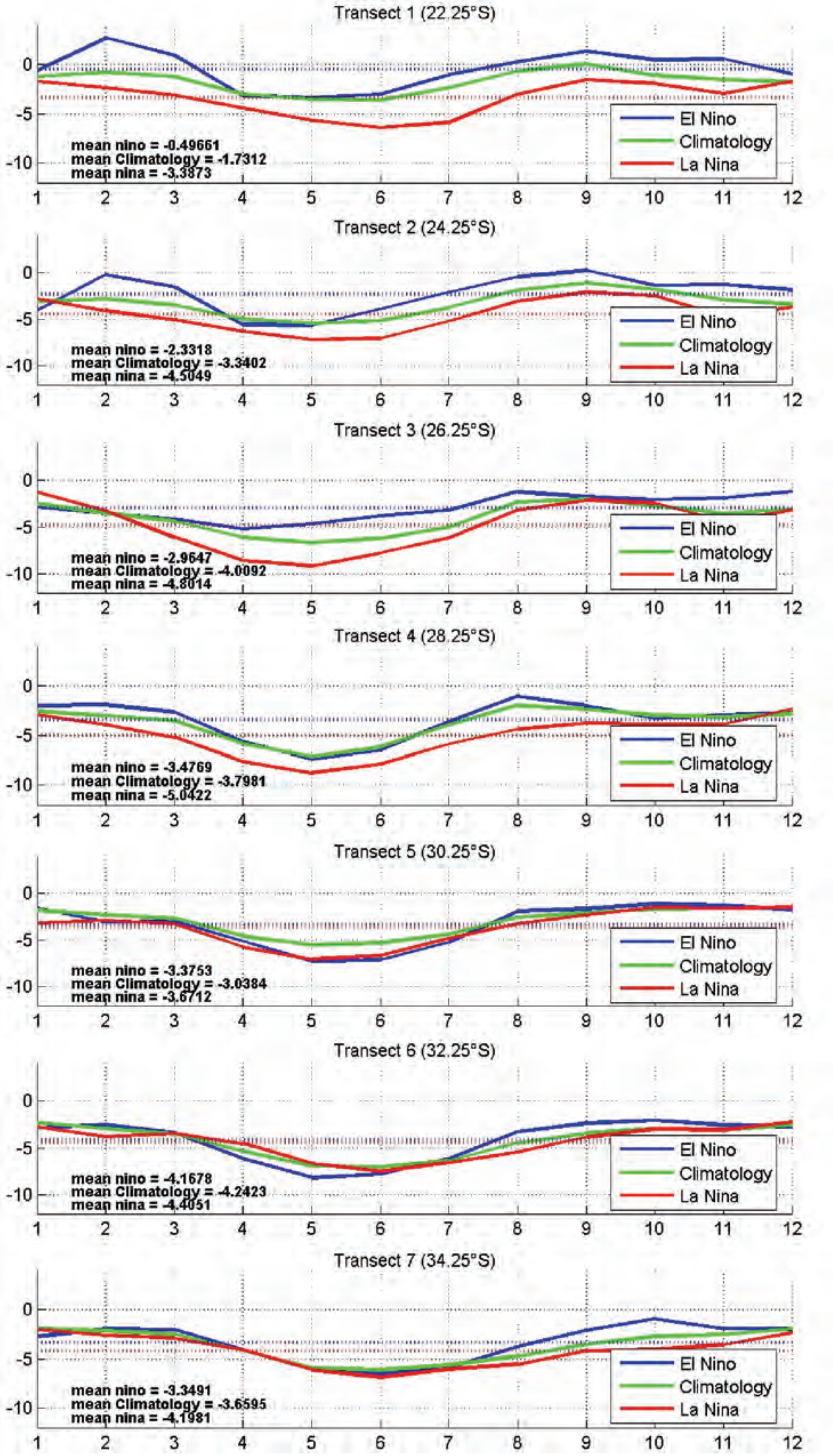

Figure 3.22: Yearly composites of the net transport (in Sv) across the seven transects along the coast of Western Australia, showing the transport variability throughout the year during El Niño and La Niña events. Negative values of transport indicate a southward transport.

Feng *et al.* (2003) showed, using XBT data, that the averaged geostrophic transport east of 110°E long 32°S was weaker all year around during El Niño years than during La Niña years. The net transport from 0-300m depth of the seven transects was calculated in two ways: first, using the SODA reanalysis velocity current; and second, by calculating the geostrophic current velocities relative to the 300 m level, using the SODA reanalysis temperature and salinity data, similar to Feng *et al.* (2003).

Only two transects are presented here (Figure 3.23a, b), one north (transect 2) and one south (transect 6) of the EKE maximum. The composite profiles were also averaged over three months. In the first 100 m depth, the transport calculated with the reanalysis velocities presented sharper variation, as the current was more variable over the continental shelf.

North of the EKE maximum (transect 2), the net transport and net geotrophic transport presented similar profiles across the depth, and the net transport during La Niña years was stronger than during El Niño years.

South of the EKE maximum (transect 6), the composites of net transport and net geostrophic transport presented similar characteristics during most of the year but not during the April–June period (i.e. transect 6, months month 4, -5, -6), the net transport calculated from actual current velocity was weaker during La Niña years than El Niño years across the whole depth, which is consistent with the results shown in Figure 3.22.

The 300 m-level is commonly used to determine the geostrophic current; it is considered the level of no motion and isolates the Leeuwin Current from the Leeuwin Undercurrent (LUC) present below this depth. However, it appeared that north of the EKE (transect 2), the net transport near the 300 m-level was weakly positive, indicating the northward flowing Leeuwin Undercurrent (i.e. positive net transport) was present between 200 and 300 m during most of the year, and was particularly strong at the end of winter (July–September) South of the EKE maximum (transect 6), the level of no motion appeared to be generally near 300 m-depth, indicating that the LUC was flowing northward below 300 m.

Discussion

Although a combination of a thermohaline forcing (McCreary et al. 1985) and remote forcing (due to interconnection between the Pacific Ocean water and the Indian Ocean) may drive the Leeuwin Current (Godfrey and Ridgway 1985), the sea surface height slope along the Leeuwin Current's maximum transport location may provide an effective quantification of this forcing and is a useful tool to describe its variability. From the results presented here, the forcing (i.e. sea surface height slope) generally appeared weaker during El Niño and stronger during La Niña. The sea surface height slope also presented a linear dependence with the different phases of the PDO. During a cool phase of the PDO, the slope increased linearly, due to the transfer of high sea surface height accumulated in the western Pacific. The reverse happened during a warm phase of PDO, with a decrease in the slope due to the transfer of low sea surface height. The Leeuwin Current forcing, represented here by the slope, responded to the PDO with similar dynamics than for ENSO, but on an inter-decadal scale.

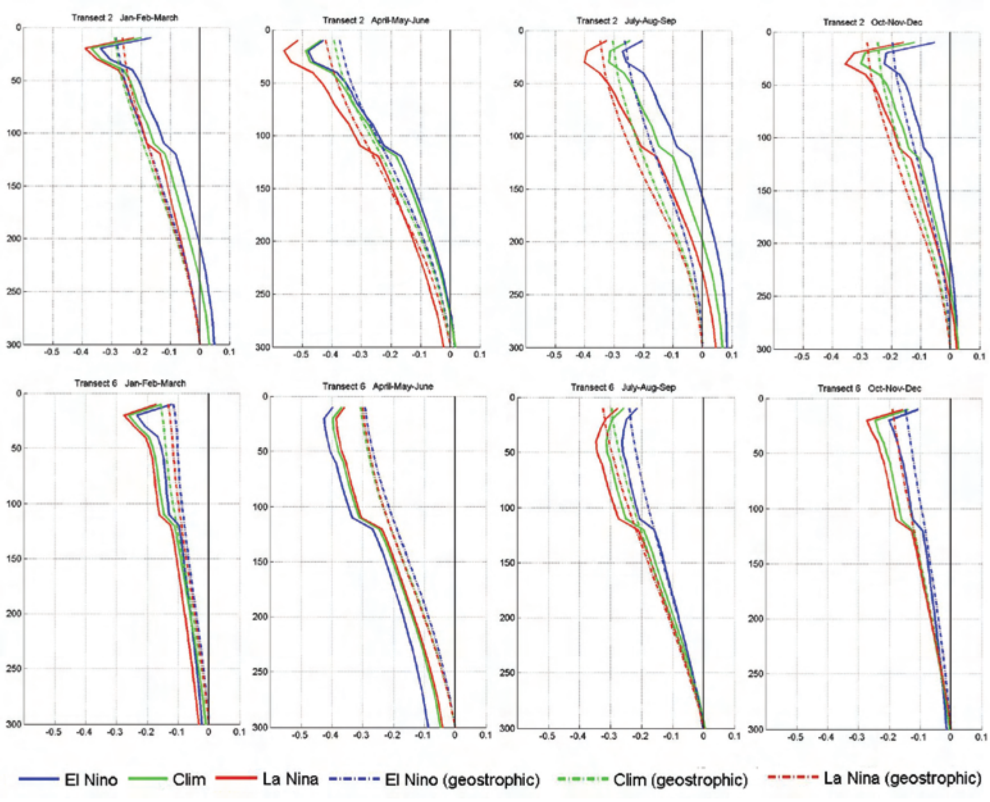

Figure 3.23: Composites profiles of the net transport (solid line) and net geostrophic transport (dashed line) across two transects along the coast of Western Australia, showing the average transport over three months during El Niño and La Niña years. Transport is in Sverdrup and negative values of transport indicate a southward transport.

Eddies develop on the offshore side of the Leeuwin Current core. As the eddies propagate westward, advection of warm water offshore, and thus energy, is drawn away from the mean current (Batteen and Butler 1998, Fang and Morrow 2003, Feng et al. 2005). The magnitude of these eddy fluxes has been estimated at 20–30% of the annual mean poleward heat and salt flux (Morrow et al. 2003). Eddies were generated at preferred locations, where the coastline significantly changed (Batteen and Butler 1998); nevertheless, an eddy kinetic energy maximum was located near 30°S (Batteen and Butler 1998, Feng et al. 2005) and near 29°S in the present study. Although it was demonstrated the EKE maximum location varied seasonally, most of the offshore advection of energy could have been occurring near 29–30°S.

Investigation of the transport along the Western Australian coastline showed the transport was very variable latitudinally. A measure of the Leeuwin Current transport at a particular point along the coast does not accurately provide insight into the Leeuwin Current's overall strength. The presence of eddies that draw energy from the Leeuwin Current into the Indian Ocean as well as the variability in the geostrophic input from the west into the Leeuwin Current may be responsible for the transport magnitude variability from the north to the south of Western Australia.

Composites of net transport along the coast showed the response to ENSO was variable between 22°S and 34°S. North of the EKE maximum, the Leeuwin Current's southward transport was stronger during La Niña years than during El Niño years. The southward transport at higher latitudes did not appear to respond to ENSO, and particularly from April to June when the Leeuwin current strength is maximum. The Leeuwin Current also appeared to be shallower at lower latitudes.

McCreary *et al*. (1986) suggested that a Leeuwin Current remotely forced by the flow of warm water from the Pacific Ocean into the Indian Ocean should weaken away from the forcing region, i.e. North West Shelf (NWS). Batteen and Butler (1998) showed that away from the source region, the influence of the NWS water diminished poleward, but was still strong enough to augment the onshore geostrophic inflow. This could partially explain the Leeuwin Current's weaker response to ENSO at higher latitudes. However, the thermohaline forcing, due to the poleward increase of surface density (McCreary 1986; Thompson 1984, Mc Creary 1986), should not be stronger during El Niño years; and therefore, the thermohaline forcing cannot be responsible for the stronger transport present at high latitudes during April—May-June of El Niño years.

Eddy energy is strong during La Niña years; more eddies are generated and more energy is advected offshore, away from the Leeuwin Current core. This may explain why the southward transport south of the maximum eddy generation was weakened. The Leeuwin Current is expected to be stronger at lower latitudes (north of 29–30°S) during La Niña years than during El Niño years. At higher latitudes, the influence of ENSO is not significant and the Leeuwin Current's strength may rely on other parameters.

Acknowledgements

This work is supported by the Strategic Research Fund for the Marine Environment (SRFME) a joint venture between the Western Australian State Government and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

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Conference attendance and presentations

M. Feng. Latitudinal response of the Leeuwin Current to inter-annual forcing using SODA re-analysis data, poster. session, 2006 Ocean Sciences Meeting., 20–24 February 2006, Honolulu, Hawaii, USA.

Publications and/or outcomes to date

Berthot, A., Pattiaratchi, C.B., Feng, M., Li, Y., and Meyers, G. (2006). Latitudinal response of the Leeuwin Current to inter-annual forcing using SODA re-analysis data. To be submitted to Journal of Geophysical Research.

3.3.4 Ecological Interactions in Coastal Marine Ecosystems: Trophodynamics

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Note: This project commenced in 2005, and this report presents preliminary findings only.

Executive Summary

Two major seasonal field studies (Autumn and Spring 2005) have been completed for the Trophodynamics project, and work is well underway towards interpreting the food web dynamics of the Jurien Bay Marine Park region. Over 500 samples have been analysed for carbon and nitrogen isotopic signatures, with an initial focus on elucidating the grazing pathway (which includes seagrass, seagrass leaf epiphytes, brown algae, red algae, gastropods and sea urchins) for Autumn 2005.

We found a distinct isotopic separation of the seagrass/epiphyte group from the red and brown algae, although some overlap in $\delta^{13}C$ signatures between the brown and red algae makes isotopic differentiation of these primary producers difficult. The grazing and detrital-feeding gastropods form a coherent group, which may be feeding primarily on brown algae with some inclusion of red algae; an additional scenario is that both red algae and seagrass (leaves and/or epiphytes) may form the diet of these gastropods. These preliminary results serve to highlight the need for further analyses using alternative biomarkers, and we will shortly move forward with fatty acid analysis of targeted samples using these C and N isotopic results as a guide.

An unexpected result was obtained for the sea urchin, *Phyllacanthus irregularis*, which was found to be heavily enriched in $\delta^{15}N$ above all organisms currently analysed (including rock lobster). Recent literature (Vanderklift *et al*., 2006) indicates that this omnivorous urchin may consume a significant amount of sponges and ascidians in its diet, which we will test further when our samples for these filter-feeding organisms are analysed.

In addition to the field-based trophic work, preliminary studies on isotope enrichment have been undertaken using two species of cultured finfish. Interestingly, both species show a significant $\delta^{13}C$ enrichment of ~ 2.5 and 3 $^{o}/_{oo}$ as compared to their food source, challenging the standard assumption of minimal C enrichment between an organism and its food source, and indicating that we should be cautious with our interpretations of trophic relationships based on the presently accepted model. We are currently designing a series of aquaria experiments to more fully explore this issue and quantify the isotopic relationships between food sources and other key consumers in the marine environment.

Introduction

A three-year program to investigate ecological interactions in midwest coastal reef communities has been built around the Jurien Bay Marine Park (Figure 3.24), using multiple-use management zones within the park as large scale manipulations of predator abundance. This focus will gives the program an emphasis that distinguishes it from core SRFME projects and takes advantage of the unique opportunities developing in the midwest area. Two groups of predators, finfish and spiny lobster, are of primary interest and the zoning of the park, into areas subject to all kinds of fishing, lobster fishing only, and no-take restrictions, will facilitate the understanding of their respective ecological roles.

Outline

The key research/management questions that exist in the context of Ecological Interactions in the Midwest are as follows:

- What are the trophic linkages of exploited species to other ecosystem components?
- What are the pathways of transport of organic matter and nutrients between habitats and across the shelf?
- How do exploited species in particular utilize the range of available coastal shallow water habitats (e.g. foraging in seagrass, sheltering on reefs)?
- What are the potential trophic (indirect) effects of variations in predator density?
- What is the relative importance of any anthropogenic variation in ecological interactions relative to natural variability at the habitat, seasonal and interannual levels (e.g. can we detect indirect ecological effects of fishing against the background of natural variability)?
- How will populations of exploited predatory species respond to marine park protection (i.e. what are the direct effects of fishing)?

The goals outlined above will be achieved through an integrated research program involving state institutions, Universities and CSIRO. In order to maximize the information gained in the Midwest region, studies of ecological interactions can usefully be divided into the following sub-sections. These do not map directly onto the goals above, rather they provide a more practical framework through which to plan the research program.

1. Habitat characterization and benthic community biodiversity studies.
2. Studies of major predator groups - finfish
3. Studies of major predator groups - rock lobster
4. Trophodynamic studies.

Ultimately this suite of studies will allow reasonably detailed quantitative models of Midwest coastal ecosystems to be developed, through the input of underpinning data, as well as through an iterative process of validation and observation. Such models are currently being developed as part of SRFME core objectives and should begin coming online around the time that the Midwest Collaborative program is being completed.

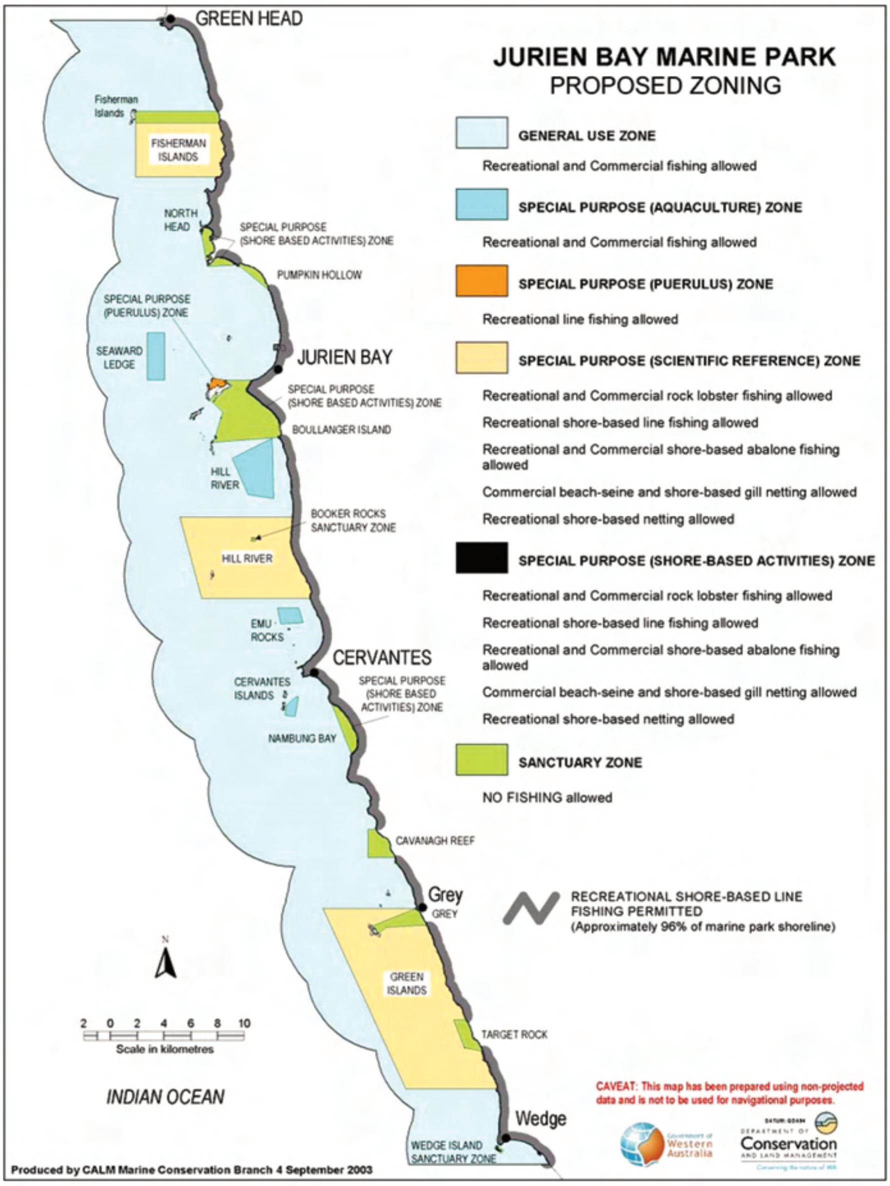

Figure 3.24: Map showing draft management zoning of the Jurien Bay Marine Park

Trophodynamic studies

Trophodynamic studies will mesh with other proposed and ongoing studies to provide a much better understanding of the flow of energy and nutrients at a range of spatial scales, from the small scale between habitats to larger cross-shelf scales. Studies on the dietary composition through gut content analyses of fish have traditionally been used to examine food webs and trophic linkages in aquatic ecosystems. However, such an approach rarely considers the ultimate source of energy and provides limited information on the interactions between the various primary producers and consumers in an ecosystem. Analyses of gut contents often provides only a snapshot of the diet of fish at a particular time, when the food consumed by fish often varies considerably over time (hours, days, seasons), during the life cycle of the fish (juveniles to adults) and among habitats (*e.g.* Werner and Gilliam 1984, Hyndes *et al.* 1997). Furthermore, different food types are digested at different rates, whereby hard-shelled prey can often be over-represented in gut-content analyses due to their recognisable fragments remaining in the guts for longer periods. In addition, the pharyngeal grinding of food by certain fish species renders the different food types consumed by these species indistinguishable.

Recently, researchers have recognised stable isotope techniques as a useful tool to identify and trace food/energy sources in coastal ecosystems (*e.g.* Kitting *et al.* 1984, Peterson and Fry 1987, Newell *et al.* 1995, Loneragan *et al.* 1997, Jennings *et al.* 1997, Pinnegar and Polunin 2000). This approach allows the linkages between fish and the various food sources in the coastal environment to be determined through measuring the natural isotopic ratios, typically $^{13}C/^{12}C$ and $^{15}N/^{14}N$, in the different primary producers and consumers. Since ^{13}C exhibits only slight enrichment in tissue from primary producers to the various consumer levels, $^{13}C/^{12}C$ typically is considered useful for tracing the source material in the food web (Peterson and Fry 1987). In comparison, ^{15}N displays a stepwise enrichment of approximately 3‰ between primary producer and each of the different consumer levels. The measurement of $^{15}N/^{14}N$ ratios has therefore been used to provide an estimate of the number of trophic levels in the food web (*e.g.* Fry and Quinones 1994). The combination of these isotopes provides a useful tool to examine the linkages among the various food sources and consumers in coastal environments and thereby provide an indication of the importance of different environments to major consumers.

Many important floral and faunal components of habitats are highly mobile, traveling large distances from one habitat to another. This transport includes the supply of drift algae or seagrass, as well as movements of reef-associated predators into other habitats to feed, or as part of seasonal foraging, ontogenetic or reproductive movements. By quantifying the abundance and origin of drift material, and by modeling the transport of algal and detrital particles we will begin to quantify the ecological linkages between habitats. Movement studies of key predatory species will provide information on the relative importance of different habitats for feeding and foraging. Biomarkers, particularly stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$), will be used to validate and calibrate the relative magnitude of energy flows within the system, as well as the potential for habitat-related and ontogenetic differences in trophic relationships of key species such as lobster.

Objectives

The broad aim of this study is to examine the trophic linkages of different habitats within a coastal marine environment. This broad aim will be achieved through investigating the following specific objectives.

1. To determine the source of primary production that drives the food web for major consumers in a coastal marine environment using biomarker techniques;

2. To determine the spatial and temporal variability in the source of production for major consumers in a coastal marine environment; and

3. To determine the movement patterns of detached reef algae and seagrass into adjacent coastal marine habitats.

Methods

The study is split into two main subcomponents; (1) biomarker analyses; and (2) movement and biomass of wrack.

Biomarkers (stable isotopes)

Examining the diets of consumers has traditionally been used as a mechanism to study food webs in marine systems. However, dietary studies can underestimate the importance of some organisms to the food web due to their rapid digestion. Furthermore, dietary studies do not provide information on whether particular organisms are assimilated. It is therefore difficult to trace the origins of nutrients and energy using dietary approaches. Measurements of natural $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotopic ratios have been shown to be a useful tool for identifying and tracing the source of carbon and nitrogen in aquatic food webs (*e.g.* Kitting *et al.* 1984, Thresher *et al.* 1992, Newell *et al.* 1995, Loneragan *et al.* 1997, Marguillier *et al.* 1997). When an organism assimilates carbon and nitrogen from a source it either assimilates the isotopes indiscriminately, or displays a preference for one isotope (the fractionation ratio) for both carbon and nitrogen, thereby acquiring $\delta^{13}C$ and $\delta^{15}N$ that reflect the source. With the use of mixing models (*e.g.* Phillips & Gregg 2003), the $\delta^{13}C$ and $\delta^{15}N$ values of an organism can be used to infer the source of carbon and nitrogen it has assimilated, provided that the $\delta^{13}C$ and $\delta^{15}N$ ratios of all possible sources are known and differ to each other.

This component of the study will be split into two sections. The first phase of the study will examine the stable isotope signatures of a range of primary producers and consumers in a range of habitats in different regions of Jurien Bay. This part of the study will provide broad information on the flow of energy and nutrients in the food web of Jurien Bay. In other words, it will provide data on the contribution of the major primary producers to the food web of this marine system, and whether there are trophic linkages among different habitats. The second phase of the study will examine the spatial patterns in the influence of primary producers in unvegetated habitats and the extent to which primary producers from reefs and seagrass meadows influence the food web of unvegetated areas with increasing distance from those plant dominated habitats.

Broad trophic study

We propose to undertake detailed analyses of stable isotope signatures for rock lobster and selected finfish species with a view to gaining a better understanding of, not only how trophic relations vary among species, but also whether they vary ontogenetically due to changes in diet of individuals of increasing size. Habitat use may also vary ontogenetically, therefore we will explore variation in trophic signature between habitats and the possibility that isotopic signatures may be the result of the interaction between size and habitat.

The study will concentrate on collecting samples of consumers [finfish (e.g. Pink snapper) and major invertebrates (e.g. Western rock lobster)] from a range of dominant habitats in Jurien Bay, as well as collecting dominant primary producers (seagrasses and seagrass epiphytes, reef macroalgae, phytoplankton and benthic micro-algae) from the region. Since detritus is likely to form a major link in the food web, samples of different fractions of detritus will be collected to determine its composition in different regions of Jurien Bay.

Fish and invertebrates will be collected from reef, seagrass and unvegetated habitats in three regions of Jurien Bay using trawls or gill nets or by spearing. Where possible, this project will link into the dietary studies by MU, but additional samples may be required for the collection of adequate sample sizes. White flesh will be removed for stable isotope analyses. Macro-invertebrates will be collected through dive collections or coring. Flesh samples will be removed and stored for stable isotope analyses. Where invertebrates are too small to remove sufficient flesh, individuals will be pooled as one sample. Samples of live algae will be collected from reefs, and seagrass and epiphytic algae will be collected from seagrass meadows adjacent to reefs. Plants will be removed of any epiphytic material.

At least three replicate samples will be collected for each organism from each habitat and region. For major consumers, attempts will be made to collect samples from different size groups to examine ontogenetic shifts in stable isotope signatures. Since diets may vary seasonally, samples will be collected during two times of the year (summer/autumn and winter/spring).

Since $\delta^{13}C$ and $\delta^{15}N$ values among primary producers can be similar, alternative biomarkers may be required to allow differentiation of primary producers as sources for consumers. Sulphur isotopes have been shown to be useful to distinguish between benthic and pelagic food webs. For this reason, we will analyse sulphur isotope for target key benthic and pelagic species for these analyses.

All samples will be processed for $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios using an ANCA-NT/20-20 stable isotope ratio mass spectrometer at ECU. The $\delta^{13}C$ and $\delta^{15}N$ values will subsequently be calculated and compared using a multiple-source mixing model (e.g. Phillips and Gregg 2003). For targeted species, samples will be processed for sulphur and sent to other facilities for analyses.

Many studies have used the assumption that $\delta^{13}C$ displays minimal enrichment while $\delta^{15}N$ displays a stepwise enrichment (3-5 ‰) between different trophic groups. However, this can be highly variable among different organisms, particularly for $\delta^{15}N$ (Vanderklift and Ponsard 2003). Interpretation of stable isotope data requires information on the enrichment of both $\delta^{13}C$ and $\delta^{15}N$ through the various trophic steps. However, there is limited information available on enrichment of these isotopes for the organisms that will be examined in this study. We therefore propose to carry out a series of experiments to examine the trophic enrichment of $\delta^{13}C$ and $\delta^{15}N$ and sulphur exhibited by some major consumers.

Selected invertebrates will be placed in aquaria and provided with food for which the $\delta^{13}C$ and $\delta^{15}N$ values are known. Consumers will be kept in the aquaria for up to two months to ensure that SI signatures derived from their existing diet has been replaced by that derived from their new diet. At the end of the experiments, consumers will be removed from the aquaria, euthanased and flesh removed for SI analyses. Differences between the $\delta^{13}C$ and $\delta^{15}N$ values will indicate the level of enrichment (or depletion). For fish and large macro-invertebrates, the turnover of $\delta^{13}C$ and $\delta^{15}N$ in the flesh is likely to occur over an extensive timeframe, thereby limiting any opportunity to carry out aquaria experiments to examine enrichment in these organisms. We therefore propose to collaborate with personnel at the TAFE Maritime Centre, where fish are being reared in captivity. We will examine the $\delta^{13}C$ and $\delta^{15}N$ of a suite of fish species (e.g. Pink snapper, Black bream and Dhufish) and their food source.

Spatial influence

As previously noted, trophic studies using stable isotopes are useful when the SI signatures of the various primary producers are widely disparate. Current work at ECU (G. Hyndes and P. Lavery) is showing that the seagrasses *Posidonia* spp. and *Amphibolis* spp. have highly enriched $\delta^{13}C$ values relative to algal species. However, the SI signatures of brown, red and green algae are relatively similar to each other, making it difficult to distinguish these groups as potential sources. The second phase of the stable isotope study will therefore attempt to fill some of the gaps that have become event from the broad stable isotope study. Potentially, by the end of Phase 1, we will not have a clear understanding of the principal sources of C and N in unvegetated areas that are adjacent to reefs and seagrass meadows, yet the transport of material from these other major benthic habitats is likely to provide significant production into these unvegetated areas.

The second phase of the study (year 2) is likely to focus on examining the change in stable isotope signatures in the benthic infauna and epibenthic fauna in unvegetated areas with increasing distance away from seagrass meadows and reefs. A current study by Mat Vanderklift is examining the hypothesis that $\delta^{13}C$ in seagrass fauna should change gradually with distance from reef, reflecting the gradual change in the relative importance of reef-derived macroalgae and seagrass. The proposed study will expand on this hypothesis by examining the hypothesis that $\delta^{13}C$ in fauna associated with unvegetated areas should change gradually with distance from reef and seagrass meadows, resulting from a shift in the relative importance of reef-derived macroalgae and seagrass.

Artificially enriching either the $\delta^{13}C$ or $\delta^{15}N$ of some of the major primary producers may be required to provide a clear demarcation of the SI signatures of those sources that will allow SI signatures to be tracked along transects away from reefs or seagrass meadows. Alternatively, other biomarkers, such as sulphur, fatty acids or amino acids, may be required to fulfill this task. Results from current preliminary work at CSIRO and ECU will be used to help direct and refine this part of the project.

Movement and biomass of wrack

Accumulations of wrack are a prominent feature of the coastline of south-western Australia. Algae from reefs and seagrasses and their associated epiphytic material become dislodged, particularly during winter storms, and are transported into adjacent habitats. It has been estimated that approximately 20% of production from reefs and seagrass meadows passes through the nearshore regions (Hansen 1984), where it has been shown to provide important habitats for a range of invertebrates and finfish species (Robertson & Lenanton 1984, Lenanton et al. 1981). Currently, a SRFME PhD study at ECU (K. Crawley) is further examining the importance of this wrack material to the habitat structure and trophic dynamics of nearshore waters in the Perth metropolitan region. This study is showing that fish species have a clear preference for particular volumes and types of wrack and that prey species have a clear preference for brown algae as a food source.

We plan to examine the movement patterns of wrack from reef and seagrass meadows into subtidal, unvegetated areas in Jurien Bay. The transport of this material is likely to contribute significantly to secondary production in these areas. We will also examine the biomass and composition of wrack material in these areas. This will be achieved through:

- Stratified random design using towed video transects, and ground truthing using large quadrats to quantify the volume/biomass of different wrack types in different regions during different times of the year. Sampling will be conducted over at least four (seasonal) sampling occasions.
- Tracking of wrack using either acoustic tags and receivers for tracking the movement of wrack, or using conventional tags or colour-dyed plant material and towed video transects to record presence of “tagged” material in adjacent unvegetated areas. The acoustic tagging approach will be dependent on the success of additional proposals to gain funds for this part of the study.

Results and Discussion

To date, we have successfully carried out the two major seasonal field studies to examine broad trophodynamics relationships within the Jurien Bay Marine Park. These were completed in autumn (April/May) and spring (October) 2005. During each field trip, sediment, seagrass, algae and invertebrate samples were collected at eight sampling sites within the Jurien Bay and Green Head regions (Fig. 3.25). These sites are subjected to different exposure regimes (i.e. inshore versus mid-shelf) and levels of marine park protection (i.e. fished versus sanctuary zones), as detailed in Table 3.3.

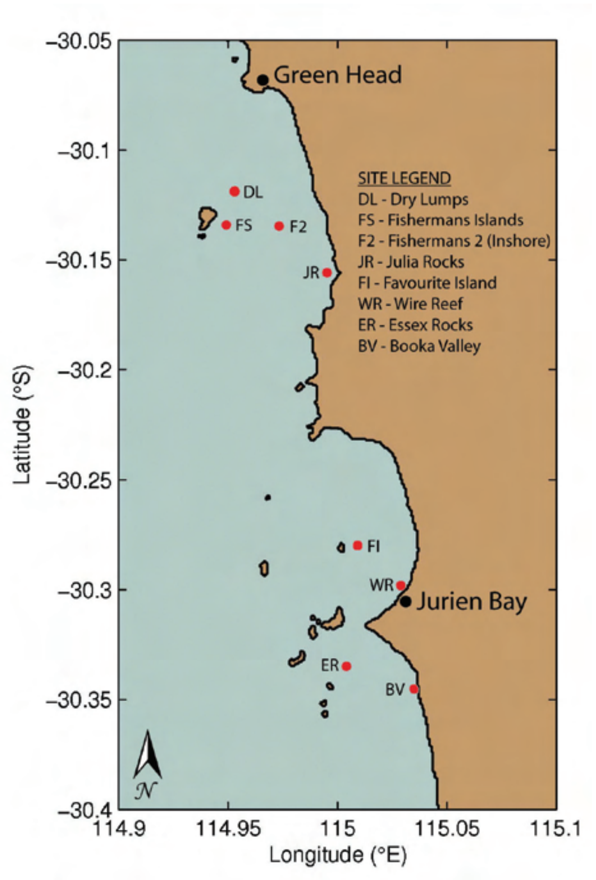

Figure 3.25: Location of the eight sampling sites for the Trophodynamics project within the Green Head and Jurien Bay regions.

Table 3.3. Details of the eight sampling sites within the Green Head and Jurien Bay regions.

Region	Location	Zoning Type	Site	Label	Latitude (S)	Longitude (E)
Green Head	Mid-shelf	Fished	Dry Lumps	DL	30°07.130’	114°57.179’
Green Head	Mid-shelf	Sanctuary	Fishermans Island	FS	30°08.050’	114°56.952’
Green Head	Inshore	Sanctuary	Fishermans 2	F2	30°08.080’	114°58.406’
Green Head	Inshore	Fished	Julia Rocks	JR	30°09.352’	114°59.712’
Jurien	Mid-shelf	Fished	Favourite Island	FI	30°16.805’	115°00.552’
Jurien	Inshore	Fished	Wire Reef	WR	30°17.887’	115°01.731’
Jurien	Mid-shelf	Sanctuary	Essex Rocks	ER	30°20.085’	115°00.246’
Jurien	Inshore	Sanctuary	Booka Valley	BV	30°20.723’	115°02.250’

Laboratory work has concentrated on carbon and nitrogen isotopic analyses of samples collected from the autumn field trip. Approximately 500 samples have been analysed to date. We have concentrated first on the elucidation of the grazing pathway, with priority analysis of seagrass, seagrass leaf epiphytes, brown algae, red algae, gastropod and sea urchin samples.

As displayed in Figure 3.26, in the autumn samples there is a distinct separation between the seagrass/epiphyte group and the red and brown algae, with the seagrass and leaf epiphytes more enriched in $\delta^{13}C$. The brown algae has overlapping $\delta^{13}C$ signatures with three species of red algae (*Hypnea* sp., *Laurencia filiformis* and *Metamastophora flabellata*; Fig. 3.26), making isotopic differentiation of these primary producers difficult. The grazing and detrital-feeding gastropods form a coherent group that is enriched in $\delta^{15}N$ compared to the brown algae, and near the upper distribution of $\delta^{15}N$ for the red algae. There is a general overlap in $\delta^{13}C$ signatures between these gastropods and both the brown and red algae. These results indicate that this group may be feeding primarily on brown algae with some inclusion of red algae; an additional scenario is that both red algae and seagrass (leaves and/or epiphytes) may form the diet of these gastropods, resulting in an intermediate $\delta^{13}C$ signal between these two plant groups. This $\delta^{13}C$ overlap between primary producers is not unexpected given previous research in this area, and serves to highlight the need for further analyses using alternative biomarkers. We will shortly move forward with fatty acid analysis of targeted samples using these C and N isotopic results as a guide.

These analyses also highlighted three species with enriched $\delta^{15}N$ signatures compared to the algal and seagrass material (Fig. 3.26), which includes one species of carnivorous gastropod (the whelk *Thais orbita*) and two species of reef-dwelling sea urchins (*Heliocidaris erythrogramma* and *Phyllacanthus irregularis*). *Thais orbita* is known to prey on other gastropod species, and its ~ 3 $^{o}/_{oo}$ $\delta^{15}N$ enrichment and similar $\delta^{13}C$ signature to the grazing gastropods provides further evidence of its trophic status. The two sea urchin species exhibit $\delta^{13}C$ signatures that are most similar to the brown algae and some of the grazing gastropod species. With the $\delta^{15}N$ signature, *H. erythrogramma* is enriched ~ 3 $^{o}/_{oo}$ as compared to the brown algae, as expected for a grazing species approximately one trophic level above these primary producers. However, *P. irregularis* was measured at a further ~ 3 $^{o}/_{oo}$ $\delta^{15}N$ enrichment above *H. erythrogramma*. Isotopic analysis of rock lobster (*Panulirus cygnus*) has also been undertaken as part of the ‘Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster’, and is presented in the accompanying progress report for that study. It is notable that the $\delta^{15}N$ signatures for the various rock lobster samples are also lower than that of *P. irregularis*. We expect, based on the recent work of Vanderklift *et al*. (2006), that this surprising result can be explained by the unique diet of *P. irregularis* as compared to other local urchin species. *Phyllacanthus* was found to be an omnivore which, in addition to a diet of macroalgae, consumed significant amounts of animal tissue, specifically sponges and ascidians. Vanderklift *et al*. (2006) also found that *P. irregularis* had an enriched $\delta^{15}N$ signature which ranged between ~ 9 and 13 $^{o}/_{oo}$.

We have also examined the differences in isotopic signatures between these two urchin species by location (Fig. 3.27), and found that $\delta^{15}N$ enrichment of *P. irregularis* is consistent throughout the study area. Of particular note, however, is the pattern of $\delta^{13}C$ depletion for both *P. irregularis* and *H. erythrogramma* between sites in the Jurien Bay region. For both of these species, the $\delta^{13}C$ signature shows the trend Wire Reef (WR) > Booka Valley (BV) > Favourite Island (FI). To determine if this is a reflection of different $\delta^{13}C$ signatures of the primary producers at these sites, we examined isotopic results for a variety of brown and red algae species by site. These results (not shown) indicated no coherent site-specific pattern in C or N isotopic signatures, and thus could not provide support for the trend in $\delta^{13}C$ observed with the sea urchins. We expect that analysis of the additional faunal samples obtained (especially sponge and ascidian samples) may help explain the observed pattern, at least for *P. irregularis*.

In addition to the field-based trophic study described above, preliminary studies on isotope enrichment have been undertaken to examine the common assumption that between different trophic groups, $\delta^{13}C$ displays minimal enrichment (0 - 1 $^{o}/_{oo}$) while $\delta^{15}N$ displays a stepwise enrichment of approximately 3 – 5 $^{o}/_{oo}$. We have begun this study by examining enrichment in two species of cultured finfish, snapper (*Pagrus auratus*) and mulloway (*Argyrosomus japonicus*). Five replicate specimens of each species were obtained from the TAFE Maritime Centre. These fish were approximately 1 year in age, and had been fed exclusively on a diet of food pellets (composed largely of fish meal, fish oil, wheat and plant protein meal).

Results from isotopic analysis of fish muscle tissue and triplicate samples of small food pellets (fed to snapper and mulloway) and large food pellets (fed to mulloway only) are displayed in Figure 3.28. Both fish display ~ 3 $^{o}/_{oo}$ $\delta^{15}N$ enrichment above their food source, which matches the common assumption used in trophic studies. However, both the mulloway and snapper also show a significant $\delta^{13}C$ enrichment of ~ 2.5 and 3 $^{o}/_{oo}$, respectively. This challenges the standard assumption of minimal C enrichment, and highlights that we should be cautious with our interpretations of trophic relationships based on the currently accepted model. Given this important result, we will continue to move forward with our isotope enrichment experimental studies and will now focus on exploring the relationships between food sources and other primary consumers.

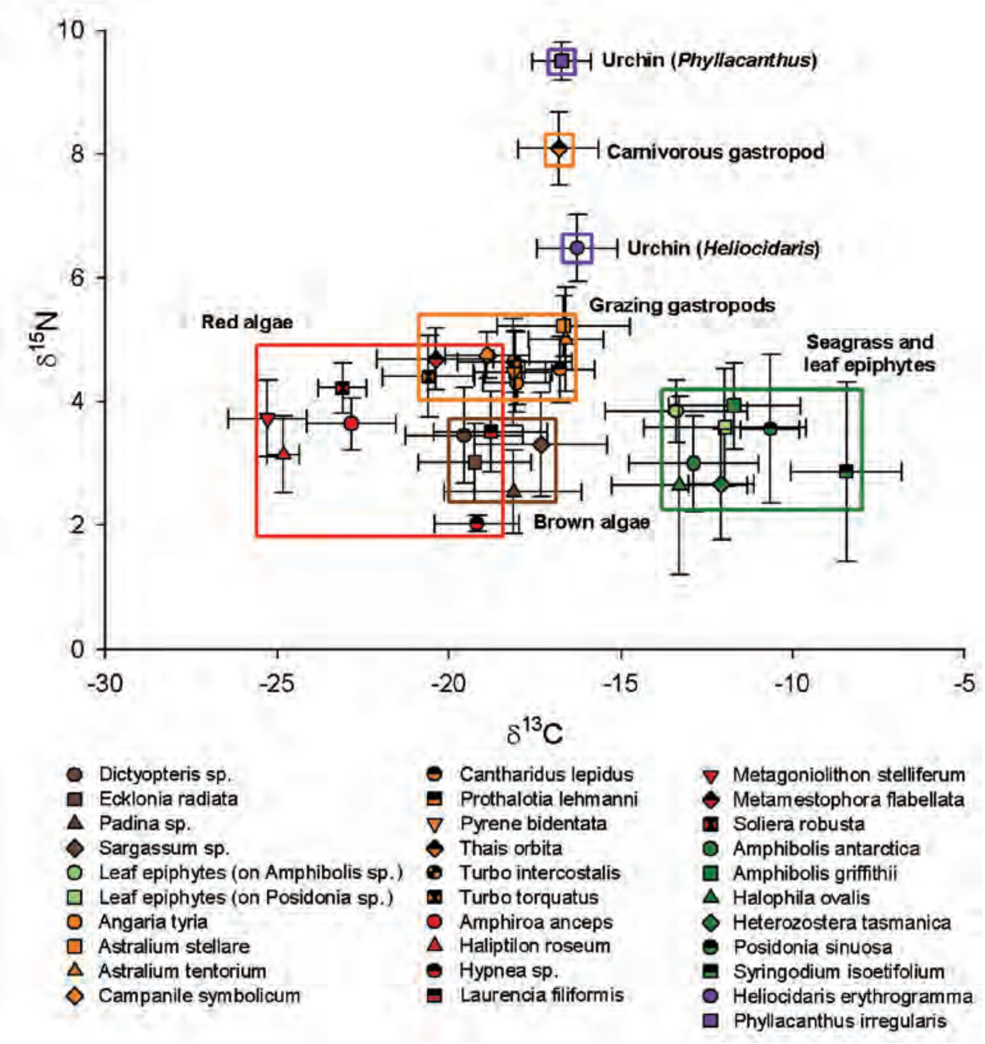

Figure 3.26: Isotopic analyses of seagrass, algae, gastropod and sea urchin samples collected in Autumn (April/May 2005) from all sites within the study area; values are mean ± s.d.

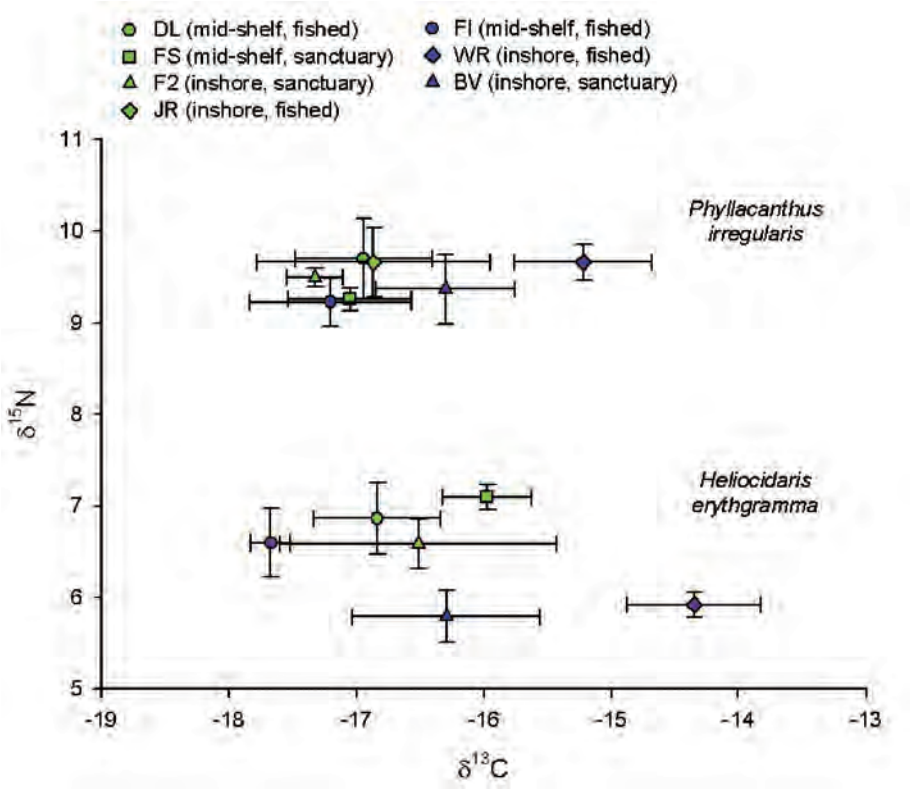

Figure 3.27: Isotopic analyses of two reef-dwelling sea urchin species by site within the Green Head (green markers) and Jurien Bay (blue markers) regions. Values are mean ± s.d.

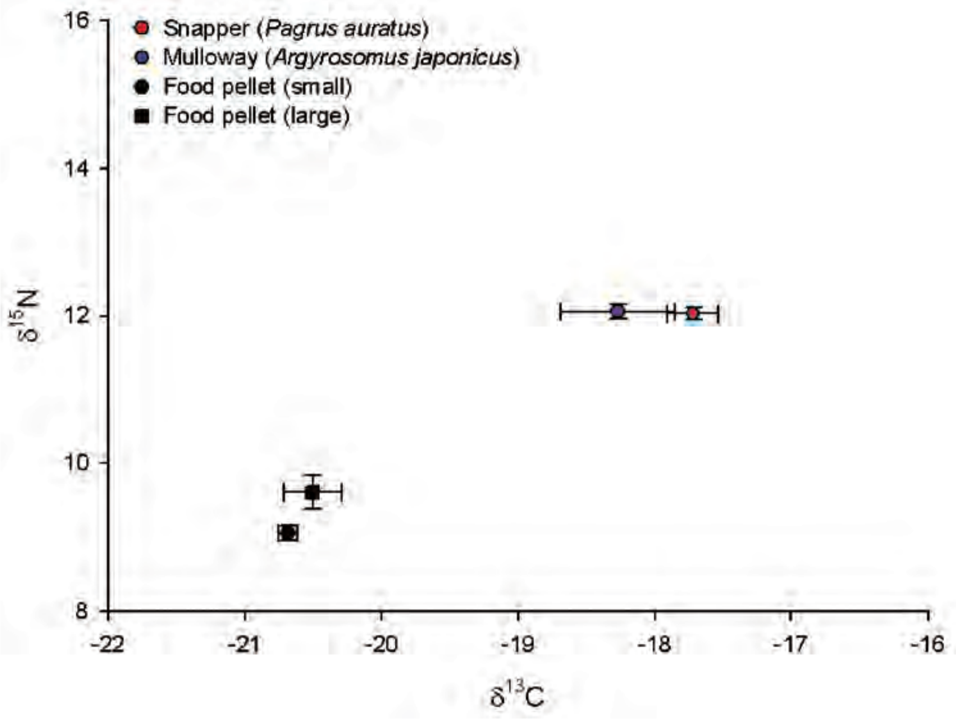

Figure 3.28: Isotopic analyses of tissue samples from two fish species that had been fed on an exclusive diet of food pellets for approximately 1 year. The snapper were fed on the 'small' pellets, while the mulloway were given a mixture of 'small' and 'large' pellets. Values are mean ± s.d.

Our upcoming research agenda focuses on the completion of laboratory processing and analysis of all remaining samples from the autumn and spring 2005 field trips. After the results from the broad trophic study have been interpreted, we will finalize the sampling design and methods for the second phase of the stable isotope study. The other main agenda item is the design and execution of the experimental isotope enrichment work for key consumer species. This work will be carried out in aquaria at ECU and, where required, at the WA Fisheries labs in Watermans. We are currently designing the experimental plan and, based on the preliminary isotopic analysis, identifying which invertebrate species to concentrate our efforts on.

Acknowledgements

We gratefully acknowledge the field and laboratory assistance of Sofie Harrison and Kylie Cook, and volunteer field assistance of Georg Christianson, Marianne Nyegaard, Lachlan MacArthur, James McLaughlin, and Andrew Tennyson. We thank Julia Phillips (CSIRO) and John Huisman (Murdoch) for algal identification, Jason Tranter (ECU) for isotope analyses and the Technical Staff at ECU's School of Natural Sciences (particularly Mark Bannister, Brad Mettam and Clay Millar) for general support.

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Conference attendance, presentations, publications and/or outcomes to date

At this early stage in the Trophodynamics project, work has concentrated on the successful execution of the two major field studies of trophic relationships within Jurien Bay Marine Park, and on the laboratory processing and analysis of samples from this field work. We are now in a position to start examining and presenting preliminary results, and this will be the focus of our future dissemination efforts.

Plans for 2006 include:

- Presentation of the Trophodynamics project outline and preliminary results at the University of Nice, France and the Dauphin Island Sea Lab, USA.
- Assisting in the organisation of, and participating in, a Jurien Bay Marine Science symposium day, to be held in Jurien Bay in conjunction with CALM. This will assist in informing the local park managers, fellow Jurien-based researchers and general public of the Trophodynamics project and its significance for the region.
- Presentation of preliminary results at the SRFME Core and Collaborative Projects Symposium, held at CSIRO.
- Presentation of the Trophodynamics project outline and preliminary results at the Centre for Ecosystem Management (CEM) Seminar Series, held at ECU.
- Creation of a large poster detailing the Trophodynamics project, including preliminary results and future plans, to be displayed at ECU and other venues where appropriate.
- Project outline and preliminary results to be posted on a Trophodynamics project webpage within the Coastal Marine Ecosystem Research (CMER) website, based at ECU.

3.3.5 Ecological Interactions in Coastal Marine Ecosystems: Rock Lobster

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Executive Summary

The density and size structure of western rock lobster (*Panulirus cygnus*) populations within the Jurien Bay Marine Park have been determined from up to 15 sites stratified by depth, cross-shelf location and benthic habitat. Surveys have been conducted over four sampling periods, with a further two remaining. The results indicate that there are larger numbers of smaller lobster less than 60 mm carapace length (CL) on shallow inshore reefs with high seagrass coverage. All sites have lobster within the 60 to 80 mm (CL) size class, although densities are lower on the more offshore sites characterised by macroalgae. However, a number of exposed sites have not been consistently sampled due to high swell conditions, and some seasons have not yet been repeated so any conclusions at this stage must be considered preliminary. In addition, gut samples and stable isotope samples have been collected from 193 lobster specimens obtained over two seasons from sites differing in surrounding benthic habitat. Early results indicate that articulated coralline algae, in particular, contributes the highest to overall diet in terms of volume consumed, and this holds true over all habitats. However, stable isotope analysis indicates that other food sources may contribute more to lobster production. Research into the movements of rock lobster is currently underway using acoustic transmitters and receivers. Results will emerge early next year and will help us understand home-range, foraging and migration patterns within coastal waters.

Studies of major predator groups - rock lobster

The Western Australian rock Lobster *Panulirus cygnus* is the dominant invertebrate predator in coastal and shelf ecosystems between Northwest Cape and Cape Leeuwin. As such it is likely to have an important role in the dynamics of these ecosystems. Because of ontogenetic changes in the spatial distribution of western rock lobster these dynamics are likely to be complex, and interactions with a large commercial fishery have the potential to add further layers of complexity. Puerulus settle on shallow coastal reefs, where they spend the first months of their lives solitary and sheltering in small crevices in limestone reefs during the day and foraging at night in algal turf and seagrass habitats (Fitzpatrick *et al.* 1989, Jernakoff 1990). As they grow the young lobsters become less solitary and move into larger caves and crevices on deeper reefs where they shelter during the day (Jernakoff 1990). Less is known about the foraging and feeding of lobsters and the range of habitats that they use at this stage, which lasts until about the age of 4 years when many of the lobsters undertake long distance migration into deeper waters (>30m), well off the coastal reef systems (Phillips 1983). It is at around this time that the lobsters reach legal size and enter the fishery.

Gaps in our knowledge of rock lobster ecology in shallow waters relate primarily to two areas: habitat use and feeding; and population structure. Our understanding of how lobsters use deeper reefs, sandy areas, and seagrass habitats such as *Posidonia* meadows with respect to shelter and foraging, and the principal prey of lobsters in these habitats, is not complete. We know that lobsters of different sizes tend to be found in different habitats but it is unclear how the population structure of lobsters in shallow water may have changed as a result of fishing. Anecdotal historical reports describe large rock lobster as being present or common in shallow reef systems in the past, yet such individuals are now very rare in shallow coastal reef systems. Consequently, the historical role of rock lobsters in shallow coastal ecosystems (and the indirect effects of fishing on ecosystem structure and function) is difficult to assess.

In order to effectively study or to demonstrate the potential role of predation by rock lobster on coastal benthic communities, we require populations of lobsters with differing population structures and that vary over a range of population densities. The reason for this is simple. For example, we may design caging experiments to exclude lobsters but if they are not present, the exclusion will make little difference to the experimental results. This may be especially relevant to determining the influence of larger rock lobsters. One way of gaining access to such populations of lobsters is to use fished and unfished areas. Such areas are currently being established at Jurien and are potentially extremely useful experimental tools. However, it is not clear whether strong contrasts in lobster density or population structure will develop.

Studies of rock lobster populations in other parts of the world have shown, using no-take marine protected areas (MPAs), that there are significant changes to population structure and also to total biomass inside these areas relative to fished areas (Kelly et al 1999, Edgar and Barrett 1999, Lafferty and Kushner 2000), but such changes are not observed universally, possibly because either they lack suitable habitat (Mayfield et al 2000) or, where species are highly mobile, MPA boundaries fragment suitable habitat (Acosta 2001). Since most *P. cygnus* reach legal size and move into deeper water at the age of around 4 years, and most of the Sanctuaries within the Jurien Marine Park are located in relatively shallow waters, it may be that there is little if any detectable effect of fishing on shallow water populations.

Developing an understanding of the variation in density and population structure of rock lobsters, and its resulting consequences, is intimately related to ontogenetic shifts in habitat utilization. Broadly speaking lobsters settle on inshore reefs as puerulus and live in inshore areas until approximately the age of 4 yrs at which time they move into deeper shelf waters. Whether there are finer scale habitat preferences of lobsters within this framework is not clear. For example, is there an incremental shift of lobsters from coastal and lagoon reefs to offshore reefs as they grow older, and do lobsters prefer particular reef habitats? Also, vital to understanding the interactions of rock lobsters with benthic assemblages is the collection of data on how diet may vary with lobster size. Finally we need to know how lobsters use their habitat and the extent to which they move from one to another.

Need

Part of the rationale for basing SRFME collaborative projects in the Midwest relates to opportunities presented by the Jurien Bay Marine Park, however it will take some time for differences in predator abundance to develop and for the park to reach its potential as a useful tool for ecological research. Nevertheless it is important for studies to commence as soon as possible, for two reasons. Firstly, the convincing demonstration of any direct or indirect effects of fishing revealed by changes of fishing pressure in the park will rely on a BACI design. Therefore, we must act now to begin collecting all the necessary baseline data. Secondly, important information relating to trophic structure of coastal communities and how it varies among habitats as well as seasonally and interannually, can be collected now and will be a vital part of interpreting and potentially predicting any changes in ecological interactions that emerge as a result of park zoning. Given the high economic value of Western rock lobster and the greater emphasis on ecological effects of fishing through the EPB act, it is imperative that we gain a greater understanding of the impact of removal of rock lobster on the broader ecosystem. This study will mesh with other proposed and ongoing studies to provide a much better understanding of the movement of lobster and the flow of energy and nutrients at a range of spatial scales, from the small scale between habitats to larger cross-shelf scales. A conceptual diagram of the processes and patterns to be investigated is provided in Figure 3.29.

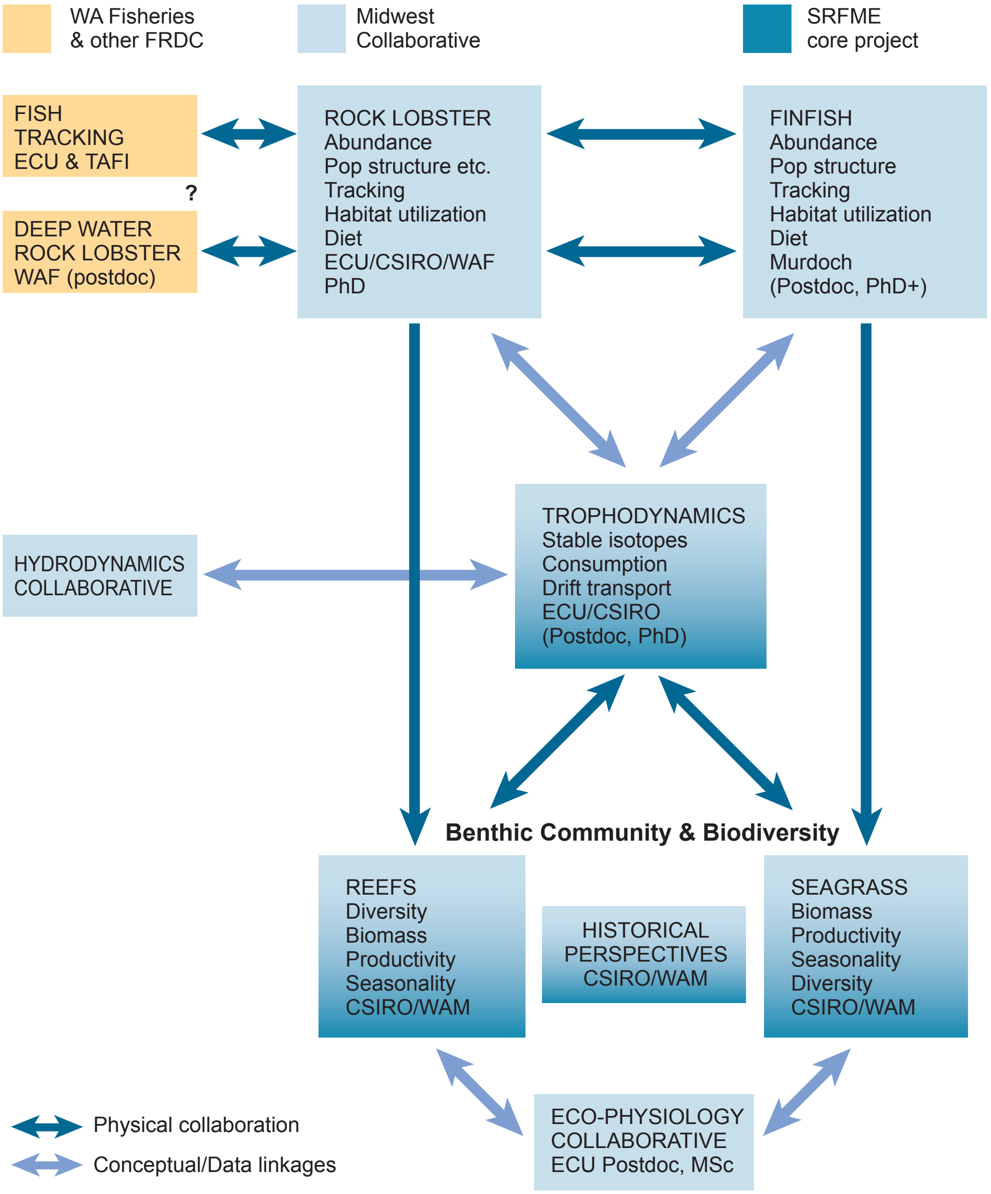

Figure 3.29: Midwest Collaborative Study Ecological interactions. The diagram indicates the main thematic components of the study, key institutional involvements, and their potential inter-relationships.

Objectives

The broad aim of this study is to determine the habitat use and trophic links of Western rock lobster in the mid-west region. This broad aim will be achieved through investigating the following specific objectives.

1. Determine the densities and size structure of western rock lobster in a range of different benthic habitats;
2. Determine the movement patterns of western rock lobster between reefs and foraging habitats;
3. Investigate dietary changes of western rock lobster with changes in size, habitat use and season; and
4. Provide baseline data that will allow the success of sanctuary zones in terms of increasing lobster abundance to be assessed in the future.

Methods

Lobster densities and population structures are being measured three time a year in October/ November, February/ March and July/ August on reefs less than 20 m depth. These sampling times allow comparisons of lobster abundance immediately before and after the 'whites' migration to deep water reefs as well as between open and closed seasons. Study sites are stratified according to habitat type, reef depth and cross-shelf location to account for physical habitat variability. In addition, sites are stratified with respect to levels of protection from fishing pressure, and include sanctuary zones, zones open only to commercial rock lobster fishing, and zones open to all kinds of fishing. Reef size, size of sanctuary and distance from sanctuary will be factored into analyses as co-variates. Sampling is being concentrated in two regions (e.g. Jurien and Green Head). The sampling philosophy is to study these areas within the Jurien Bay Marine Park intensively, rather than study all the zones in the park extensively. Portions of the core survey will be conducted in collaboration with CSIRO Marine Research as required to complete or extend the design as required.

Adult and sub-adult lobsters are being censused by divers using 30 x 5 m transects deployed parallel to the reef slope over reef habitat. Within each strata there are three sites, and four transects per site. The Carapace Length (CL) of all lobsters seen within transects is being estimated visually by trained and pre-calibrated divers. Data, including general habitat type, will be recorded in 5m blocks to enable subsequent spatial analysis.

Lobster diet is being determined from the gut contents of lobsters collected by divers within 1 hour of sunrise. Collections have been made in April and October 2006 from eight sites within four habitats (*Amphibolis* meadow, *Posidonia* meadow, shallow macroalgae/ *Amphibolis* pavement and deep sand/ pavement). Guts were taken from as wide a size range as possible and dissected immediately before being preserved in 70% ethanol. Contents are being identified to the lowest possible taxonomic level, classified according to trophic level, and quantified using image analysis of relative abundance.

In addition to gut content analysis, stable isotope analysis, to determine the levels of $\delta^{13}C$ and $\delta^{15}N$ in lobster flesh, is being conducted on the lobster collected from the habitats outlined above. Samples of primary producers, e.g. algae and seagrass, and potential lobster prey, e.g. gastropods and crustaceans, have also been collected concurrently from the same sites or sites adjacent to lobster collection sites. This will allow for the identification of primary producers and prey that are likely to contribute most to lobster production.

Lobster movements are being assessed across a range of spatial scales using several techniques. Standard Capture-Mark-Recapture using "spaghetti" tags inserted ventrally between the tail and carapace have been used to attempt to capture some information from the commercial and recreational fisheries. A subset of these animals have been tagged using colour coded tags placed around the base of the antennae and will allow for medium term re-sighting and identification of lobsters by divers. This method allows animals to be individually identified without handling and has proven useful in assessing levels of site fidelity over periods of 6-12 months.

Twenty four lobsters have been tagged using acoustic tags attached dorsally to the carapace using cable ties. This is allowing larger scale movements of animals to be tracked with an accuracy of approximately ±100 m using an array of receivers covering an area of approximately 19 km^2. In particular, 4+ and 5+ year class animals have been targeted post-moulting in November and December 2006 as "whites". Most will be expected to take part in offshore migrations and may be picked up by offshore acoustic arrays, however some may remain in near-shore waters and establish long-term residence there (in the absence of fishing mortality). Therefore, in order to establish whether some animals remain resident on coastal reefs, the tracking is being conducted in the Boullanger sanctuary zone.

In addition, 18 lobster have been tracked over three sites differing in surrounding benthic habitat in order to assess important foraging habitat and lobster foraging range over typical coastal benthic habitats. These lobster have been tagged with acoustic tags in the manner outlined above and tracked using a boat operated acoustic receiver and directional hydrophone. Lobster were tracked during February 2006.

Results and Discussion

Lobster density and size-structure

Lobster density and population structure have been measured on coastal reefs during four sampling periods to date: November 2004, February /March 2005, August 2005 and November 2005. A further two trips remain (February /March 2006 and August 2006). The reefs surveyed are stratified by depth, distance from shore and major benthic habitat in order to determine how these factors may influence lobster density and population size-structure. In addition, some of these reefs are located within sanctuary zones and results will provide baseline data for examining the impact of these no-take zones on lobster populations. Reefs are sampled by SCUBA with the number of lobster and size estimates recorded over 4 replicate 30 x 5 m transects.

Results indicate that there is high inter-site variability in lobster densities as well as variability between sampling times (Fig. 3.30). There does not appear to be any clear relationship between habitat type and lobster densities nor between distance from shore and lobster density. For the midshore sites which were sampled on all occasions there does appear to be higher densities during November 2004 and 2005 than at other sampling times. The highest lobster densities were found at two inshore, seagrass dominated sites in November 2005 although further sampling is required to assess if this trend will repeat during subsequent years. A number of offshore sites have not been able to be sampled consistently due to high swell conditions (Fig. 3.30).

Length frequency histograms reveal that the carapace length (CL) of the majority of lobsters sampled fall between 45 and 80 mm (Fig. 3.31). Lobsters between 60 and 90 mm CL are found at nearshore, midshore and offshore sites, however smaller juveniles between 45 and 60 mm CL are more abundant in midshore and particularly nearshore sites and have not been recorded from offshore sites. For those sites located midshore there does not appear to be any relationship between lobster size and habitat type in that all sizes of lobster are found at both seagrass and macroalgae dominated habitat (Fig. 3.31).

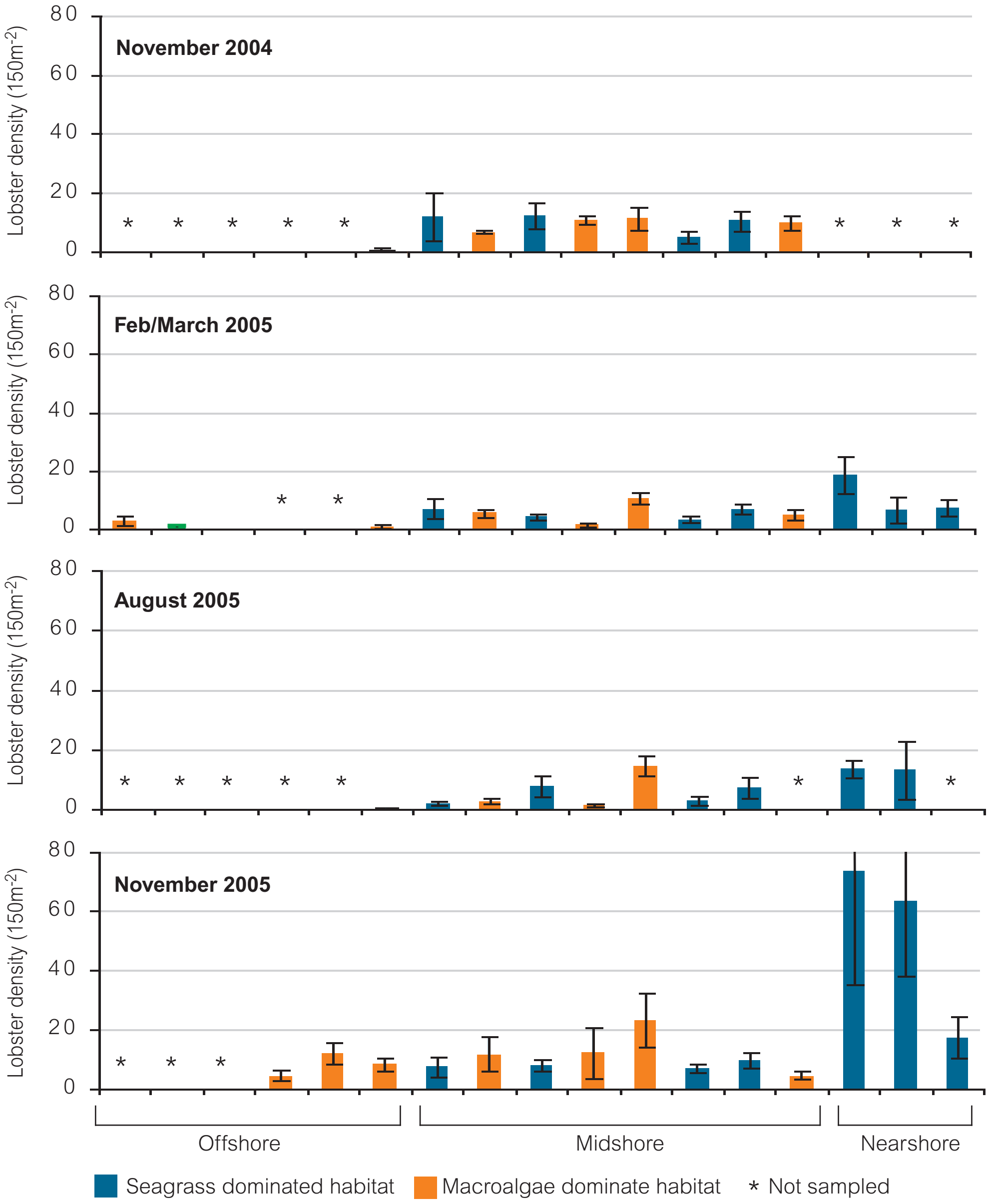

Figure 3.30: Density of lobster (± 1 se) surveyed between November 2004 and November 2005. "*" indicates site not sampled.

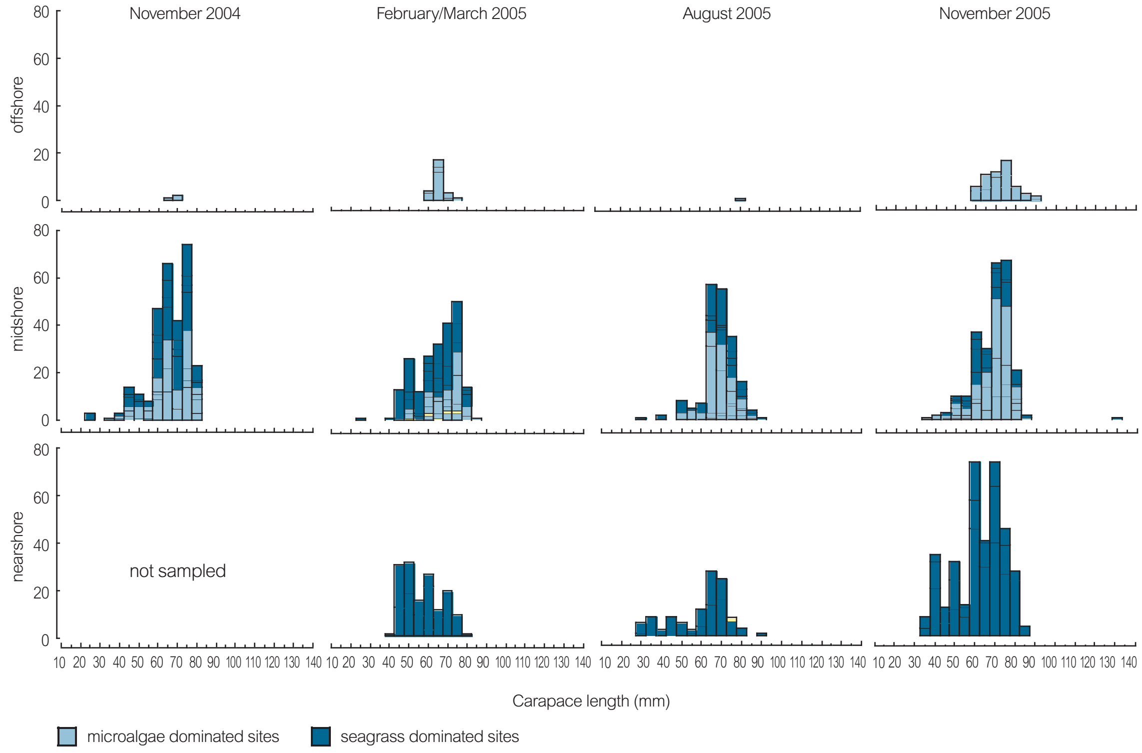

Figure 3.31: Carapace length frequency histograms of lobster collected between November 2004 and November 2005.

Lobster diet and trophic linkages

To investigate the diet and trophic interactions of western rock lobster 193 gut and stable isotope samples have been collected. Lobster were collected from four benthic habitat categories and from as wide a size range as possible (Table 3.4)

Table 3.4. Lobster numbers collected in April and October/ November 2005

	Habitat							
	Deep low seagrass		Shallow pavement/ *Amphibolis*		*Posidonia sinuosa* meadow		*Amphibolis griffithii* meadow	
Carapace length size class (mm)	**Site**							
April 2005	DC	DW	FN	FW	FS	OR	FE	BK
26-50	1	0	1	0	0	1	1	1
51-75	16	8	12	5	13	6	12	9
76-100	0	1	0	1	3	2	2	5
All sizes	17	9	13	6	16	9	15	15
October/ November 2005								
26-50	0	1	0	1	0	0	2	0
51-75	5	7	14	14	8	2	7	10
76-100	2	2	0	3	3	3	4	5
All sizes	7	10	14	18	11	5	13	15

Lobsters were collected within two hours of sunrise to minimise digestion of gut contents. Gut samples were then stored in 70% ethanol whilst flesh samples were frozen as soon as possible. To determine lobster diet, guts have been dissected and the volume of prey items contributing to each gut determined. This has been conducted for 50 of the guts collected to date.

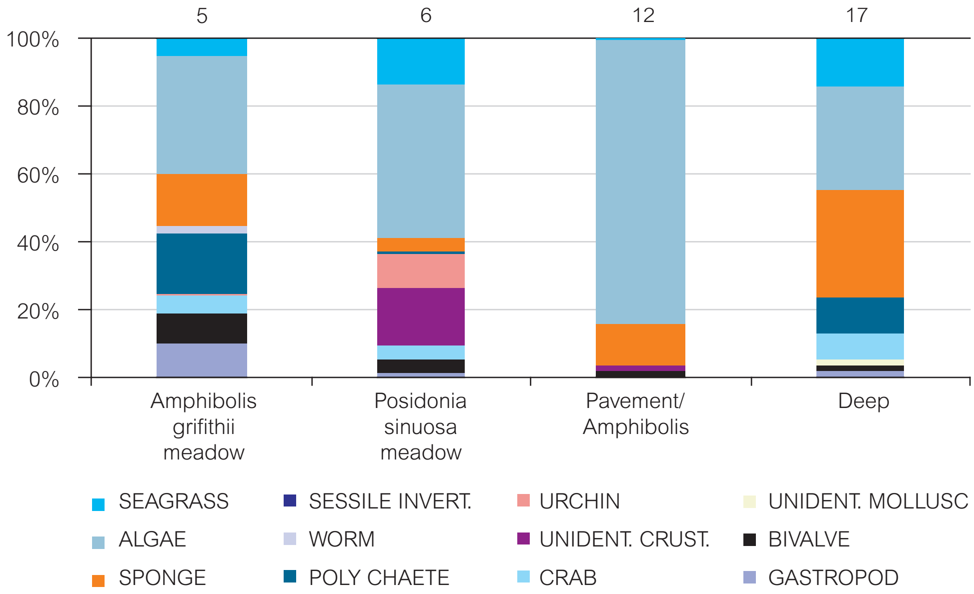

Figure 3.32: Major taxa contribution to total gut volume for lobster collected from four habitats during April 2005.

Preliminary results indicate that algae contribute greatly to overall gut volume for lobster from all habitat categories (Fig. 3.32). These algae comprise mainly articulated coralline algae such as *Haliptilon* and *Metagoniolithon* sp. Seagrass, sponge and polychaetes also comprise a relatively large proportion of gut volume in general. These results, although preliminary, indicate that lobster collected from shallow pavement/ *Amphibolis* habitat have a greater contribution of algae to their diets when compared to lobsters from other habitats, and consume only relatively small quantities of other food sources.

Stable isotope analysis, to determine the levels of $\delta^{13}C$ and $\delta^{15}N$ in lobster flesh, has been completed for a subset (87) of samples from the April 2005 collection period. Samples collected from the October/ November period are yet to be analysed. In addition, samples of primary producers, e.g. algae and seagrass, and potential lobster prey, e.g. gastropods and crustaceans, have been collected concurrently from the same sites or sites adjacent to lobster collection sites. This will allow for the identification of primary producers and prey that are likely to contribute most to lobster production.

Results from April 2005 indicate that whilst coralline algae such as *Haliptilon* and *Metagoniolithon* contribute a large amount to gut volume, the average $\delta^{13}C$ for these prey items are quite separate from that of lobster tissue (Fig. 3.33). This may indicate that other food sources may contribute more to lobster production.

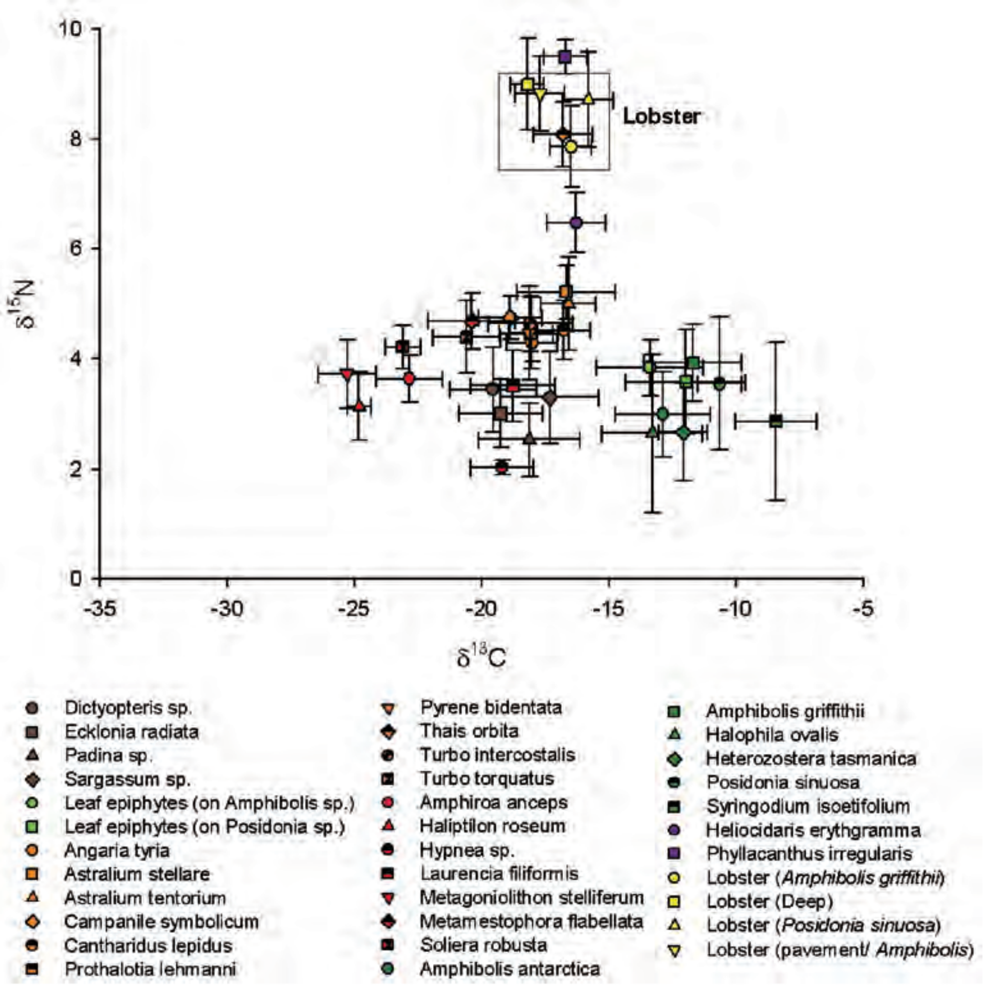

Figure 3.33: δ^{13}C and δ^{15}N signatures of lobster, primary producers and potential prey items collected from Jurien Bay during April 2005.

Lobster Movements

Lobsters movements are being assessed by the use of acoustic tags to study large-scale movements such as migration and nightly foraging movements. Twenty four lobsters have been tagged in the Boullanger sanctuary area within an array of fixed receivers. These receivers record lobster identification and time of reception when lobsters move within range. Lobsters were tagged in early December 2005 and we anticipate that migration movements may be recorded when data is uploaded and analysed.

Additionally, 18 lobsters have been tagged in three distinct benthic habitats (*Posidonia sinuosa*, *Amphibolis griffithii* and deep macroalgae habitat) and tracked using a manual receiver to determine foraging position during the night. On analysis, this data should reveal which habitats are used by foraging lobster and indicate how far lobster move during nightly foraging activities.

Acknowledgements

We wish to thank all the staff, students and volunteers who have assisted with the fieldwork to date. We also acknowledge funding support and in-kind support from the Strategic Research Fund for the Marine Environment, The Centre for Ecosystem Management and the School of Natural Sciences, Edith Cowan University.

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Conference attendance and presentations

The main objective of the outputs and extension plan is to provide regular updates on the progress of the study to the funding body and stakeholders, and finally provide coastal managers with information pertaining to the linkages between different habitats within a marine mid-west coastal marine environment.

Information arising from the study will be disseminated through scientific publications, reports and presentations. Progress reports will regularly be provided to SRFME and a final report will summarise the overall findings. Scientific Publications will be submitted to appropriate peer-reviewed journals. Seminars will be presented at SRFME Symposia, relevant national and international conferences, and where deemed necessary, interest groups. A web site will be constructed and continually updated to inform stakeholders of new results.

Methods and preliminary results from the Rock Lobster Project have been disseminated through a PhD research proposal seminar within the School of Natural Sciences entitled "Habitat use, movements and trophic linkages of the western rock lobster within the Jurien Bay Marine Park".

A seminar of the same name was also given at the Australian Marine Sciences Association postgraduate student workshop held at Rottnest Island, 30 June - 1 July 2005.

Publications and/or outcomes to date

The study will provide descriptions of abundance, population structure, diet, home range and seasonal movement patterns of rock lobster in Jurien Bay Marine Park, thereby providing information on the temporal and spatial habitat utilization and population structure of western rock lobster and any ontogenetic, temporal and spatial shifts in its diets. The study will provide a sound basis for understanding trophic relations at higher levels and will lay the groundwork for understanding what, if any, are the direct and indirect effects of fishing on coastal ecosystems. Furthermore, in combination with the compilation of data from the other related projects within the program, this study will help establish baseline data on the biodiversity and ecology of Jurien Bay Marine Park. Such base-line data is essential for assessing whether the size of current management zones within the marine park are adequate, and for future assessment of the effectiveness of management zones in the newly established Jurien Bay Marine Park.

3.3.6 Ecophysiology of Benthic Primary Producers

Investigators / Institutions

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Dr Russ Babcock	Marine and Atmospheric Research, CSIRO
Dr Ray Masini	Department of Environment (WA)
Dr Kathryn McMahon	Centre for Ecosystem Management, Edith Cowan University

Executive Summary

Reduction in the availability of light, due to a range of anthropogenic activities, has been identified as a major cause of benthic habitat loss. Understanding the role of light as a driver of ecosystem integrity is fundamental to managing the State's benthic marine ecosystems. Such knowledge can underpin the development of environmental quality criteria and identify indicators of sub-lethal stress in marine ecosystems, permitting early management intervention. To help fill current knowledge gaps, this project aims to determine the effect of different intensities, durations and timing of light reductions on *Amphibolis* ecosystems and to determine the subsequent patterns of recovery. The project is in its second year, and is due to be completed in late 2007.

In a two-phase project the response of the meadow-forming seagrass *Amphibolis griffithii* (Black) den Hartog to light reduction was examined. The first phase examined severe (>90%) light reductions over a 3-month period and a subsequent one month recovery period. The second phase examined the effects of varying the intensity and duration of light reductions. Morphological and physiological variables were measured in meadows subjected to reduction in light and in control plots. In the first phase experiment, leaf biomass, leaf cluster density and the number of leaves per cluster all declined in shaded plots and after 3 months were about 30%, 50% and 60% of the controls, respectively. Leaf extension was one third that of the control plots. Epiphyte biomass in shaded plots was 44% of the controls after 6 weeks shading and 18% after 3 months shading. Leaf chlorophyll concentration was affected by shading, but only in the upper canopy: shaded leaves had 55% more chlorophyll than control leaves. Shading reduced the carbohydrate stored in the rhizomes of shaded plants: sugars declined rapidly and continuously and after 3 months were less than 20% of controls; a decline in starch concentrations lagged that of sugars. All variables showed a significant shift towards the values in control plots 42 days after removal of shading, indicating capacity for recovery, though in many cases these remained significantly lower than the controls.

In the subsequent, phase 2 experiment significant reductions in seagrass and algal biomass were observed following three, six and nine months of moderate and heavy light reduction in plots shaded at the end of summer, where the maximum carbohydrate reserves were expected. After nine months shading no leaves remained. The abundance of macroinvertebrate fauna also reduced after 3 months of shading. In direct contrast to the phase 1 study, there was no recovery in the plots shaded for three and six months up to four months after shading was removed. Additional samples will be taken to determine when the shaded plots return to the same conditions as the control plots. There was some recovery in algal epiphyte biomass, though it did not return to control conditions. This implies that three months of continuous shading on *Amphibolis* meadows has a significant impact on the flora and fauna in the ecosystem and recovery will not occur in the short-term, though the basis of the contrast in Phase 1 and Phase 2 outcomes for seagrass recovery remains unclear and is being investigated further.

From our results, the minimum light requirements of *A. griffithii* are estimated at greater than 10% of surface irradiance. *A. griffithii*, its epiphytes and the associated fauna respond rapidly to severe, short-term reductions in light availability. Ongoing work will determine the longer-term recovery, if any, and apply the finding to the development of criteria for assessing the potential significance of light reduction in *A. griffithii* ecosystems.

Introduction

Light is probably the single most important environmental factor controlling coastal benthic primary productivity. A broad range of coastal and marine developments can lead to a reduction in PAR availability at the seabed. In this context, understanding of light and its co-variates as a driver of ecosystem structure is of fundamental importance for the management of the State's marine environment.

Robust and ecologically meaningful indicators of sub-lethal environmental stress must underpin such management. Sound science to inform the development of these indicators and their associated criteria is therefore critical to achieving sustainability in Western Australia. The objectives of this research program are to fill gaps in our understanding of how ecosystems respond to variation in light, in order to improve our ability to understand variations in habitat structure at the ecosystem level and to assess and manage impacts associated with human use of these systems.

Key benthic habitats along the central west coast for which scientific research is required are primarily seagrass meadows and macroalgal reefs. There are particular gaps in the understanding of the effects of light stress on *Amphibolis* species (*A. antarctica* and *A. griffithii*). In the context of allowing the correct balance to be struck between protecting the environment without unnecessarily constraining development, quantitative assessments of the degree of light reduction that can be sustained without irreversible or long-term damage are urgently required.

Only by conducting controlled field experiments that involve the manipulation of known factors are we able to limit the relative contribution of potentially confounding factors to the research outcomes. The research project involves the establishment of treatment and control sites to determine the effect of reduced PAR and the timing and duration of light reduction on *Amphibolis* ecosystems.

Aims/objectives

1. To determine the effect of different intensities, durations and timing of light reductions on *Amphibolis* ecosystems; and
2. To determine the subsequent patterns of recovery.

Methods

A two-stage approach was used to address the aims. In stage 1, a preliminary field experiment examined the effects of intensive, short-term shading on *Amphibolis griffithii* meadows. This yielded important information on the response to light reductions and also clarified key variables to be measured in Stage 2.

Stage 2 comprised of a more extensive field experiment in which *A. griffithii* ecosystems were subjected to a range of intensities and durations of light reduction and with these treatments commencing at different times of year. Stage 2 commenced in March 2005 and is due to finish in November 2007. The results presented here are, therefore, interim.

Study Site

Both stages of the project were conducted at Jurien Bay, a relatively pristine system on the central Western Australian coast. The Jurien Bay region is dominated by seagrass, patchy sand and macro-algal reef habitats. The study site was located on an extensive (> 6 ha) *Amphibolis griffithii* meadow, on level bathymetry with an approximate depth of 4.0–4.5 m, located 200-300 m NE of Boullanger Island (308402E 6645234N; WGS84 datum). The site was sheltered from the predominant south-westerly winds and swells.

Stage 1 Experiment – High Intensity, short duration Light Reduction

A Before After Control Impact Repeated measures (BACI-R) field experiment was conducted in late summer, the period when *Amphibolis griffithii* plants have their highest levels of carbohydrate storage reserves (Carruthers & Walker 1997) and, possibly, the greatest capacity to withstand reductions in light availability.

Replicate treatment plots (n=4) of *A. griffithii* meadow were subjected to 80% PAR attenuation by shade screens for 106 days, the intensity and duration reflecting those observed in areas adjacent to harbour dredging programmes in the region (Unpublished data, Geraldton Port Authority). Each experimental unit measured 4.5 m x 3.0 m and was covered by a shade screen suspended on metal pickets. Control plots were constructed as above but lacked the suspended shade cloth. Attempts to establish procedural controls, with monofilament net suspended from the pickets, proved useless; they fouled rapidly with epiphytic algae, resulting in a 20-30% reduction in PAR after a few days. Consequently, the procedural controls were abandoned. Previous attempts at maintaining procedural controls for shading have also appeared futile (Bulthius 1983; Collier unpubl).

To validate the reduction in light availability in the treatments, photosynthetic photon flux density (PPFD) was measured at the top of the seagrass canopy across the plot, using a Li-Cor™ quantum photometer. The final workable area used for experimental sampling was approximately 4.5m^2 in the centre of the plots.

Morphological and physiological variables were sampled just prior to imposing the treatments and after 42, 66 and 106 days. After 106 days the shade screens were removed from the treatment plots and all plots were re-sampled after a further 42 days to test for any evidence of recovery following removal of shading.

Differences within and between treatments over time were tested using repeated measures ANOVA, with treatment and time as fixed factors. Prior to conducting ANOVA, all data were tested for compliance with assumptions of homogeneity of variance and normality. Non-compliant data were transformed as per the recommendations of Fowler & Cohen (1990).

Stage 2 Experiment – Multiple intensities and durations and timing of light reductions

Following analysis of the Stage 1 experimental outcomes, a second BACI-style field experiment was established in the study area with three main effects: intensity (high, medium or none), duration (0, 3, 6 or 9 months) and timing (end of winter or summer, to coincide with minimum and maximum carbohydrate reserves) of PPFD reduction. The intensities and durations of shading reflect those typically resulting from dredging programmes in the region (Unpub, Geraldton Port Authority).

Experimental units were constructed as in Stage 1 but with either 80% or 50% light attenuating shade screens. Five replicate plots have been established for each intensity-duration-timing combination, yielding an orthogonal design with 120 plots. Morphological and physiological variables (Table 3.5) have been sampled prior to imposing the treatments (T_o) and after 3, 6 and 9 months of treatment. The plot is re-sampled 3 months after removing shading (recovery period).

Table 3.5. Variables collected in Stage 1 and 2 of the research project.

Variable

Collected in Stage 1 & 2	**Collected in Stage 2 only**
Above- & below-ground seagrass biomass (leaf, stem, root and rhizome)	Epiphytic and epibenthic faunal composition & biomass
Seagrass morphology (height; stem, cluster & leaf density, leaf length & width, Leaf Area index)	Benthic infauna composition & biomass
Algal epiphyte biomass and composition	MPB composition and relative biomass
Leaf extension rates	Sediment composition and chemistry
Pigment concentration (seagrass leaves and selected algal epiphytes)	C^{13}, N^{15} and fatty acid signatures of fauna and primary producers
Carbohydrate concentrations (seagrass leaves & rhizome)	

In addition to the variables sampled in Stage 1, Stage 2 involves the collection and analysis of fauna and microphytobenthos samples, to determine any consequences of light reduction or seagrass loss for these components of seagrass ecosystems.

Sampling Methods

Photosynthetic Photon Flux Density (PPFD)

PPFD (µmol photon $m^{-2} s^{-1}$) was measured at the top of the seagrass canopy in one randomly chosen control and treatment plot using 'Odyssey Dataflow' submersible incident light sensors with an automated wiper unit to keep the sensor clean. PPFD attenuation through the water column, shade screens and seagrass canopy was determined during and after shading using a Li-Cor™ LI1000 quantum photometer.

Meadow morphology and biomass

Stem density (m^{-2}), percentage cover and maximum and average canopy heights (cm) were measured non-destructively in permanent 0.04 m^2 quadrats in the centre of each experimental plot, as per Duarte & Kirkman (2001). Above-ground biomass was measured destructively from a 20 x 20cm (0.04 m^2) quadrat placed randomly in each plot and separated into leaf, stem and epiphyte components. A core sample (11cm i.d., 0.01 m^2, 20 cm deep) was collected from inside the same 0.04 m^2 quadrat to quantify below-ground biomass (g DW m^{-2} of root, rhizome and detritus).

Leaf productivity, pigments and carbohydrates

Leaf extension was measured over the 2 weeks preceding sampling events, using the procedures of Short & Duarte (2001). Leaf clusters were collected from both the top and bottom of the leaf canopy for pigment and carbohydrate analysis. A 30 mm section from the youngest mature leaf was analysed for chlorophyll following the methods described by Granger & Iizumi (2001) and Longstaff & Dennison (1999). to ensure fully developed pigment characteristics (Hemminga & Duarte, 2000). Total soluble sugars and starch analyses were performed on ground, dry leaves and rhizomes twice extracted in hot 80% ethanol. Spectrophotometric concentrations were determined as per Dubois & Gilles (1956). Starch content of the remaining material was analysed according to Quarmby and Allen (1989).

Fauna

Epibenthic and epiphytic fauna are collected in calico bags lowered over 0.04 m^2 of seagrass canopy. Benthic infauna are collected by coring sods of sediment (11 cm diameter, 15 cm deep). Fauna are being separated into the size categories of Edgar (1990) to allow biomass and secondary production estimate to be made.

Results

Response to high intensity, short duration light reduction

The seagrass canopy in the shaded treatment plots received 10% of the PPFD in control plots, indicating that the shade screens attenuated 90% of the incoming PPFD. At the end of the shading experiment, there were significant differences in the PPFD attenuated by the canopy in the shaded and control plots (LAC = 2.38 and 0.59 m^{-1}, respectively), representing almost two orders of magnitude difference in light penetration. Once shade screens were removed, the differences in canopy attenuation coefficients resulted in far greater penetration of PPFD through the previously shaded canopies, with 68 ± 7 μmol m^2 s^{-1} reaching the bottom of the previously shaded plots and 10 ± 1 μmol m^2 s^{-1} reaching the bottom of the control plots (Fig 3.34).

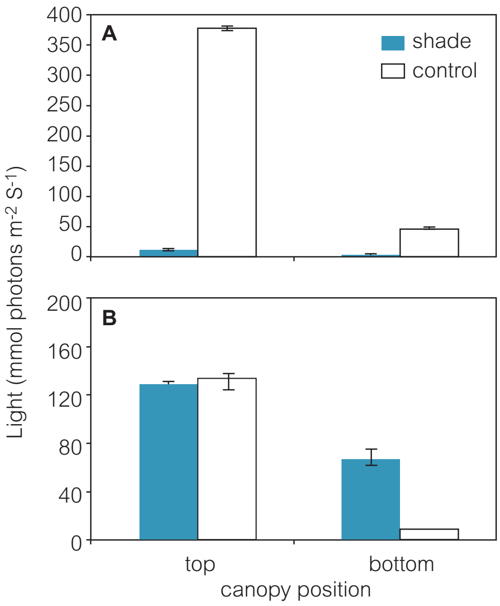

Figure 3.34: Light (PPFD) at the top and bottom of *Amphibolis griffithii* canopies that were subjected to shading (dark) or controls (open). A = during the shading period and B = immediately after removal of shading screens.

Above-ground morphology & biomass

The most obvious effect of shading was a dramatic reduction in the number of leaves and leaf biomass. Total leaf biomass displayed marginal increases over time in the control plots, but declined significantly in shaded plots (Fig 3.35; Table 3.5). After 106 days, the shaded plots had about one-third of the leaf biomass in unshaded plots (150 ± 38 g m^{-2} and 452 ± 103 g m^{-2}, respectively). Following removal of the shade screens, leaf biomass increased in the shaded plots and, after 42 days, was similar to the controls.

The reduction in leaf biomass in the shaded plots was due to a loss of leaves from each stem, in each cluster and from a reduction in the number of leaf clusters (Fig 3.35). Following removal of shading, the numbers of leaves per stem and the density of clusters in the shaded treatment increased and after 42 days were similar to the controls. The differences in the number of leaves per cluster persisted after shading treatment was removed.

Stem biomass and stem density in both treatment and control plots remained relatively stable and ranged from approximately 250 – 400 g DW m^{-2} and 250 – 400 stems $m\text{-}^{2}$ throughout, respectively (Fig. 3.35), as did canopy heights (average heights ranging from 25 – 38 cm; Fig 3.35).

Epiphyte biomass followed a similar trend to leaf biomass, remaining relatively constant in the control plots but declining in the shaded plots (Fig 3.35). After 42 days of shading epiphyte biomass was less than half that in the control plots (211 ± 122 and 476 ± 200 g m^{-2}, respectively) and at the end of the shading period was less than 20% of that in the control (92 ± 82 and 500 ± 29 g m^{-2}, respectively). By the end of the recovery period, 42 days after shading had been removed, these differences were much reduced.

Root biomass, rhizome biomass and detrital biomass remained relatively stable throughout the study with little difference between treatments and control (Fig 3.36).

Physiological and growth responses

Leaf extension in control plots remained constant over the experimental period, at about 0.6 mm $leaf^{-1}$ d^{-1} but in the treatment plots decreased to approximately one half and one third of this after 66 and 106 days of shading, respectively (Fig 3.37). In the recovery phase (after removal of shading), the differences between control and shaded plots persisted after the first 12 days but were not significant after 42 days. Areal leaf production (mm m^{-2} d^{-1}) followed similar patterns to leaf extension rates (Fig 3.37).

In the rhizomes, sugar concentrations declined sharply in the shaded treatments but remained relatively constant in the controls (Fig 3.38A). At the end of the shading period rhizome sugar concentrations in shaded treatments were 19% of the controls. Following removal of shading, rhizome sugar concentrations increased but were still significantly lower than the controls. Concentrations of starch in the rhizome declined significantly with shading, to 50% of the controls and showed only a minor increase 42 days after removal of shading (Fig 3.38B).

In the leaves, total soluble sugar concentration was significantly affected by shading but not starch concentrations (Fig 3.38C,D). After 38 days, the sugar concentrations in the shaded treatments were 47% of that in the control plants. For the remainder of the shading period, the concentration of sugars in the shaded leaves remained constant while in the controls it fell, so that by the end of the shading period, and throughout the recovery period there were no significant differences between the two. Concentrations of starch in the leaves at the start of the experiment were significantly higher in the treatment plots than controls, making control vs impact comparisons difficult.

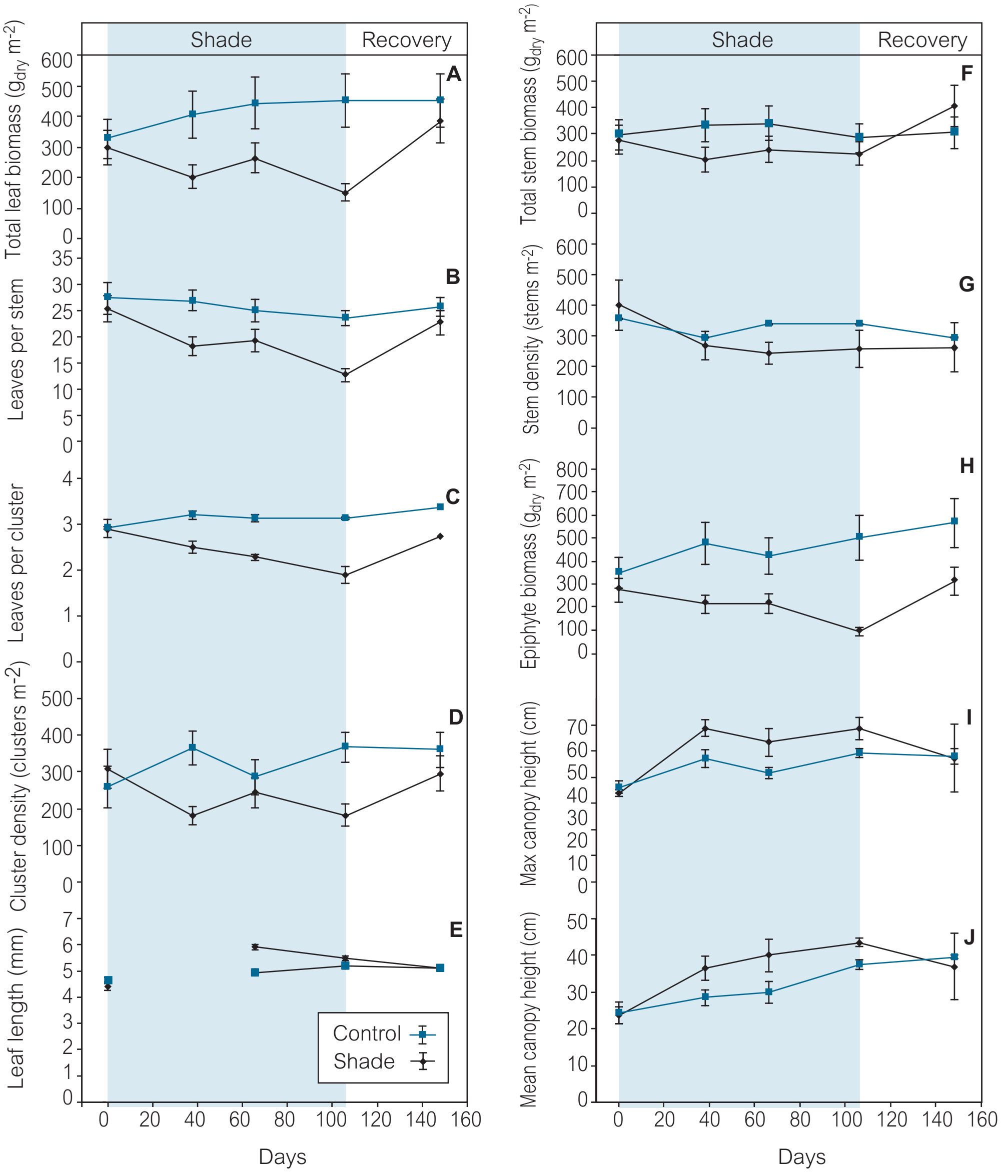

Figure 3.35: Above ground shoot and meadow characteristics of *Amphibolis griffithii* meadow meadows during shading and subsequent recovery periods in shaded (black) and control (grey) plots. A) leaf biomass, B) leaves stem^{-1}, C) leaves cluster^{-1}, D) cluster density, E) leaf length, F) stem biomass, G) stem density, H) epiphytic algae biomass, I) maximum canopy height, J) mean canopy height. Data are means (n=4) ± SE.

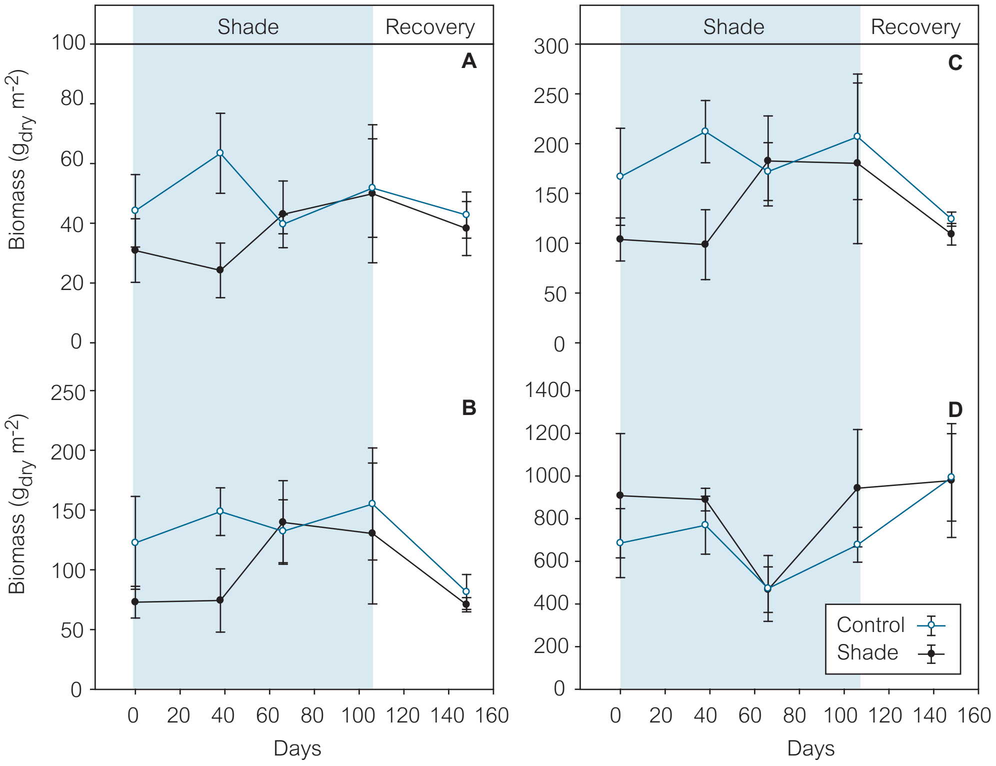

Figure 3.36: Below-ground biomass characteristics of *Amphibolis griffithii* meadow during shading and subsequent recovery periods in shaded (black) and control (grey) plots. A) Total below-ground biomass (rhizome + root + detritus), B) rhizome biomass, C) root biomass, D) detritus biomass. Data are means (n=4) ± SE.

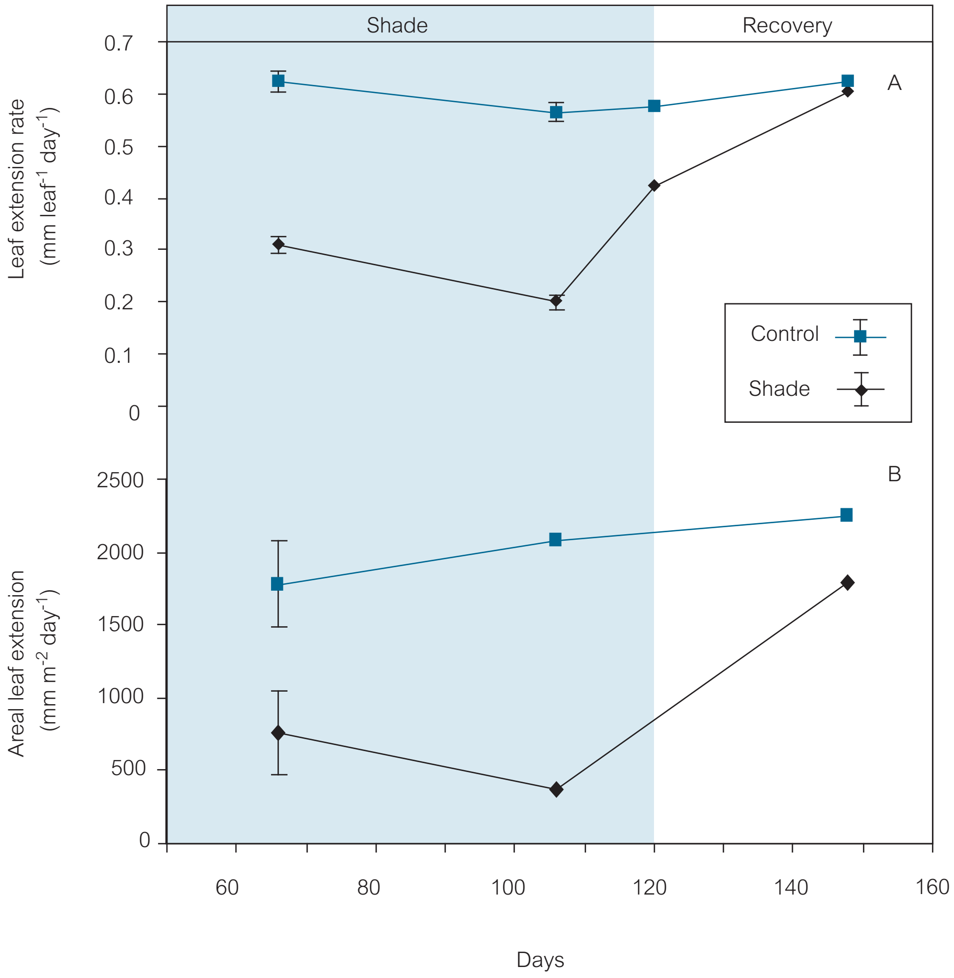

Figure 3.37: Leaf extention rates (A) and aerial leaf extension rates (B) in *Amphibolis griffithii* meadow during shading and subsequent recovery periods in shaded (black) and control (grey) plots. Data are means (n=4) ± SE.

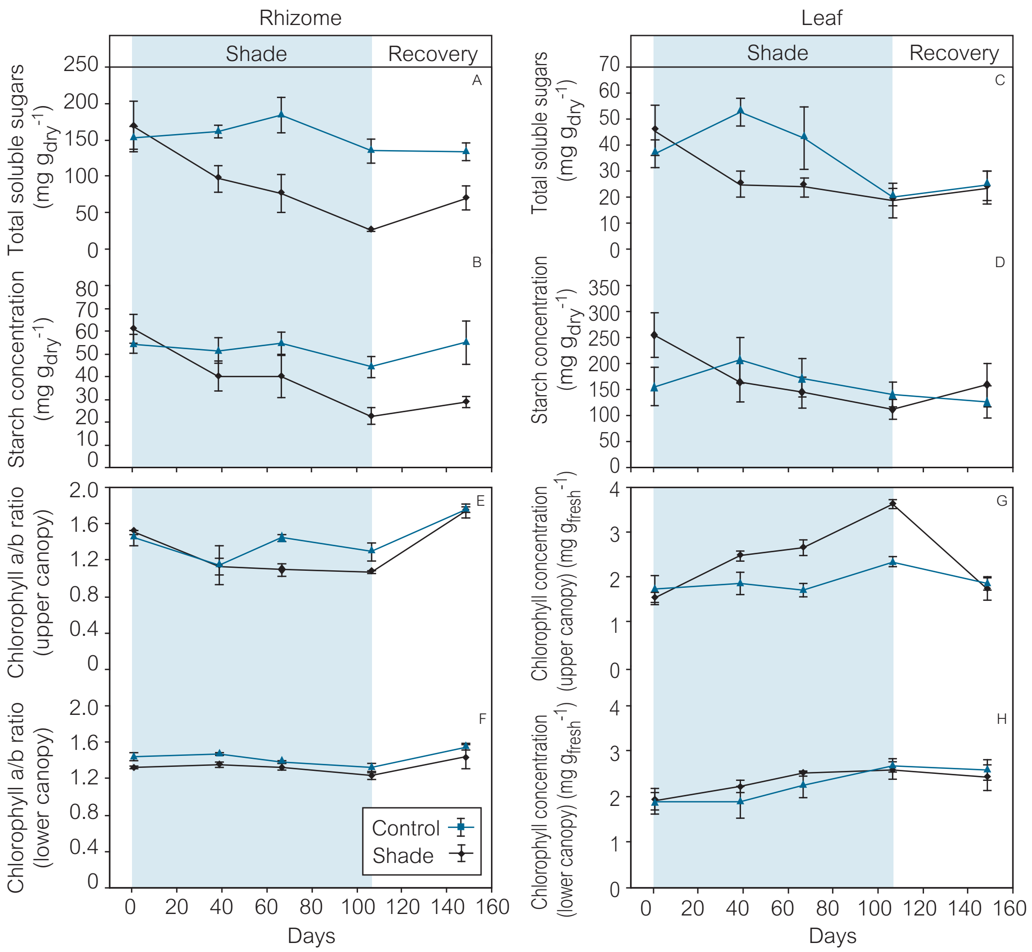

Figure 3.38: Carbohydrate and chlorophyll characteristics of *Amphibolis griffithii* meadow during shading and subsequent recovery periods in shaded (black) and control (grey) plots. A) soluble sugars in the rhizome, B) starch in the rhizome, C) soluble sugar in leaves, D) starch in leaves, E) chl *a*/*b* in upper canopy leaves, F) chl *a*/*b* in lower canopy leaves, G) chl (*a*+*b*) in upper canopy leaves, F) chl (*a*+*b*) in lower canopy leaves. Data are means (n=4) ± SE.

Shading had a significant effect on the chlorophyll concentration of leaves but only in the upper canopy (Table 3.5 & Fig 3.38F). At the start of the shading period shaded and control plants had similar concentrations of chlorophyll in upper canopy leaves (about 1600 ug chl g^{-1}) but after 66 days the mean concentration was higher in control leaves and after 106 days had increased to 3.6 ± 0.1 mg chl g^{-1} in shaded plants, 55% greater than control plants (2.3 ± 0.1 ug chl g^{-1}). Once shading was removed, the chlorophyll concentration of the upper leaves in the shaded treatments fell and after 42 days were similar to those of the controls.

Response to differing intensities and durations and timing of light reduction

The Stage 2 experimental study extended on the Stage 1 project to examine the effects of differing intensities and longer durations of light reduction, and any effect the timing of light reductions. At this stage, preliminary results are available for different intensities and durations of shading commenced in summer.

The stage 2 results extended the observations from Stage 1 to 6 and 9 months of shading. As in the Stage 1 studies, significant reductions in seagrass and algal biomass were observed after three months of light reduction at the end of summer. After 3 months of shading, above ground biomass had declined to 50% of the controls in the moderate and highly shaded treatments (Fig 3.39). After 9 months, however, no leaves remained in either the moderate or heavily shaded treatments and the above ground seagrass biomass comprised of stems only, being about 40% of controls in moderately shaded plots and 25% in the heavily shaded plots.

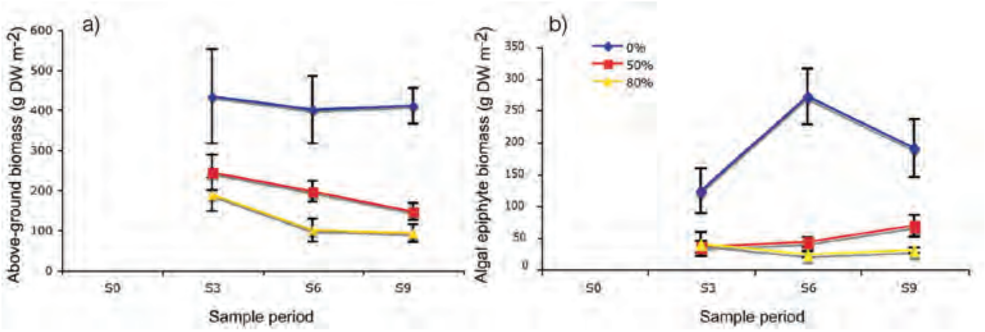

Figure 3.39: Total above-ground biomass (a) of, and algal epiphyte biomass (b) on *A. griffithii* in plots shaded at the end of summer for 3, 6 and 9 months with moderate and high light reduction.

Leaf productivity was significantly lower in the shaded treatments after 3 and 6 months of shading, being about 30% (0.25 mm d^{-1} m^{-2}) and 19% (0.16 mm d^{-1} m^{-2}) of that in the controls, respectively. This reduction was not evenly distributed across all clusters. For example, after 3 months of shading 40% of clusters in moderate shading and 34% in heavily shaded plots showed no growth, while the remainder showed some leaf extension.

The loss of seagrass biomass was paralleled with a loss of epiphyte biomass (Fig 3.39). As in the stage 1 studies, epiphyte biomass fell dramatically in the first 3 months of shading, to about 20% of the controls. This loss was similar under both moderate and heavy shading. After 9 months of shading, the epiphyte biomass was about 28% and 12% of that in controls for moderately and heavily shaded treatments, respectively.

Four months after shading ceased, there was no recovery of above-ground seagrass in the plots shaded for three and six months (Fig 3.40). There was some recovery in algal epiphyte biomass, though it did not return to control conditions.

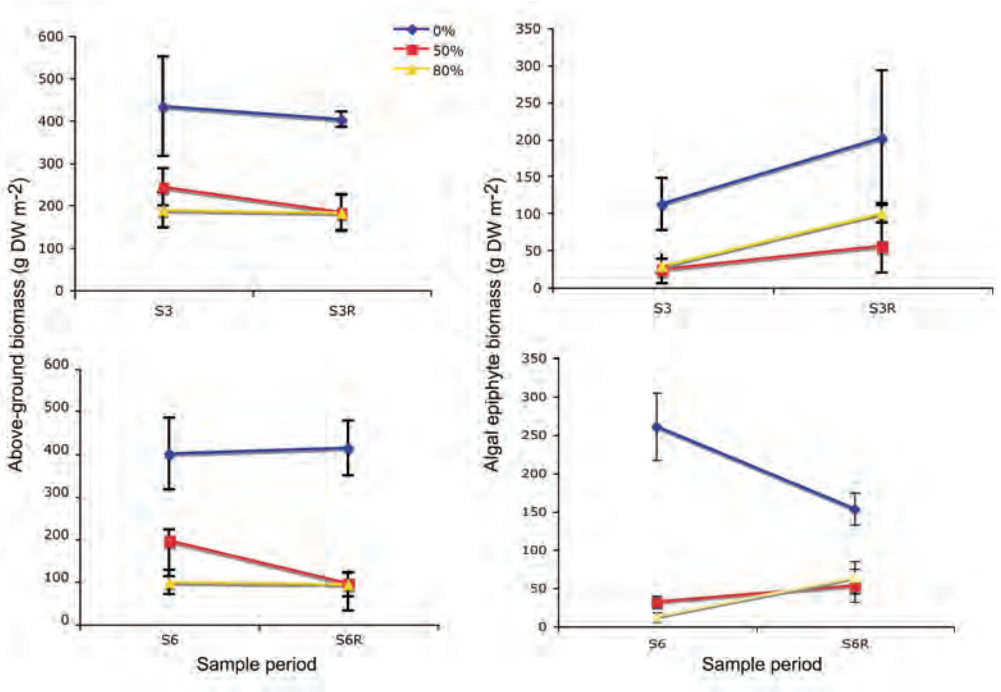

Figure 3.40: Above-ground biomass of and algal epiphyte biomass on *A. griffithii* in plots shaded at the end of summer for 3 and 6 months with moderate and high light reduction, and the recovery of these shading durations.

The abundance of macroinvertebrate fauna in the seagrass canopy also reduced after 3 months of shading (Fig 3.41). This decline was consistent across all three groups of fauna examined, crustacea, molluscs and polychaetes, but was more severe in the heavily shaded treatment than the moderate.

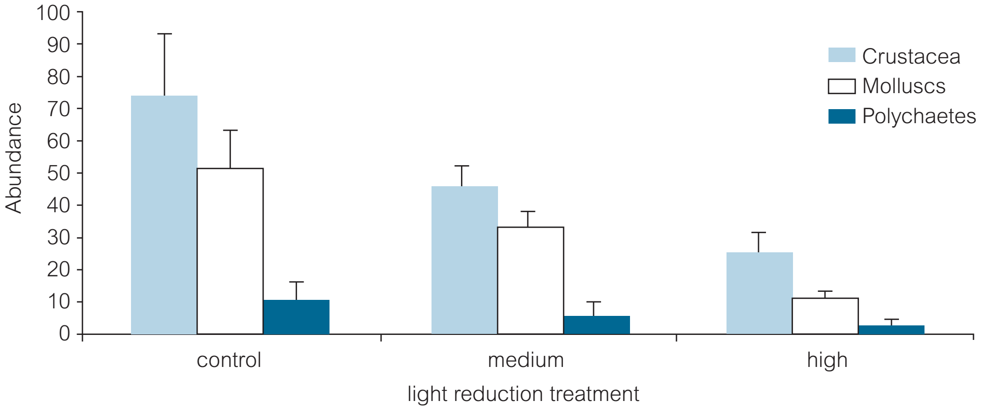

Figure 3.41: Faunal abundance in three taxonomic groupings, crustaceans, molluscs and polychaetes after 3 months shading with moderate and high light reduction.

Discussion

The morphological changes we observed were mainly in the canopy and were consistent with a strategy to reduce carbon-demand of the plants and increase light availability to the leaves that were retained. At the individual stem and shoot level, plants shed leaves from all clusters and stems. Leaves can have respiratory loads up to six times that of below-ground material (Masini et al. 1995) and the above-ground to below-ground biomass ratio in the genus

Amphibolis is approximately 6 (Paling & McComb 2000). Therefore, the dramatic reduction in above-ground tissue that we noted would have the effect of reducing the total plant respiratory load and allow the plant to meet more of its carbon demand from that fixed in the reduced light climate.

The reduction in above-ground biomass at the individual stem and shoot level also had the effect of thinning the seagrass canopy at the meadow-scale and reducing the degree of self-shading, as evident in the lower light attenuation coefficients of treatment canopies after shading. This response has been noted for other seagrasses (Via et al. 1998; Peralta et al. 2005) and may assist in recovery of the remaining leaves once light conditions improve (Carruthers & Walker, 1997).

Presumably, shedding leaves, which have a high-respiratory cost (Masini et al. 1995) was not sufficient to balance the plants' carbon budgets in this experiment, since carbohydrate reserves in the rhizome were simultaneously depleted. In shaded plots, leaf sugars initially declined rapidly following reductions in light, then stabilised. Rhizome sugar concentrations also declined following shading, though this decline continued through the shading period, possibly reflecting ongoing translocation to the leaves. Starch concentrations in the rhizome also declined, but much later than rhizome sugars. The lag in the rate of rhizome starch decline relative to rhizome sugars is indicative of a physiological reallocation of resources (Touchette & Burkholder 2000) found in other seagrasses and probably reflects a reallocation of rhizome sugars and, later, starches to the leaves.

The combined morphological and physiological responses displayed by *A. griffithii* to the reduction in light availability allowed some plants to survive, in a reduced biomass state, for at least 3-6 months of severe reduction in light and 6-8 months of moderate light reduction. While the plants remained functional, they were clearly demonstrating a carbon deficit, and they had lost all their photosynthetic tissue by about 6 months under heavy shading and between 6 and 9 months under moderate shading. Given this, it appears as though the minimum light requirements of *A. griffithii* are probably significantly greater than the global seagrass average of 11% of sub-surface light reported by (Duarte 1991).

Recovery

The majority of variables measured in the stage 1 experiment showed substantial recovery within 42 days. The number of leaves per stem, leaf extension, leaf cluster density, total leaf and total epiphyte biomass and the upper canopy total leaf chlorophyll all displayed full recovery. However, the recovery of seagrass above-ground biomass was not noted in the stage 2 experiment, despite both experiments occurring at the same time of year. The extent and rate of the recovery in the stage 1 experiments suggests *Amphibolis griffithii* is, at times, able to withstand a single episode of high intensity PAR reduction over the timescale of this study (3 months) but the stage 2 results suggest that this is not a consistent capacity. The factors influencing the ability to recover are not clear and are currently being examined. The carbohydrate stores at the commencement of a shading period may be crucial in determining the capacity and rate of recovery and this is being investigated.

Trophic implications

Ecologically, one of the most significant responses noted in the experiment was the rapid decline in epiphyte biomass. The loss of macroalgae in shaded conditions may reflect their limited capacity to store reserves. Alternatively it may have been associated with a shift in top-down control mechanisms induced by the experiment, though we did not monitor herbivore density in the treatments and controls. If the loss of epiphytes was due to light-limitation, it has potentially profound trophic implications. Seagrass epiphytes are an important food source for a range of vertebrate and invertebrate grazers (Nielsen & Lethbridge, 1989; Heck et al., 2000), presumably due to palatability and nutritional value (Klumpp et al. 1992). While it is difficult to extrapolate small-scale experimental results to whole ecosystem consequences, it is clear that if the decline in epiphyte biomass noted here were replicated over large spatial scales then, even ignoring any negative consequences of seagrass loss, the trophic implications of epiphyte loss would be significant, as would the flow-on effects for biodiversity functions of seagrass meadows. The significantly lower abundances of epibenthic fauna after 3 months of shading is further evidence that shading of seagrasses may have profound trophic consequences. The precise mechanism of the decline is unclear, and is the subject of ongoing studies. However, the changes in seagrass that we have observed would affect the quality of the habitat as both a food resource (reduced algal biomass) and shelter (reduced leaf biomass and leaf area index).

In summary, at this point of the project it is necessary to be cautious about over-extrapolating the results. However, it is clear that moderate and severe shading in the order of three months can cause dramatic losses of photosynthetic tissue in *Amphibolis griffithii*, and after 6-8 months almost complete loss. The data on the capacity for recovery are inconsistent, but in some cases we observed no recovery of seagrass biomass up to 4 months after a 3 month shading period. Earlier experiments yield contrasting outcomes, with significant recovery within a month of shading being removed. Clearly, this variability in recovery has important implications in terms of developing management criteria and gaining a better understanding of what drives the highly variable responses will be a priority for the remainder of the project. Ongoing work will also explore in more detail the trophic implications of seagrass loss.

Acknowledgements

We gratefully acknowledge the assistance of post-graduate students and research assistants P. Quintana, M. Mulligan, A. Tennyson and P. Mackey for field, laboratory and data processing and Dr A. Brearley for macroinvertebrate fauna processing, as well as numerous ECU students for field assistance.

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Conference attendance and presentations

6th International Seagrass Biology Workshop, Townsville, QLD: November 2004.

SFRME Mini Symposium – Benthic Ecology of the mid-west coast; April 2005.

Stockholm University – Botany Institute: The effects of light reduction on seagrass ecosystems and the trophic implications.

Publications and/or outcomes to date

Mackey, P., Collier, C. and Lavery P.S. (in review, MEPS). The effects of reduced light availability in *Amphibolis griffithii* ecosystems.

3.3.7 Biodiversity of Marine Fauna on the Central West Coast

Investigators / Institutions

Jane Fromont (Project Leader), Loisette Marsh, Glenn Moore, Mark Salotti, Melissa Titelius, Corey Whisson

Western Australian Museum

Executive Summary

This study was designed to document marine fauna of the Central West Coast. It will provide quantitative information on the proportion of tropical, temperate and Western Australian endemic species of corals, crustaceans, echinoderms, fishes, molluscs and sponges occurring in this biogeographic overlap zone.

The first fieldwork component of the study at Jurien Bay and Green Head was completed in April-May 2005. The second fieldwork component, at Cervantes and Dongara, was undertaken in March 2006.

All specimens from the first field trip have been fine sorted to species level for identification. Echinoderm and fish identifications have been completed while some of the crustaceans, mollusc and sponges are still to be identified. Corals will be identified during 2006.

So far 96 fish species, 54 echinoderm species, 74 mollusc species, 25 crustacean species and 132 sponge species have been documented in this study. Four species of the isopod family Sphaeromatidae collected in this study are new records for Western Australia. Extended species ranges have been determined for nine species of echinoderms found in the area: seven northwards from the Fremantle – Rottnest area and two southwards from Dongara and Shark Bay.

The preliminary results from this study suggest a greater incidence of temperate species of fishes, molluscs, echinoderms and crustaceans in the Jurien Bay and Green Head area, confirming the dominance of temperate species in this region. Preliminary results from mollusc and echinoderm identifications show 20% and 32% of the species respectively are west coast endemics.

Fewer echinoderm species were found in the Jurien Bay and Green Head area (54 species) than in Albany (81 species) or at Rottnest Island (86 species). It may be that species of this phylum are in low numbers in this area for biological or physical reasons. Alternatively, the sampling methods may not have detected all species present. No sand habitats were sampled in this study which may have contributed to the lower species numbers. Future analyses of the data may assist with explaining this result.

A comprehensive voucher collection of identified species has been entered into the WA Museum collections database and lodged in the Museum collections.

Introduction

This study is part of a larger program to investigate ecological interactions of the coastal marine communities in the Central West Coast region of Western Australia. The focus of the Western Australian Museum (WAM) is on documentation of the fauna of the region and specifically to examine the diversity of fishes, molluscs, crustaceans, echinoderms, scleractinian corals and sponges. The WAM also contributes to identification of other significant space-occupying taxa such as ascidians, soft corals, zoanthids and anemones.

In addition to characterising habitats and identifying community biodiversity, the results obtained in this study will contribute to the program by providing data on major predators and biota associated with trophic linkages.

The methodology used in the fieldwork program also provides a basis for detecting longer term changes in the benthic communities of the region. This study will make a significant contribution to determining baseline variability in a warm temperate marine ecosystem in WA by establishing a baseline data set for comparative studies in the future.

The Central West Coast region is considered to lie in a biogeographic overlap zone that has a mixture of tropical, temperate and west coast endemic biota. Little is known about the relative proportions of these biota, but preliminary evidence suggests that temperate species dominate with a smaller proportion of tropical species and endemics. No quantitative studies have examined this question until this study which will provide new information into the abundance of species as well as their distributions, and the proportions of the biota that are tropical, temperate or endemic to the west coast.

Aims and Objectives

- To investigate benthic community biodiversity on the Central West Coast of Australia.
- Quantitatively document the fishes, molluscs, crustaceans, echinoderms, scleractinian corals and sponges of the region.
- Determine if the biota present in the Jurien Bay Marine Park is representative of the region.
- Determine the proportions of tropical, temperate and endemic biota in the region.

Methods

Four locations were selected for study, Jurien Bay and Green Head (with a focus on the Jurien Bay Marine Park), Cervantes (in the south of the Marine Park), and Dongara (north of the Marine Park). These latter two localities provide a latitudinal component to the study, testing the hypothesis that the faunal biodiversity of Jurien Marine Park is representative of adjacent areas in the Central West Coast region of WA.

Fieldwork conducted in April and May 2005 was in the Jurien Bay and Green Head areas, and was undertaken jointly with a team of CSIRO scientists led by Dr. Russ Babcock. Fieldwork in Cervantes and Dongara will be undertaken in March 2006.

Preliminary discussions with CSIRO, Murdoch and ECU collaborators determined that sampling should be undertaken on a range of sampling scales, i.e. 0.25m^2, 1m^2, 5m^2 and 250m^2. Two dominant habitats of the region would be sampled, namely limestone reefs and seagrasses. Although sand habitat is also represented in the region, fieldwork logistics and time constraints did not allow for this habitat to be sampled.

The sampling design also had a cross-shelf (distance from shore) component with inshore, midshore and offshore (exposed and sheltered) reefs sampled.

Within sites, dominant cover was recorded and targeted sampling ensured that various covers were sampled. For example at some reef sites *Sargassum* and red foliose algae occurred adjacent to *Ecklonia* dominated areas. In this case quadrats and transects were located in both floral areas. Seagrass habitats either had beds of *Amphibolis* or *Posidonia* and both types of seagrass were sampled for faunal biodiversity.

A summary of the sampling procedure is presented in Table 3.6.

Fish were surveyed by two additional methods. Trawling was undertaken in a seagrass habitat to collect cryptic fishes, and a reef site was selected as a rotenone station, to assess fish diversity not detected in visual census transects. Small cryptic fishes discovered incidentally during sorting of the quadrat material were also recorded, as were several species opportunistically observed while swimming between transects, or while assisting with other activities.

A total of 16 sites were examined at Jurien Bay and Green Head (Figure 3.42 & 3.43a,b).

Table 3.6. Fieldwork sampling program for reef and seagrass habitats at Jurien Bay and Green Head.

Taxon	Sampling scale			
	0.25m^2 quadrat	**1m^2 quadrat**	**5m^2 transect**	**250m^2 transect**
	Replication			
	n = 5	**n = 5**	**n = 3**	**n = 3**
Algae	CSIRO Harvest quadrat			
Crustaceans	CSIRO/WAM Sieved from harvested algae and rock		WAM Crustacea larger than 1cm collected for ID	
Molluscs	CSIRO/WAM Sieved from harvested algae and rock	CSIRO Molluscs larger than 1cm counted and measured *in situ*	WAM Molluscs larger than 1cm collected for ID	
Sponges	CSIRO/WAM Photographed then harvested from quadrat		WAM Sponges larger than 1cm counted, measured *in situ* and collected for ID	
Echinoderms	CSIRO/WAM Sieved from harvested algae and rock	CSIRO Echinoderms larger than 1cm counted and measured *in situ*	WAM Echinoderms larger than 1cm counted, measured *in situ* and collected for ID	
Ascidians	CSIRO Harvested from quadrat	CSIRO Ascidians larger than 1cm counted and measured *in situ*		
Corals		CSIRO Small corals e.g. *Plesiastrea* counted *in situ*	WAM Corals larger than 1cm counted and measured *in situ*, and collected for ID	
Fish				WAM Visual census
Habitat				WAM 25m^2 Video transect

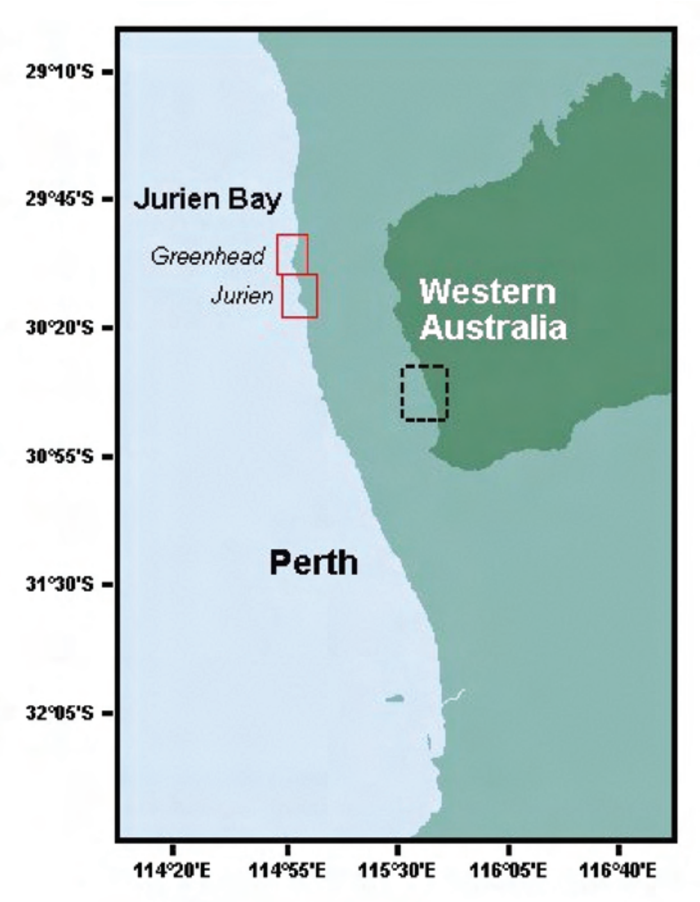

Figure 3.42: Map of Jurien Bay region

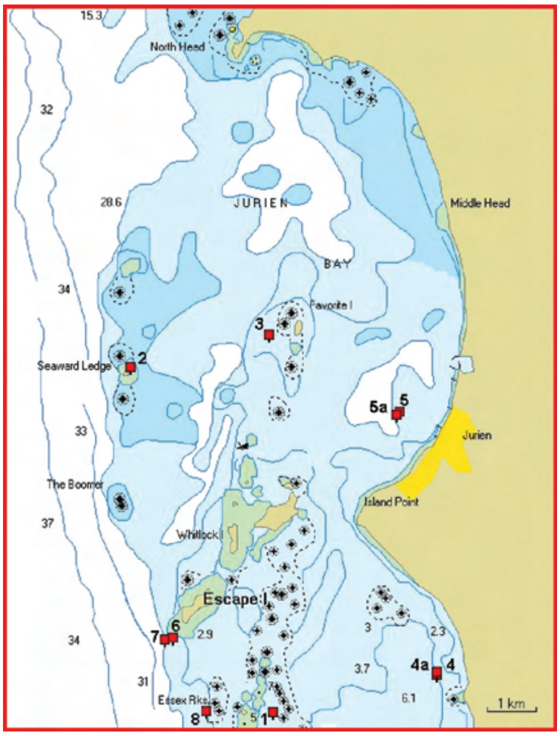

Figure 3.43a: Map of Jurien sites sampled.

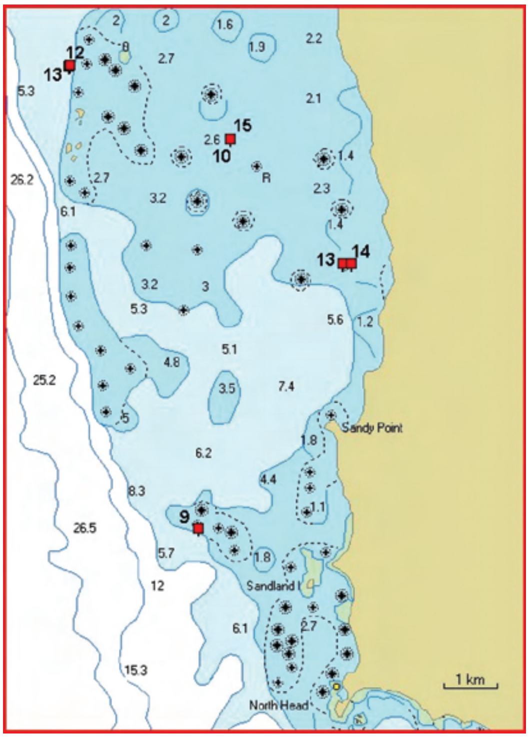

Figure 3.43b: Map of Green Head sites sampled.

Results

Full species lists for the study to date are available in:

Fromont, J., Marsh, L., Moore, G., Salotti, M., M Titelius, M., Whisson, C. (2005). Biodiversity of Marine Fauna on the Central West Coast. Second Milestone Report to the Strategic Research Fund for the Marine Environment (SRFME), 46pp.

Crustaceans

A total of 25 crustacean species (excluding Amphipoda) have been identified to date, with the isopods being the most diverse (12 of the 25 species). The majority of the isopods (eight species) belong to the family Sphaeromatidae. The other two isopod families recorded, Paranthuridae and Stenetriidae, had relatively fewer species (one and three, respectively). The sponge-associated isopod *Amphoroidella elliptica* (Sphaeromatidae) was the most widespread species in the collections, occurring at five of the 16 stations sampled. The stenetriid isopod *Stenetrium* sp.1 occurred at four stations.

The order Decapoda were only slightly less diverse than the isopods, with 11 species recorded from eight families: Alpheidae, Porcellanidae, Diogenidae, Dromiidae, Majidae, Hymenosomatidae, Pilumnidae and the Trapeziidae. Only the alpheids had more than one species (four). Decapod species were not widespread, with only the porcellanid crab, *Ancylocheles gravelei*, recorded at three sites. The remaining 10 species were found at two or fewer sites.

A single species of barnacle, *Acasta* sp. (Order Sessilia: Family Archaeobalanidae) was recorded from a sponge taken from south west of Escape Island (JWAM 6) and one specimen of an unidentified mysid shrimp, Mysid sp.1 (Order Mysida) was collected from Booker Rocks (JWAM 4a).

The highest diversity of crustaceans, measured by number of species, was recorded at Booker Rocks (JWAM 4a, eight species) and inside Favourite Is. (JWAM 3, six species). Eight stations had two or less species.

Distributions are known for 17 of the identified crustacean species and 11 of these (65%) have southern distributions, four have west coast distributions (24%), and two species have a northern distribution (12%). Four new records for Western Australia have resulted for the isopod family Sphaeromatidae: *Amphoroidella elliptica*, *Cymodoce septemdentata*, *Haswellia glauerti* and *Pseudocerceis trilobite.* The single specimen of *Oxinosphaera australis* in these collections extends the range of this species north from Cottesloe, WA.

The crustaceans reported here are largely the result of incidental collection off, or in, the various sessile benthic invertebrates sampled from the transect lines and many are known associates of sponges. The sphaeromatid isopod, *Amphoroidella elliptica*, is found on the surface of sponges (Hale, 1929) and the two species of *Oxinosphaera* (Sphaeromatidae) burrow holes into sponges in which they live (Christine Hass pers. com.). Similarly, the barnacle genus *Acasta* is only found embedded in the tissue of sponges. While the alpheid shrimp are not fully identified at present, many members of the genus are known to live in association with sponges, even utilising the internal canals (Poore, 2004).

The decapod species *Halicarcinus ovatus* (Hymenosomatidae), *Pilumus rufopunctatus* (Pilumnidae), *Fultodromia spinifera* (Dromiidae) and *Calcinus dapsiles* (Diogenidae) have been recorded from a variety of habitats including sheltering in sponges, ascidians and other sedentary marine invertebrates (Hale, 1927; Davie, 2002; Poore, 2004).

Echinoderms

Overall the species richness of echinoderms was low given the intensity of sampling. There was a total of 54 species of echinoderms: five crinoids of three families, 10 asteroids of five families, 25 ophiuroids of seven families, nine echinoids of five families and five species of holothurians from four families.

Nine species records extend current known distributional ranges: seven northwards, mostly from the Fremantle-Rottnest area, and two southwards, one from Dongara and the other from Shark Bay.

Crinoidea: In this study the family Comasteridae, (which has several tropical and temperate species in south-western Australia and usually predominates in samples) is represented only by *Comatulella brachiolata,* not previously recorded north of the Fremantle area. Three species of the family Antedonidae and one of the family Aporometridae were found. The latter species, *Aporometra occidentalis* has not previously been recorded north of the Perth metropolitan area and is endemic to southern and south-west Australia.

Asteroidea: This class was represented by south-west Australian species. One asteriid, *Uniophora dyscrita*, has not previously been found north of Lancelin. The remainder were species expected from the Central West Coast. Three were south-west endemic species.

Ophiuroidea: Brittle stars were the most speciose echinoderm group collected, partly due to the sampling methods which facilitated the extraction of small species from samples of rock, algae and sponges. Those collected in this study consisted of 11 northern, four southern, three south-west endemics, one circum-Australian and one cosmopolitan species. One tropical species has had a small range extension southwards, (from Dongara to Jurien) while another tentatively identified species, has not previously been found south of Shark Bay. Of interest was the collection of *Amphiura ptena*, a west coast endemic species which has rarely been collected previously.

Echinoidea: Sea urchins were represented by many small juvenile specimens that are difficult to identify with certainty as they have not developed adult characters. Two species have southern Australian distributions, one is a tropical species of sand dollar (*Peronella lesueuri*) which extends to the south coast of W.A., and five are south-west Australian endemic species. One small specimen was tentatively identified as *Pseudechinus hesperus*, previously only known from Rottnest Island. A large number of juveniles were tentatively identified as *Temnopleurus michaelseni* but no adults were found. This species has not been recorded north of Fremantle. The most common species, found at eight sites, was *Holopneustes porosissimus* and 61 of these were juveniles.

Holothuroidea: All but one of the sea cucumbers were either juveniles or very small species, with *Holothuria hartmeyeri* only represented by juveniles. One species, *Stichopus mollis*, is a widespread southern species; the remainder are endemic to the south-west, two extending to South Australia. The range of *Australocnus occiduus* is extended northwards from Rottnest Island to Jurien, *Trachythyone glebosa* has not previously been recorded on the west coast and its distributional range is now extended from Albany to Jurien. A specimen of *Taeniogyrus* was tentatively identified as *T. heterosigmus* which has only previously been recorded from Bunbury.

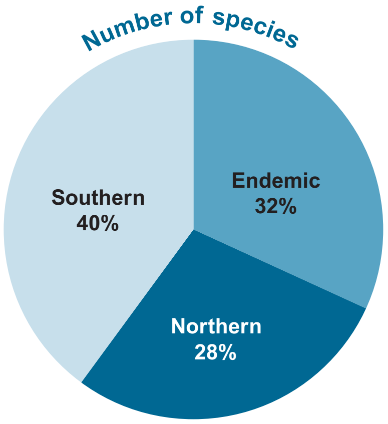

Figure 3.44: Preliminary affinities of the Jurien echinoderm fauna, based on number of species of tropical, temperate and endemic species.

The 54 species of echinoderms collected in this study was fewer than from other localities studied in south-west Australia: Albany (83 species; Marsh, 1991); Rottnest Island (86 species; Marsh and Pawson, 1993) and the Houtman Abrolhos, where the influence of the Leeuwin Current is more pronounced and tropical species predominate, where 172 species were recorded (Marsh, 1994).

Fishes

A total of 76 species of fishes (~4500 individuals) were recorded during the visual censuses. A further 20 species were added from opportunistic sightings and the trawl, rotenone and quadrat collections. The community was dominated by the wrasse *Coris auricularis*, which accounted for more than 35% of all individuals observed, and occurred at every site.

Warm-temperate species were dominant, although sub-tropical fish were numerically the most abundant (Figure 3.45). A component of the community was tropical in origin.

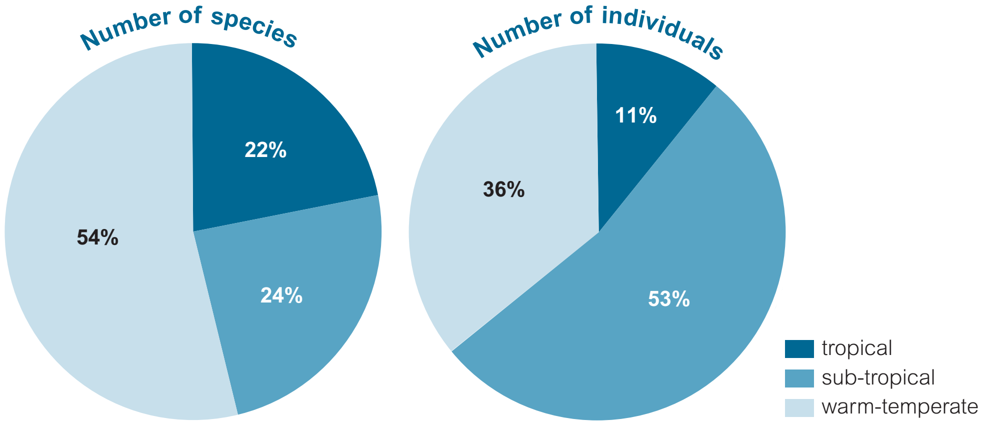

Figure 3.45: Composition of Jurien fish community, based on number of species and number of individuals. Distribution classifications after Hutchins (1994).

There was considerable variation in species richness between sites of the same habitat, but reefs were consistently more diverse than seagrass, and reef habitats maintained much higher population densities than seagrass habitats (Table 3.7).

Table 3.7. Summary of species richness and number of individuals for each site in the two major habitat groupings at Jurien.

	Seagrass		Reef	
	Mean	**Range**	**Mean**	**Range**
Species	10	4 – 15	22	13 – 28
Individuals	55	14 – 123	353	122 – 608

Inshore reefs (Sites 4, 5 and 13) had the greatest fish diversity and maintained the most individuals (Figure 3.46). Midshore and offshore reefs were similar in both number of species and individuals. Analysis of Similarity detected a significant difference between sites based on gradient from shore (ANOSIM (in vs. mid vs. off); $R = 0.225$; $p = 0.048$).

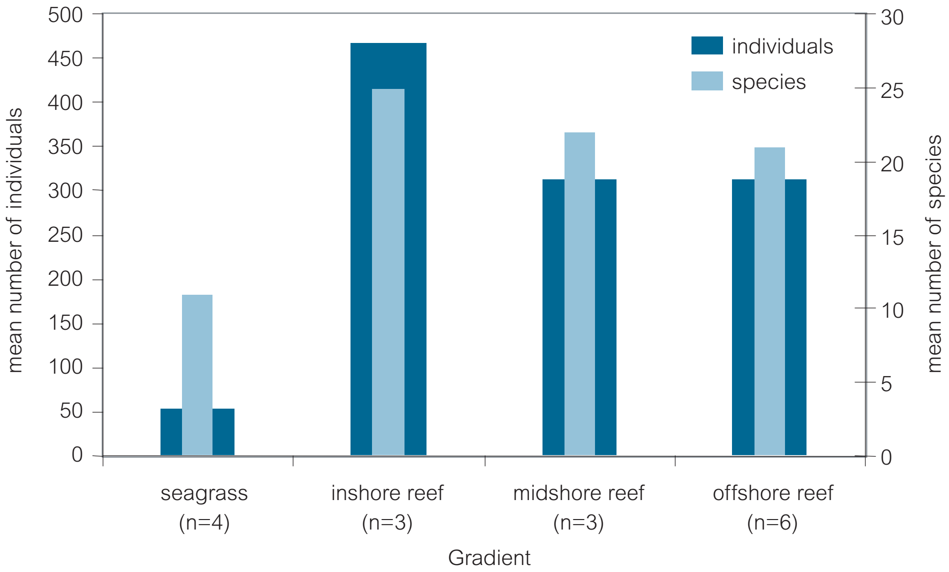

Figure 3.46: Species richness and number of individuals for each habitat (reefs as gradient from shore) at Jurien.

Similarity Percentage analysis using species abundance data indicates that several species can be considered typical of reef or seagrass habitats and contribute most towards the 'similarity' within each main habitat. Additionally, a set of species account for the detected 'dissimilarity' between the two habitat types (Table 3.8).

Table 3.8. Similarity Percentage analysis using species abundance data from the two major habitat groupings at Jurien. Listed are the five most important representative species for each habitat and the percentage each contributes to the similarity coefficient. Also listed are the five most important representative species to differentiate the habitats and the percentage each contributes to the dissimilarity coefficient.

Similarity (seagrass)		**Similarity (reef)**		**Dissimilarity (seagrass/reef)**	
Species	%	Species	%	Species	%
Halichoeres browfieldi	40	*Coris auricularis*	60	*Coris auricularis*	34
Coris auricularis	31	*Parma mccullochi*	8	*Parma mccullochi*	6
Notolabrus parilus	11	*Notolabrus parilus*	7	*Pomacentrus milleri*	6
Apogon victoriae	4	*Kyphosus cornelii*	4	*Apogon victoriae*	5
Pentapodus vitta	4	*Pomacentrus milleri*	3	*Kyphosus cornelii*	5

Molluscs

A total of 74 mollusc species have so far been recorded in this study, with 52 species being live-taken macro-molluscs. The remaining 22 species were micro-molluscs or freshly dead-taken. Of the 45 identified to species level, 16 were tropical (36%) and 20 were warm temperate (44%). Nine species were endemic to Western Australia (20%).

There was a notable high diversity of the gastropod families Columbellidae, Turbinidae and Trochidae. Together these families account for 26% of species recorded thus far and these appear to be widespread. *Pyrene bidentata* (Menke, 1843) has so far been found at 8 sites, *Astralium tentorium* (Thiele, 1930) at 7 sites, and *Cantharidus lehmanni* (Menke, 1843) at 5 sites in the study area.

Porifera

So far 132 species of sponges have been identified. A reasonable proportion of these species belong to the Class Calcarea (23 species) while the remainder belong to the Class Demospongiae (109 species). The demosponges are the primary component of shallow water marine sponge faunas worldwide.

Only 12 of the 132 species could be readily given a species name and the distribution of two others (*Chondrilla* sp. 2 and *Chondrilla* sp. 3) is well known from other studies (Usher *et al*., 2004). Of these 14 species, 6 are temperate, 5 are widespread and occur in temperate and tropical habitats, 1 is tropical and 2 are west coast endemic species. Only with further identification of species will a biogeographic analysis of the sponges of this region be possible.

The four most speciose sponge orders found to date are the Poecilosclerida (36 species), Dictyoceratida (22 species), Haplosclerida (22 species) and Halichondrida (12 species). All but the Dictyoceratida have a strong mineral component to the skeleton, with large numbers of spicules of silica dioxide often supplemented by spongin fibre. The Dictyoceratida lack spicules, have a dominant fibre skeleton (bath sponges occur in this order) and accrete sandgrains and spicules from the environment to supplement their skeletons to varying degrees.

The highest sponge diversity to date has been found around Essex Rocks and Escape Island, with site JWAM 6 (south west of Escape Island) being most diverse with 30 species recorded on the three 5m^2 transects. Sites JWAM 1 at North Essex and JWAM 8 at Essex Rocks were also diverse with 22 and 21 species recorded respectively. Lowest diversity was at site JWAM 2 on Seaward Ledge where no sponges were found on the transects.

Discussion

The Central West Coast region of Western Australia is considered to lie in a biogeographical overlap zone that has a mixture of tropical, temperate and endemic biota. Few studies have been undertaken in this region that combine detailed taxonomic inventories with quantitative assessment of species distribution and abundance.

At this stage of the project some phyla have been completely identified (fishes and echinoderms) while other target phyla have had varying proportions of the collected material identified (crustaceans, molluscs and sponges). Scleractinian corals and zoanthids still need to be identified.

Preliminary results from the identification of crustacean (65%) and mollusc (44%) specimens suggest the shallow water marine fauna of the region has a greater component of temperate than tropical species. The mollusc and echinoderm faunas also had a notable number of west coast endemic species (20% and 32% respectively). This dominance of temperate species is supported by the results of the fish component of the study, with 54% of fishes being warm temperate and 46% subtropical or tropical in origin.

So far 96 fish species, 54 echinoderm species, 74 mollusc species, 25 crustacean species and 132 sponge species have been identified. The number of fish species found in this study fall in the anticipated range for the area, taking into account the sampling methods used did not target cryptic species. However the 62 echinoderm species was lower than expected.

Four species of the isopod family Sphaeromatidae collected in this study are new records for Western Australia. Extended species ranges were established for nine species of echinoderms; seven northwards from the Fremantle – Rottnest area and two southwards from Dongara and Shark Bay.

Of the 96 fish species recorded in this study, 20 were collected using methods that target cryptic species (rotenone, trawl, quadrat and opportunistic sightings) not normally seen using visual censusing techniques. This clearly shows that visual censusing techniques underestimate fish biodiversity.

Burt and Anderton (1997) reported 62 species of fishes from Jurien Bay (c.f. 96 species in the present study), and included identification errors (e.g. several listed species have an eastern Australian distribution). This present study detected a far greater site diversity than that reported by Burt and Anderton (1997). Seagrass sites averaged 10 species per site (compared with 7 by Burt and Anderton, 1997) and reef sites proved to be much richer (22 species per site compared with 13). However, based on samples from the trawls, rotenone collections and WA Museum records, there is clearly an even higher diversity than either of these transect-based surveys. Hutchins (1994) reported 171 species for the area ranging from Port Denison to Jurien Bay. That number of species was achieved by surveying across different years and seasons (including effects of phenomena such as the Leeuwin Current) and with a goal of maximising diversity rather than providing a repeatable, quantified survey.

The reef sites considered to be 'inshore' (JWAM4, 5, 13) are the most important fish habitats in terms of both species richness and abundance, compared to the more exposed reefs. This is consistent with the findings of Hutchins (1994) who noted that the lagoon-like areas supported more diverse faunas than the rich macroalgal communities of the exposed reefs. By contrast, seagrass habitats are often mono-specific stands, sometimes with a dense canopy, or punctuated with patchy rocks, and contain a more depauperate fish fauna.

Very few thorough surveys of molluscs of inshore waters along the Central West Coast have been undertaken. Burt and Anderton (1997) reported 34 species of molluscs (>10mm) from Jurien Bay, in contrast to the 74 species reported in this present study. The low diversity recorded during the 1997 survey could be attributed to the size of molluscs collected and differences in methodology. A checklist by Wells and Bryce (1997) of the marine molluscs of the nearby offshore Houtman Abrolhos Islands contains 492 species.

Although preliminary at this stage of the project evidence suggests the Trochidae, Turbinidae and Columbellidae families are the most diverse and widespread molluscs in this area. Most of the species recorded from these families are grazers on epiphytes of seagrass and macroalgae which provide surfaces for colonisation, enable cover from predators, create habitat complexity and are a rich food source for many small benthic invertebrates (Edgar 1990).

The large number of calcareous sponge species found in this study is similar to previous findings in shallow temperate water environments in Western Australia. For example, McQuillan (2006) found 45 calcareous species from a total sponge fauna of 243 species in the Marmion Lagoon. We are uncertain as to why such relatively high proportions of Calcarea occur in temperate areas of Western Australia. Calcareous sponges are generally small and cryptic, restricted in growth by their simple construction. They have spicules made of calcium carbonate while the Demosponges have either a spongin fibre skeleton and/or spicules composed of silica dioxide. In contrast, in the tropical Dampier Archipelago where a total of 275 sponge species were recorded, only five species belonged to the Calcarea (Fromont, 2003). There is a marked difference in the incidence of calcareous species occurring in temperate versus tropical habitats in Western Australia and this result should be investigated further.

Burt and Anderton (1997) noted that the faunal diversity of the Central West Coast was dominated by sponges and fishes, which contributed 31% and 24% of overall species diversity respectively. The sponge component is also significant in this study with 132 species recorded so far. Many sponge species in this study could not be given a species name. Firstly, identification is reliant on very old literature requiring extensive revisions. Secondly, time constraints of the project do not allow thorough taxonomic searches or histological preparation of specimens. It is too early in the identification phase to interpret the sponge fauna of Jurien Bay and Green Head except to note that it is speciose. Whether this study will find a similar magnitude of sponge species to that of the Marmion lagoon (243 species) will be determined as identifications progress.

When the final field program is undertaken this year and invertebrate species identifications are completed, the analyses of the complete data set will begin. This will relate environmental factors to species numbers, such as whether more species occur in algal covered reef habitats versus seagrass environments, and whether an inshore to offshore abundance gradient of species or individuals exists.

This project will enable a detailed interpretation of the fauna communities surveyed at Jurien Bay and Green Head, and a comparison of localities to the south (Cervantes) and north (Dongara). This study examined seagrass communities of *Amphibolis* and *Posidonia*, and reef communities with varying suites of algae, either *Ecklonia* or *Sargassum* dominated, or with a mixture of red foliose or brown alga. This intensive quantitative sampling of both the fauna and flora of the region will build a detailed biological picture of the communities that dominate this region and their fine scale habitat associations.

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Acknowledgements

We gratefully acknowledge the following:

Kaye Grubb, Tenneill Houlahan, and Elaine Oldham, for assistance in the field.

CSIRO for additional SCUBA tanks and video camera.

Ian Stiles and *Hot Tuna* for diving activities and helpful local knowledge and advice.

Tim Daly and the DEP vessel *Zoila* for diving and fieldwork.

Sue Morrison, Oliver Gomez and Jenny Hutchins, WA Museum for assistance with logistics and lab work.

Conferences, presentations and publications.

Fromont, J., Marsh, L., Moore, G., Salotti, M., M Titelius, M., Whisson, C. (2005). Biodiversity of Marine Fauna on the Central West Coast. Second Milestone Report to the Strategic Research Fund for the Marine Environment (SRFME), 46 pp.

Fromont, J., Moore, G., M Titelius, M., Whisson, C. (2005). Biodiversity of Marine Fauna on the Central West Coast. First Milestone Report to the Strategic Research Fund for the Marine Environment (SRFME), 10 pp.

Moore, G. (2005). Preliminary results of the fish survey at Jurien Bay and Green Head. Midwest workshop, CSIRO, 7-9th June.

It is anticipated that dissemination of the findings of this study will be achievable after the quantitative analyses have been completed, which will allow for more detailed interpretation of the results. This will occur after the second component of the fieldwork is completed.

Editor’s Note: Since this report was prepared the final report for this study has been completed:

Fromont, J., C. Hass, L. Marsh, G. Moore, M. Salotti, M. Titelius and C. Whisson (2006). *Biodiversity of Marine Fauna on the Central West Coast.* Final Milestone Report to the Strategic Research Fund for the Marine Environment (SRFME), 85pp. Unpublished Report.

3.3.8 Ecological interactions in coastal marine ecosystems: The fish communities and main fish populations of the Jurien Bay Marine Park

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Executive summary

Quantitative data on the diversity, densities and species compositions of assemblages of fish in reef, seagrass and unvegetated sand habitats in three management zones of the Jurien Bay Marine Park have been obtained for each season during the first year of this project. The three management zones are (1) general use zones, which are open to all types of fishing, (2) scientific reference zones, which are open to commercial and recreational rock lobster fishing and selected shore based fishing, and (3) sanctuary zones, which are closed to all types of fishing. The study has used both traditional sampling methods, such as seine netting and trawling, and underwater visual censuses. The results will act as baseline data for analysing whether there is evidence that, in the Jurien Bay Marine Park, the closing of areas to fishing influences the characteristics of the fish fauna. The size and age compositions, growth, reproductive biology and diets of three abundant species of labrid are also being studied.

The most abundant fish species over reefs were the western king wrasse *Coris auricularis* and McCulloch's scalyfin *Parma mccullochi*. Preliminary multivariate analyses demonstrate that the species compositions of the fish faunas of reefs in the Jurien Bay Marine Park are strongly influenced by their distance from shore and thus degree of exposure to wave action. At present, there is little evidence that the type of management zone has a conspicuous influence on the species composition of its reef faunas.

The number of fish caught by trawling in seagrass far exceeded the small number of fish caught by trawling over bare sand. The most abundant species by far over seagrass were the rough leatherjacket *Scobinichthys granulatus* and the brownspotted wrasse *Notolabrus parilus* followed by the rainbow cale *Odax acroptilus* and the western gobbleguts *Apogon rueppellii*. The fauna over neashore bare sand was dominated by the weeping toadfish *Torquigener pleurogramma*.

There are strong indications that the three species of labrid selected for biological study, *i.e. Notolabrus parilus*, *Ophthalmolepis lineolatus* and *Coris auricularus*, are protogynous hermaphrodites, *i.e.* change from female to male at some stage in life. The trends exhibited throughout the year by gonadal data, such as the gonadosomatic index, demonstrate that the three labrid species spawn at different times. Thus *N. parilus* breeds in late winter and early spring, whereas *O. lineolatus* spawns in spring and summer and *C. auricularus* in late summer and autumn.

Introduction

The Jurien Bay Marine Park, which extends along the west coast of Australia between approximately Green Head (30º 4.13'S) and Wedge Island (30º20.33'S), was declared a Class A marine park in August 2003 and contains a number of management zones (see Fig. 3.24). The major zones are (1) general use zones, which are open to all types of fishing, (2) scientific reference zones, which are open to rock-lobster fishing and other selected shore based fishing (see Fig. 3.24), and (3) sanctuary zones, which are closed to all types of fishing.

The establishment of the Jurien Bay Marine Park provides the opportunity to obtain baseline data on the diversity, densities and compositions of the fish faunas in different habitats in the above zones of a marine park during the early stages of the development of that park. Comparisons between the data obtained for these three biotic variables in these zones in the future and the baseline data acquired at the

present time will facilitate an examination of the impact of the establishment of management zones in the Jurien Bay Marine Park on the characteristics of the fish faunas of that park.

This collaborative project has only been underway for approximately one year and is scheduled to last for three years. Thus, this report provides the results of preliminary analyses of the data collected during the initial period of the project.

Objectives

The fish faunas and selected fish species are being sampled at sites in zones in the Jurien Bay Marine Park, which are (1) open to all types of fishing, (2) only open to rock-lobster fishing and selected shore based fishing and (3) closed to all types of fishing. The data resulting from this sampling regime will be able to be used to determine the impact of different levels of protection on fish communities and selected fish species in the future. The sampling of different habitats in each zone, *e.g.* reefs, seagrass and unvegetated sand, and in different depths will facilitate an understanding of the ways in which ichthyofaunal composition is influenced by habitat type and/or water depth.

Biological data is being collected for the most abundant labrid species, *i.e.* Western King Wrasse *Coris auricularis*, and two other abundant labrids, *i.e.* Brownspotted wrasse *Notolabrus parilus* and Maori Wrasse *Ophthalmolepis lineolatus*, and these will include the size and age compositions, reproductive biology and diets of those species. The data on reproductive biology will be used to determine whether these labrid species are protogynous hermaphrodites, like many other labrids, and if they have determinate or indeterminate fecundity and when and where they spawn. We will also obtain data on the dietary compositions of each labrid species to elucidate the ways in which the prey of those species change with increasing body size and also the extent to which dietary composition is influenced by depth and time of year.

Individuals of selected species will be tracked by using acoustic tagging techniques to assess the extent to which the species move between habitats and thus how different levels of protection can benefit such species.

Attention will also be focused on obtaining sound data on the fish faunas over bare sand and seagrass in nearshore waters to establish whether any species use that type of habitat as a nursery area and later move onto reefs as they increase in size and reach maturity.

Our data will be considered in the context of the results obtained from other studies in the Jurien Bay Marine Park to refine our interpretations of the factors that influence the characteristics of the fish communities in that park.

Methods

The study is focusing on sampling sites in (1) general use zones, (2) scientific reference zones and (3) sanctuary zones. Within each zone, sampling is being conducted in each season in nearshore shallow, lagoonal/mid-depth and offshore deeper waters using techniques that are appropriate for sampling the different habitat types, *i.e.* reefs, seagrass and sand. A preliminary sampling trip was conducted in summer 2004/05 to establish appropriate representative sampling sites. Sampling trips are now being conducted seasonally for two years using the following regime.

Reef habitats

The reefs in the study area are categorised as follows. (1) Outer reefs, which are located in deeper waters and are exposed. (2) Mid reefs, which lie between outer and nearshore reefs and are less exposed and in shallower waters than outer reefs. (3) Nearshore reefs, which are located in shallow waters and are close to shore. Sites in each of the three reef categories in the three major management zones in two regions of the marine park, *i.e.* Green Head to Sandy Point and Jurien Bay to Hill River, are sampled using underwater visual census (UVC) (Fig. 3.47). Seven 25 x 5 m strip-transect surveys are conducted at each site on each sampling occasion and the number of individuals of each fish species and the lengths of selected commercial, recreational and abundant species are estimated and assigned to 50 mm total length categories. Whenever possible, the sex of individual fish is identified using known morphological or colour phase (juvenile, intermediate, terminal) characteristics. The approximate percentage coverage of algae in five 5×1 m blocks in each transect is recorded. Baited underwater video are used, whenever possible, in conjunction with visual census, to determine the relative abundance of predatory species that, due to their high mobility, are usually underestimated by visual census (for full description of methodology see Willis and Babcock, 2000). For this purpose, 30 min of baited underwater video is being recorded at each UVC site.

Nearshore sand and seagrass habitats

Nearshore unvegetated sites in each of the three zones in each of the three main regions, *i.e.* Green Head to Sandy Point, Jurien Bay to Hill River and Cervantes to Wedge Island, are sampled using a 21.5 m long seine net, comprising two 10 m long wings, each with 6 m of 9 mm mesh and 4 m of 3 mm mesh, and a 1.5 m bunt made of 3 mm mesh (Fig. 3.47). In contrast, seagrass and unvegetated sand sites in lagoonal waters in the three zones in the Green Head to Sandy Point and Jurien Bay to Hill River regions are sampled using a small tri-net (otter trawl) (Fig. 3.47). The tri-net, which is 5 m long, has a 2.6 m wide and 0.5 m high mouth, 50 and 13 m warp and bridle lengths and contains stretched mesh of 51 and 25 mm in the wings and bunt, respectively. The net is towed at a speed of *ca* 3 – 4 km h^{-1} and for a distance of *ca* 150 m. The distance trawled during each replicate is measured using a Garmin GPS Map 178c global positioning system, which, together with the width of the mouth of the net, enables the area of substrate trawled to be determined. This, in turn, enables the density of each fish species to be estimated. Four replicate seine net samples and trawl net samples will be obtained during the day in each season from each site using those two methods.

Analysis of fish community data

The number of each fish species and the total number of fish observed or caught at each site on each sampling occasion will be converted to a density. After appropriate transformation, these data and the corresponding values for the number of species will be analysed using ANOVA to determine whether the above biotic variables are significantly influenced by region, zone, season and, in the case of underwater visual censuses over reefs, the reef category (Underwood, 1997).

The mean densities of each species at each site on each sampling occasion, determined from data derived using the different sampling methods, were log transformed and used to construct Bray-Curtis similarity matrices employing the PRIMER *v* 6 package (Clarke and Gorley, 2004). The matrix was then subjected to non-metric multidimensional scaling ordination (MDS). One-way analysis of similarities (ANOSIM) was employed to test whether the compositions of fish species in each habitat type, *i.e.* reefs, seagrass and unvegetated sand, differed between region, season and zone and, in the case of underwater visual censuses over reefs, between reef category (Clarke, 1993). The null hypothesis that there was no significant difference between species composition for each of those factors was rejected when the significance level (*p)* was > 5%.

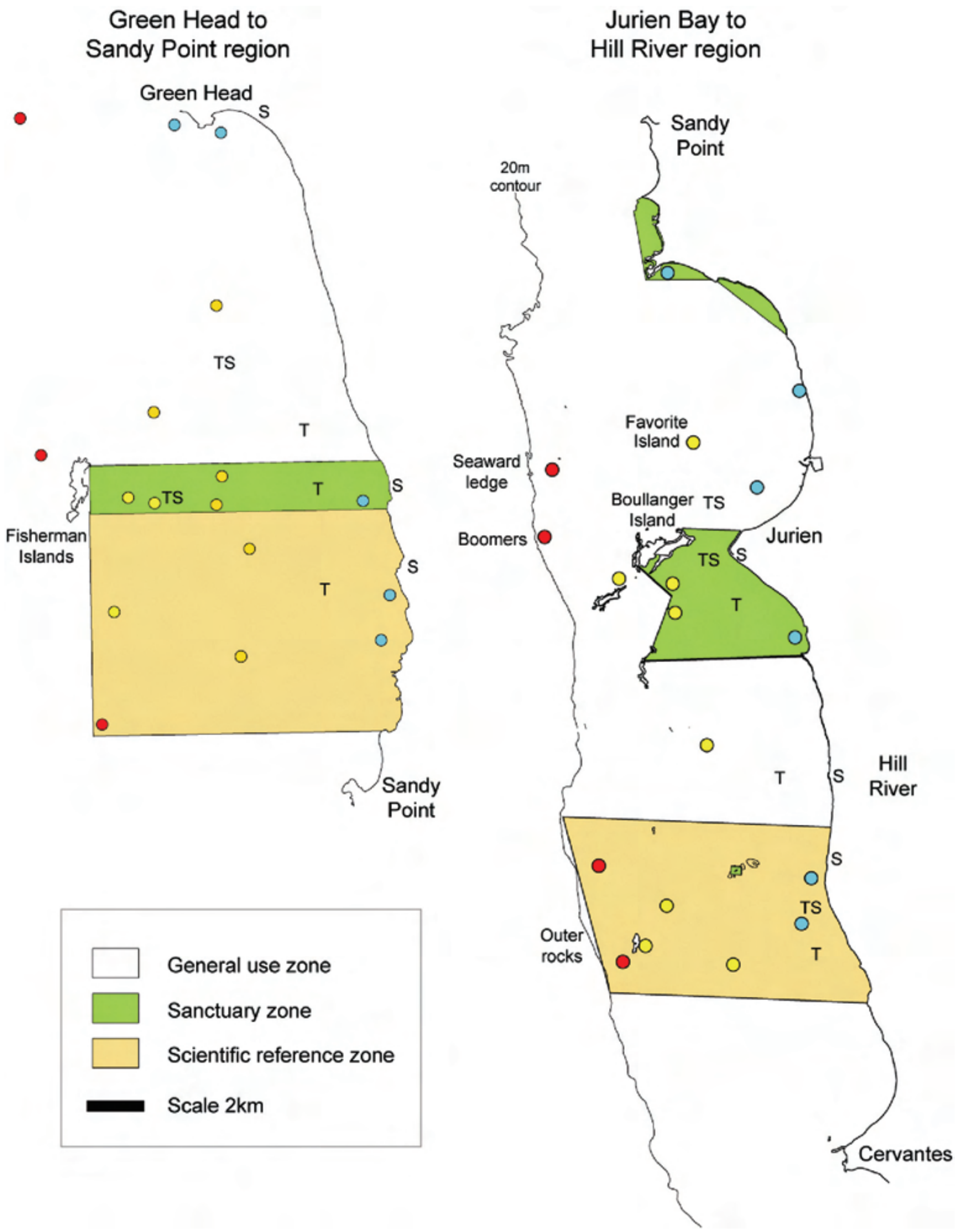

Figure 3.47: Map of sites sampled in the Green Head to Sandy Point and Jurien Bay to Hill River regions. Sites sampled are underwater visual census sites in outer reef habitat (🔴), mid-reef habitat (🟡) and nearshore reef habitat (🔵), trawl sites in seagrass (T) and sand (TS) and seine sites (S).

The associated *R*-statistic values in the ANOSIM test range largely from 1, *i.e.* the compositions of all samples in a group are more similar to each other than to those in the samples for any other group, down to *c.* 0, *i.e.* all samples in all groups are similar in composition (Clarke, 1993). When ANOSIM detected a significant difference between groups, Similarity Percentages (SIMPER) was used to determine which species typified the samples in a group and distinguished between the samples from different groups (Clarke, 1993).

Fish movement

Tagging, using acoustic tags and receivers, will be used to trace the movements of individual fish of selected species. Up to 20 fish of different species, particularly species which are likely to demonstrate territoriality and or home range behaviour, will be tagged using acoustic tags (VEMCO VR2) that are surgically inserted into the fish. This will allow larger scale movements of animals to be tracked with an accuracy of approximately ±100 m using an array of receivers.

Biological studies

(1) Size and age compositions and reproductive biology: Samples of the three labrid species selected for biological study are being collected from a range of sites. Fish are being aged using the number of opaque annuli in otoliths, a technique that has been successfully used for many species in our laboratory, *e.g.* Australian herring and dhufish (see Fairclough *et al.*, 2000a; Hesp *et al.*, 2002). The von Bertalanffy growth curve will be fitted to the lengths at age of the individuals of each species.

The patterns of gonadal development and determination of the spawning period of the three labrid species and, where applicable the type of hermaphroditism, will be ascertained using traditional methods, *e.g.* trends exhibited by gonadal and oocyte stages and gonadosomatic indices, an approach that we have also employed successfully on many previous occasions (see Fairclough *et al.*, 2000b, 2004; Hesp and Potter, 2003; Hesp *et al.*, 2004).

(2) Dietary composition: Samples covering the full size range of the three labrid species are being collected seasonally by line fishing at sites representing the three main zones of the marine park. Stomachs are removed and stored in 70% ethanol. The diets are being analysed using traditional methodology that will enable the size-related changes in the diets of those species to be elucidated, *e.g.* Platell and Potter (2001). Comparisons between the dietary compositions of the three labrid species in different habitats will be made using nonmetric multidimensional scaling ordination and associated tests (see Clarke and Gorley, 2004; Platell and Potter, 2001).

Results and discussion

Fish community studies

A total of 101 fish species have been recorded during underwater visual censuses of reefs in the Green Head to Sandy Point and Jurien Bay to Hill River regions (Table 3.9). The most abundant twenty species contained six labrid species and five pomacentrid species. The most abundant labrid species were the western king wrasse *Coris auricularis* and the brownspotted wrasse *Notolabrus parilus*, while McCulloch's scalyfin, *Parma mccullochi*, and Miller's damselfish, *Pomacentrus milleri*, were the two most abundant pomacentrids (Table 3.9). Among recreationally and/or commercially important species, the Australian herring *Arripis georgiana* was the most abundant, ranking twentieth in the overall species list. However, the majority of individuals of that species was recorded at one site. Other important recreational and/or commercial fish species were not numerous and thus ranked low in the abundance list, *e.g.* breaksea cod *Epinephelides armatus*, western foxfish *Bodianus frenchii*, pink snapper *Pagrus auratus*, West Australian dhufish *Glaucosoma hebraicum* and samson fish *Seriola hippos* (Table 3.9).

Table 3.9. Numbers of individuals of each species recorded during underwater visual censuses of reef sites in each zone in each region of the Jurien Bay Marine Park during autumn, winter and spring 2005.

	Region						
	Green Head to Sandy Point			Jurien Bay to Hill River			
Species	Open	Sanctuary	Scientific reference	Open	Sanctuary	Scientific reference	Total
Abudefduf vaigiensis	0	0	0	0	0	2	2
Acanthaluteres vittiger	3	0	2	1	0	3	9
Acanthistius pardalotus	1	1	0	0	0	0	2
Anampses geographicus	8	0	57	11	6	26	108
Anoplocapros lenticularis	1	1	3	3	1	0	9
Anoplocapros robustus	5	2	4	4	4	4	23
Apogon rueppellii	8	0	0	18	0	0	26
Apogon victoriae	182	110	418	254	52	590	1606
Arripis georgiana	400	2	0	0	33	24	459
Austrolabrus maculatus	333	298	147	312	197	174	1461
Bodianus frenchii	22	15	13	36	51	19	156
Brachaluteres jacksonianus	0	0	0	0	1	0	1
Chaetodon assarius	5	1	15	10	4	20	55
Cheilodactylus gibbosus	4	0	3	3	2	2	14
Cheilodactylus rubrolabiatus	3	3	8	18	5	4	41
Chelmonops curiosus	147	55	59	96	63	65	485
Choerodon rubescens	62	34	84	69	21	44	314
Chromis klunzingeri	73	0	22	254	145	14	508
Chromis westaustralis	9	0	4	440	457	56	966
Cirripectes hutchinsi	3	2	14	1	2	1	23
Coris auricularis	3408	2532	2472	2640	2720	2009	15781
Dactylophora nigricans	5	0	1	2	4	7	19
Dasyatis brevicaudata	1	1	0	0	0	0	2
Diodon nicthemerus	0	0	1	0	1	2	4
Dotalabrus alleni	106	143	36	56	70	65	476
Enoplosus armatus	46	8	34	29	18	50	185
Epinephelides armatus	38	29	39	22	25	4	157
Epinephelus rivulatus	1	1	2	0	0	9	13
Eupetrichthys angustipes	2	0	0	2	0	0	4
Girella tephraeops	3	0	0	0	3	0	6
Girella zebra	1	0	0	0	0	0	1
Glaucosoma hebraicum	4	1	0	14	5	0	24
Gymnothorax woodwardi	0	0	1	0	0	0	1
Halichoeres brownfieldi	721	410	461	736	591	943	3862
Helcogramma decurrens	4	5	1	1	0	2	13
Hypoplectrodes nigrorubrum	0	1	3	0	0	2	6
Hypoplectrodes wilsoni	0	0	0	0	1	0	1
Kyphosus cornelii	833	507	1050	125	469	147	3131

	Region						
	Green Head to Sandy Point			Jurien Bay to Hill River			
Species	Open	Sanctuary	Scientific reference	Open	Sanctuary	Scientific reference	Total
Kyphosus sydneyanus	346	128	1	253	35	30	793
Labracinus lineata	103	65	42	106	51	62	429
Leptoscarus vaigiensis	0	0	4	0	0	1	5
Lethrinus nebulosus	5	0	2	3	0	0	10
Meuschenia flavolineata	6	2	1	10	1	0	20
Meuschenia galii	1	2	0	15	9	1	28
Meuschenia hippocrepis	11	7	1	3	1	10	33
Microcanthus strigatus	11	0	0	191	0	0	202
Neatypus obliquus	41	50	17	250	36	9	403
Notolabrus parilus	938	710	447	489	462	829	3875
Odax acroptilus	17	19	7	18	11	14	86
Odax cyanomelas	23	35	8	79	66	57	268
Ophthalmolepis lineolatus	66	65	2	72	53	24	282
Othos dentex	2	0	0	0	2	0	4
Pagrus auratus	0	0	5	0	1	0	6
Parapercis haackei	15	7	7	39	2	17	87
Paraplesiops meleagris	22	11	12	14	18	4	81
Parapriacanthus elongatus	90	1105	0	955	140	56	2346
Parma mccullochi	1190	730	776	577	861	464	4598
Parma occidentalis	86	25	69	79	69	214	542
Parma victoriae	0	0	0	5	0	0	5
Parupeneus chrysopleuron	0	0	5	2	0	0	7
Parupeneus spilurus	25	11	69	15	2	31	153
Pempheris klunzingeri	849	130	637	1529	641	737	4523
Pempheris multiradiata	12	86	177	9	93	11	388
Pempheris ornata	1	0	0	0	0	0	1
Pentapodus vitta	2	0	0	22	11	16	51
Phyllopteryx taeniolatus	0	1	0	0	0	0	1
Pictilabrus laticlavius	42	55	16	81	79	26	299
Pictilabrus viridis	43	25	9	12	64	60	213
Plectorhincus flavomaculatus	27	20	19	15	18	52	151
Plotosus lineatus	0	0	100	0	130	0	230
Pomacentrus milleri	633	440	282	722	73	602	2752
Psammoperca waigensis	2	0	11	11	6	8	38
Pseudocaranx dentex	179	80	8	23	14	23	327
Pseudojuloides elongatus	0	0	0	2	0	0	2
Pseudolabrus biserialis	96	107	131	224	162	26	746
Rhabdosargus sarba	0	0	1	0	0	0	1
Scarus sp.	12	6	1	19	1	1	40
Schuettea woodwardi	201	42	0	78	517	6	844
Scobinichthys granulatus	0	0	8	3	1	7	19

	Region						
	Green Head to Sandy Point			Jurien Bay to Hill River			
Species	Open	Sanctuary	Scientific reference	Open	Sanctuary	Scientific reference	Total
Scorpis aequipinnis	0	0	0	0	1	0	1
Scorpis georgianus	19	58	0	68	32	18	195
Seriola hippos	2	2	0	10	1	0	15
Siganus fuscescens	0	6	0	422	0	0	428
Siphamia cephalotes	0	13	4	11	31	0	59
Siphonognathus beddomei	69	60	0	30	6	0	165
Siphonognathus caninus	1	3	2	6	0	0	12
Sphyraena obtusata	3	133	0	183	67	0	386
Spratelloides robustus	20	250	0	0	0	0	270
Stegastes obreptus	16	3	131	0	0	2	152
Stethojulis strigiventer	0	0	3	0	0	0	3
Stethojulis bandanensis	1	0	0	0	0	0	1
Suezichthys cyanolaemus	0	0	6	7	0	4	17
Thalassoma lunare	29	5	74	0	5	0	113
Thalassoma lutescens	55	26	122	30	26	13	272
Thalassoma septemfasciata	10	9	6	0	0	2	27
Torquigener pleurogramma	1	6	2	6	5	5	25
Trachinops noarlungae	74	305	0	695	0	1	1075
Trygonoptera ovalis	4	3	5	7	0	4	23
Trygonorhina fasciata	1	0	0	0	0	0	1
Upeneichthys vlamingii	0	1	5	1	3	0	10
Urolophus circularis	0	0	0	1	0	0	1
Total number of fish	**11846**	**9011**	**8192**	**12562**	**8760**	**7738**	**58094**

Following MDS ordination of the mean densities of each fish species at each of the 35 sampling sites in spring 2005, the samples form essentially a progression from left to right on the ordination plot according to distance offshore (Fig. 3.48). Thus, the samples from the outer reefs, which formed the tightest group, lay on the left side of the plot and did not overlap those from the nearshore reefs on the right. The samples from mid-reefs occupied an intermediate position, but overlapped more markedly those from nearshore reefs than outer reefs. ANOSIM demonstrated that the compositions of the fish faunas of the three reef categories were significantly different (Global R = 0.37, $p = 0.001$). When the data were coded for marine park zone, the compositions of the fish faunas in the different zones were not found to be significantly different (Global R = 0.047, $p > 0.1$).

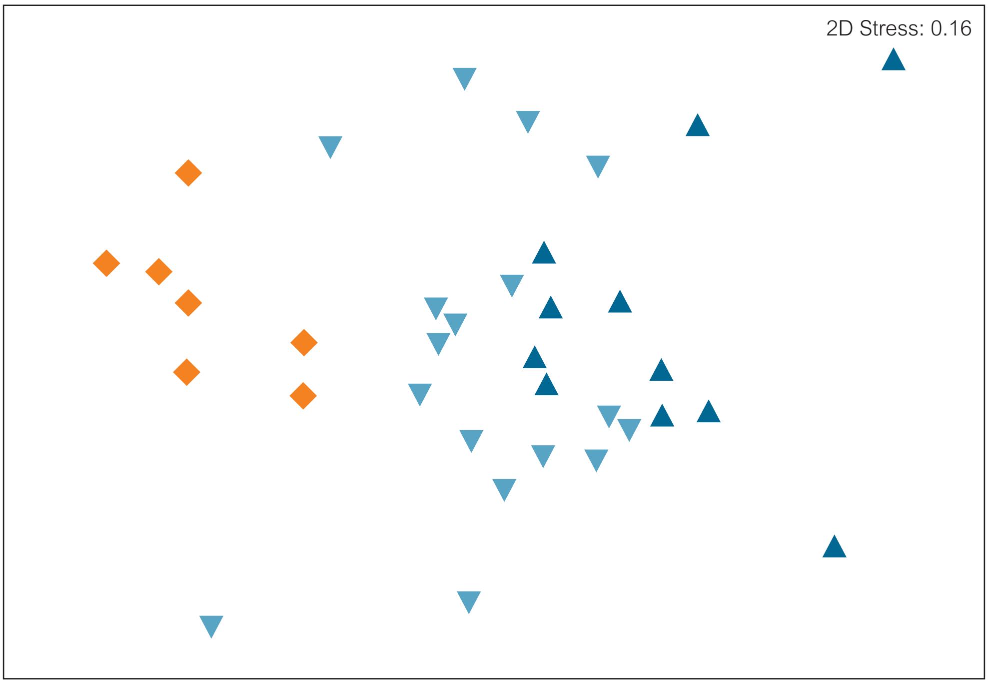

Figure 3.48: Nonmetric multidimensional scaling ordination plot of the mean densities of each fish species recorded during underwater visual census of 35 reef sites in outer reefs (◆), mid-reefs (▼) and nearshore reefs (▲) in the Jurien Bay Marine Park in spring 2005.

The compositions of species collected by trawling in seagrass and sand habitats in the first three seasons of sampling are listed in Tables 3.10 and 3.11. A total of 496 fish representing 32 species were caught by trawling over seagrass, whereas only 42 fish representing 20 species were caught by trawling over sand. The most abundant species by far over seagrass were the rough leatherjacket *Scobinichthys granulatus* and the brown-spotted Wrasse *Notolabrus parilus* followed by the rainbow cale *Odax acroptilus* and the gobbleguts *Apogon rueppellii* (Table 3.10). Seine netting of nearshore habitats yielded 2998 fish representing 33 species (Table 3.12). The most numerous of these species by far was the banded toadfish *Torquigener pleurogramma*. However, the catches of two species of hardyhead, *Atherinomorus ogilbyi* and *Leptatherina presbyteroides*, and the yelloweye mullet *Aldrichetta forsteri* were ≥ 100 fish.

Biological studies

Emphasis is being placed on obtaining sufficient numbers of the three labrid species, *i.e.* western king wrasse *Coris auricularis*, brown spotted wrasse *Notolabrus parilus* and maori wrasse *Ophthalmolepis lineolatus*, that were selected for detailed biological studies. The largest individuals of each of these species were males. These indications that each of these labrids is a protogynous hermaphrodite is supported by a preliminary examination of histological sections of their gonads. Thus, the gonads of the large fish could be categorised as secondary testes *sensu* Sadovy and Shapiro (1987), *i.e.* these testes retained the membrane-lined lumen and lamellar structure, characteristic of the ovaries found in smaller fish.

The trends exhibited throughout the year by preliminary gonadal data, such as gonadosomatic indices, demonstrate that the three labrid species are likely to spawn at different times (Fig. 3.49). Thus *Coris auricularus* is likely to spawn in autumn and early winter, whereas *Notolabrus parilus* breeds in late winter and early spring and *Ophthalmolepis lineolatus* spawns in spring and summer.

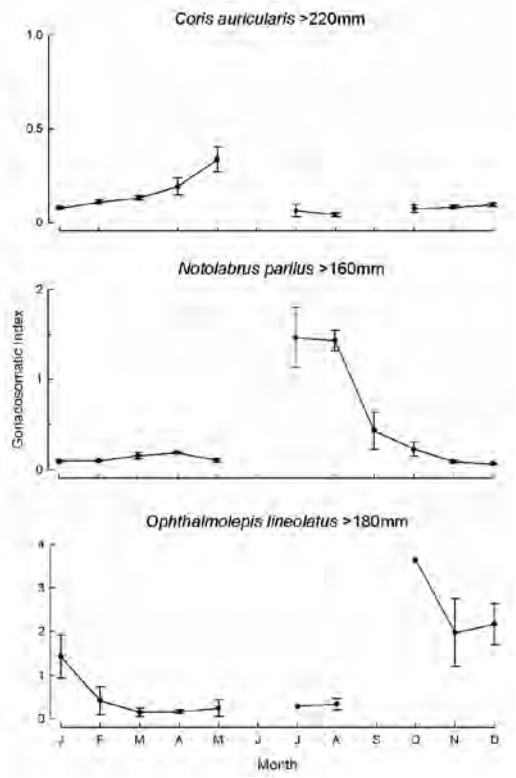

Figure 3.49: Mean monthly gonadosomatic indices for female *Coris auricularis*, *Notolabrus parilus* and *Ophthalmolepis lineolatus* for fish collected between January 2005 and March 2006.

Table 3.10. Numbers of individuals of each fish species collected during trawling of seagrass habitats in each zone in each region of the Jurien Bay Marine Park during autumn, winter and spring 2005.

	Region						
	Green Head to Sandy Point			**Jurien Bay to Hill River**			
Species	**Open**	**Sanctuary**	**Scientific reference**	**Open**	**Sanctuary**	**Scientific reference**	**Total**
Acanthaluteres spilomelanurus	3			3	3		9
Acanthaluteres vittiger	4			3		1	8
Aploactisoma milesii	1				2		3
Apogon ruepellii	4				34		38
Apogon victoriae	5	1			7		13
Aracana aurita		2					2
Brachaluteres jacksonianus	2						2
Centropogon latifrons					1		1
Choerodon rubescens		1					1
Cnidoglanis macrocephalus	4	6	1	4	1	2	18
Cristiceps australis		3					3
Cynoglossus broadhursti	1						1
Diodon nicthemerus	3	4	1		1		9
Enoplosus armatus	1		1				2
Epinephelus rivulatus						1	1
Haletta semifasciata	2	4	1	1	1		9
Hypopterus macropterus	3		2		2		7
Leviprora inops	6	2	2	1	11	2	24

Monacanthus chinensis	3	2	1		9		15
Notolabrus parilus	42	27	7	4	11	5	96
Odax acroptilus	13	11	7	8		6	46
Paraplotosus albilabris	1	1					2
Platycephalus laevigatus						1	1
Psammoperca waigiensis	1						1
Scobinichthys granulatus	49	19	15	1	51	21	165
Scorpaena sumptuosa	1				4		5
Siganus fuscescens	8	2	1				11
Siphonognathus argyrophanes					1		1
Siphonognathus radiatus	1	2	1		2		6
Torquigener pleurogramma	1					1	2
Trygonoptera ovalis	1						1
Upeneichthys vlamingii	2	1					3
Total number of fish	**162**	**88**	**40**	**25**	**141**	**40**	**496**

Table 3.11. Numbers of individuals of each fish species collected during trawling of sand habitats in the three different zones in each region of the Jurien Bay Marine Park during autumn, winter and spring 2005.

	Region						
	Green Head to Sandy Point			**Jurien Bay to Hill River**			
Species	**Open**	**Sanctuary**	**Scientific reference**	**Open**	**Sanctuary**	**Scientific reference**	**Total**
Species							
Acanthaluteres spilomelanurus						1	1
Anoplocapros robustus		1				1	2
Brachaluteres jacksonianus		1					1
Chaetodermis penicilligera						3	3
Cnidoglanis macrocephalus			1				1
Filicampus tigris		1					1
Halichoeres brownfieldi						1	1
Monacanthus chinensis			1				1
Nelusetta ayraudi					1		1
Notolabrus parilus		1					1
Odax acroptilus		4					4
Paraplagusia unicolor				1			1
Parequula melbournensis				1			1
Platycephalus speculator			1				1
Polyspina piosae		1					1
Pseudorhombus jenynsii					2	2	4
Scobinichthys granulatus		7			1	1	9
Torquigener pleurogramma	1	2			2		5
Trygonoptera mucosa	1						1
Upeneichthys vlamingii	2						2
Total number of fish	**4**	**18**	**3**	**2**	**6**	**9**	**42**

Table 3.12. Numbers of individuals of each fish species collected during seine netting on beaches in the three different zones in each region of the Jurien Bay Marine Park during autumn, winter and spring 2005. When very large samples were obtained, *e.g.* in the case of *Torquigener pleurogramma*, subsamples of approximately 50-100 fish were retained and the remainder returned to the water alive (Numbers returned alive are shown in parentheses).

Green Head to	Jurien Bay to Sandy Point			Cervantes to Hill River			Wedge Island			
Species	**Open**	**Sanct.**	**Scien. ref.**	**Open**	**Sanct.**	**Scien. ref.**	**Open**	**Sanct.**	**Scien. ref.**	**Total**
Acanthaluteres spilomelanurus	1									1
Aldrichetta forsteri	1	48		1	25		25			100
Apogon ruepellii	13	1	1							15
Arripis truttaceus				4						4
Atherinomorus ogilbyi		18	131		41	29				219
Cheilodactylus rubrolabiatus								1		1
Cnidoglanis macrocephalus		2	2		2	39		4		49
Cristiceps australis						1				1
Cynoglossus broadhursti					1					1
Enoplosus armatus	1	21					1	1		24
Hyperlophus vittatus			1							1
Leptatherina presbyteroides		129	13		12					154
Lesueurina platycephala	5		41	15	4	7			12	84
Microcanthus strigatus		2								2
Monacanthus chinensis	1	1	1					1		4
Mugil cephalus	22	3	1			1		2		29
Notolabrus parilus	1	1								2
Paraplagusia unicolor	3	5	1		3			8	1	21
Pelates sexlineatus								53		53
Pelsartia humeralis	2	8	27	3	2	28	2			72
Pentapodus vitta					1					1
Petroscirtes lupus		1								1
Platycephalus speculator	4	2			5		2	3		16
Platycephalus sp.1								1		1
Pomatomus saltatrix		2				2				4
Psammoperca waigiensis								1		1
Pseudorhombus jenynsii	2	2			8		1	1	1	15
Rhabdosargus sarba		6								6
Scobinichthys granulatus		1	1							2
Sillago bassensis	3	1	31		6	9	28	2	1	81
Sillago schomburgkii		7			1				1	9
Siphamia cephalotes	7	8			3	1				19
Torquigener pleurogramma	10	1123 (856)	353 (185)	6	397 (344)	22	1	90	3	2005 (1385)
Total number of fish	**76**	**1392 (856)**	**604 (185)**	**29**	**511 (344)**	**139**	**60**	**168**	**19**	**2998 (1385)**

Acknowledgements

Gratitude is expressed to Steven Moore, Pete Coulson, Matt Klezckwoski, Timothy Carter and Mike Travers for their invaluable help with field sampling and to Ian and Sharon Stiles of Jurien

Dive Charters. Financial support was provided by the Strategic Research Fund for the Marine Environment and Murdoch University. Elaine Lek, who is conducting the biological studies of labrids, is funded by a Murdoch University Scholarship.

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Underwood, A. J. (1997). Experiments in ecology: their logical design and interpretation using Analysis of Variance. Cambridge University Press, Cambridge.

Willis, T. J. and Babcock, R. C. (2000). A baited underwater video system for the determination of relative density of carnivorous reef fish. *Marine and Freshwater Research* 51**:** 755-763.

Conference attendance and presentations

Preliminary data on the fish fauna in reef habitats in the Jurien Bay Marine Park, which were recorded by underwater visual censuses in Autumn 2005, were presented to stakeholders and members of the scientific community involved in the collaborative SRFME project in Jurien Bay at a workshop at CSIRO on the 7th to 9th of June, which was co-ordinated by Dr Russ Babcock.

Publications and/or outcomes to date

No refereed publications have been produced at this stage. An article detailing the aims of the project and some preliminary results has been submitted to the magazine “West Coast Diver” for publication.

CHAPTER 4

4. COLLABORATIVE LINKAGES PROGRAM: STATE LINKAGES PROJECTS

4.1 SRFME State Linkages Projects

The objective of this program was to engage state government agencies in the delivery of strategic research outcomes, in conjunction with CSIRO, Universities and other research providers. A total of $155,00 has been committed to the funding of 9 state linkages projects, to institutions such as the WA Museum, Department of Environment, Department of Conservation and Land Management, Department of Fisheries, and Murdoch University. Leaders from these projects have given presentations at SRFME symposia in June 2003 and 2004. Two of the projects listed below began very late in SRFME or were funded to supplement other projects in SRFME. As a result they are not reported on in this report.

4.2 SRFME State Linkages Projects, PI's, and Affiliations

Project Title	**Institution**	**Principal**
Funding for the 12th International Marine Biological Workshop in Esperance, WA held in Feb. 2003	Western Australian Museum	Dr Fred Wells
The Marine Flora and Fauna of Esperance, WA	Western Australian Museum, Department of Fisheries WA	Dr Fred Wells
Assistance to Staff Members of the Western Australian Museum to Participate in the Biological Cruise of the Southern Surveyor off Western Australia in 2005	Western Australian Museum	Dr Jane Fromont
Funds to Facilitate Student Research Projects at the Abrolhos Islands	Department of Fisheries WA	Mr Kim Nardi
Baseline Biodiversity Monitoring in the Proposed Jurien Bay Marine Park – survey 3	Department of Conservation and Land Management	Dr Chris Simpson
WA Marine Algae: Taxonomic Studies and Identification Guide	Department of Conservation and Land Management Murdoch University	Dr Chris Simpson Dr John Huisman
Establishing Reference and Monitoring Sites to Assess a Key Indicator of Ecosystem Health (seagrass health) on the Central West Coast of Western Australia	Department of Environment	Dr Ray Masini
Supplemental Grant for Seagrass Responses to Light Availability (*note: no report required*)	Edith Cowan University Through Department of Environment	Dr Paul Lavery Dr Ray Masini
Consequences of Reduced Light availability in Seagrass Meadows for Fauna and Fisheries	Edith Cowan University Through Department of Environment	Dr Kathryn McMahon Dr Ray Masini

4.3 SRFME State Linkages Projects Reports

4.3.1 Twelfth International Marine Biological Workshop: The Marine Flora and Fauna of Esperance, Western Australia

Investigators / Institutions

Dr Fred E Wells	Western Australian Museum
Prof Diana I Walker	The University of Western Australia
Dr Gary Kendrick	The University of Western Australia

Executive Summary

A marine biological workshop was undertaken in Esperance in February 2003 during which 28 scientists from Western Australia, South Australia, Victoria and six overseas countries each conducted 17 days of field oriented research in Esperance Bay and the Recherche Archipelago. There were 28 participants in the field program. In late 2005, the Western Australian Museum published the 2 volumes, 727 pages, *The Marine Flora and Fauna of Esperance, Western Australia.* The volumes contain 29 scientific papers discussing a wide range of ecological and taxonomic studies of the marine plants and animals of the southeastern part of Western Australia.

Background

Western Australia is a huge State, occupying the western third of the continent. Until relatively recently, this vast coastline had been largely unexplored by scientists. The presence of some groups of organisms in the marine environment of Western Australia is still totally unknown. In 1986 Dr Fred Wells of the Western Australian Museum proposed that a series of marine biological workshops be held in Western Australia to allow scientists from interstate and overseas the opportunity to work with Western Australian scientists to generate scientific information about the marine environment of Western Australia. The proposal was accepted by the Museum and the WA Branch of the Australian Marine Sciences Association. From the outset the workshop has been a cooperative venture which has also included organisers from CSIRO (Dr Hugh Kirkman), and Murdoch University (Assoc Prof Roger Lethbridge). While the workshop organisers have changed from time to time, Prof Di Walker of The University of Western Australia has been actively involved since the Albany workshop. The Western Australian workshops have attracted about 200 scientists from leading institutions throughout the world: about one-half have been from overseas; one-fourth from the eastern states; and one-fourth from Western Australia.

The workshops are modelled on workshops held at the University of Hong Kong since 1977, and are numbered as part of an international series. Two other workshops have been held in Australia: Darwin in 1993 and southeast Queensland in 2005. Other workshops, devoted specifically to molluscs, have been held in Hong Kong, California, Portuguese Azores, Florida Keys, and Thailand. A similar marine biological workshop is scheduled for Singapore in 2006.

Format

Established researchers were invited to participate in the workshop. The Australian Marine Sciences Association has provided funds to allow one or two graduate students to participate. Each participant was responsible for obtaining his/her own fare for travel to/from Perth, to the workshop locality and the cost of the workshop. Workshops are held in as inexpensive a manner as possible.

The local organisers provided basic accommodation, laboratory space, access to dive gear and boats. The workshops allow participants the opportunity to work on their own research projects with a minimum of hassle and organisational responsibilities. The presence of a number of other scientists at the workshop provides opportunities for joint research and a number of Western Australian scientists have taken advantage of the opportunities provided.

It takes two years to plan and organise a workshop, and for the participants to obtain funding for their participation. The field portion of the workshop is for 17 days. Each participant is expected to undertake one or more research projects in his/her area of expertise and publish the results in a workshop proceedings. Proceedings are published three years after completion of the field portion of the workshop. All papers are refereed.

To date eight workshops have been held in Australia (including Esperance), and a total of 10 volumes have been published. A substantial portion of the workshop output has been devoted to documenting the marine flora and fauna of Western Australia, the Northern Territory and Queensland. There has also been considerable work on the ecology, physiology, functional morphology, and other aspects of the biology of various organisms. Recent WA workshops have benefited considerably from the preparation of papers by Alan Pearce of CSIRO and others which have drawn together published and unpublished information on the physical oceanography of the Houtman Abrolhos and the Dampier Archipelago.

Much of the work has been of immediate practical advantage to managers of the marine environment, including the Environmental Protection Authority, Department of Conservation and Land Management and the Department of Fisheries Western Australia.

Esperance Workshop

SRFME generously supported part of the costs of the field and publication components of the Esperance workshop, which was undertaken in February 2003. There were 28 participants in the field program. In addition to participants from WA, there were scientists from South Australia and Victoria. Overseas participants were from China, Germany, Singapore, Thailand, United Kingdom, and United States.

The goal of the marine biological workshops is to substantially increase the rate of exploration of the marine biology of Western Australia by attracting interstate and international colleagues to the State to work in a particular geographic area for a short period of intensive fieldwork. As the participants pay their own fares, etc, no attempt is made to specify what research they should undertake. However, as with previous workshops, the research can be divided into several components:

Documentation. There is considerable need in the State for basic documentation of the biota which inhabits our waters. Many groups have never been examined by specialists. In conjunction with examination of specimens at the WA Museum, the workshops offered a unique opportunity for systematic research. New species were found at Esperance of marine mites, oligochaetes, molluscs, mysids, tanaids, and pycnogonids. Range extensions, often on the scale of hundreds of kilometres, were made in many taxa.

Animal biology. A number of studies were made of the biology of animals, including reproductive biology of coralliophilid snails, feeding of the snail *Lepsiella* on limpets, ecology of trochid snails, infauna of Bandy Creek, bivalve ecology and morphology, and epiphytic grazers on seagrasses.

Plant biology. There is a rich diversity of marine algae and seagrasses in the Recherche Archipelago. Considerable work was undertaken in documenting this biota and exploring the roles the plants play in the ecosystems, both algae and seagrasses. Studies included the distribution of rhodoliths, growth rates of seagrasses, nutrient status of inshore and offshore plants, and experimental work with the plants.

Plant-animal interactions. Two studies integrated relationships between plants and animals.

One was on the diverse fauna inhabiting the algal rhodoliths. The other was on an intriguing sponge-algal association found during the workshop.

Benthic mapping project. A group led by Dr Gary Kendrick of the University of Western Australia conducted a major program of benthic habitat mapping in the Recherche Archipelago, funded by the Fisheries Research and Development Corporation and the Strategic Fund for Research in the Marine Environment. Many of the WA scientists at the workshop were also involved in the habitat mapping project, allowing considerable synergies between the two programs which will benefit both.

Publicity. One important aspect in furthering marine science in Western Australia is to make the findings available to the public. This was done in the following ways: newspaper articles in the *The Age (Melbourne), The West Australian, Esperance Express,* and *Kalgoorlie Miner*; radio interviews on ABC regional radio, ABC Perth and ABC Melbourne; and a television interview on GWN News. In addition, Sarah Coote and Corey Whisson visited local primary schools to talk to students about the workshop and what was happening.

A formal launch of the volumes was held at the WA Fisheries and Marine Research Laboratory at Hillarys in February 2006.

Publications and/or outcomes to date

Wells, F.E., Walker, D.I., A. Kendrick, G. (2005). *The Marine Flora and Fauna of Esperance, Western Australia.* Western Australian Museum, Perth. 727 pages.

4.3.2 Assistance for the Publication of The Marine Flora and Fauna of Esperance, Western Australia

Principal Investigator / Institution

Dr Fred E Wells	Western Australian Museum (currently on secondment to the WA Dept of Fisheries)

Collaborating Personnel and Agencies

Prof Diana I Walker	Department of Plant Science (Botany) University of Western Australia
Dr Gary Kendrick	Department of Plant Science (Botany) University of Western Australia

Introduction

Since 1988, the Western Australian Museum, University of Western Australia, WA Branch of the Australian Marine Sciences Association and other agencies have combined to conduct a series of marine biological workshops in Western Australia. The State covers a huge area with a coastline of over 12,000 km and three marine biogeographic regions. The WA coast has impressive sections which have been established as marine parks, and marine ecosystems support productive fisheries which underpin the economies of many coastal towns. The short European history, large distances, inaccessible coastline, few marine biologists, and other factors combined to make the marine ecosystems of Western Australia poorly known, and the rate of discovery was low. In recognition of this, the marine biological workshop series was established to encourage interstate and overseas scientists to come to Western Australia to work in a single area for about 17 days on one or more research projects of their choosing, with the goal of publishing the results three years later in a joint workshop proceedings.

The workshops have been held as part of a numbered international series which started at the University of Hong Kong. Similar workshops, which concentrated on molluscs, have been held at the University of Hong Kong, in the Portuguese Azores, California and the Florida keys. A similar marine biological workshop was be held by AMSA SE Queensland in Moreton Bay in February 2005, and further mollusc workshops are planned for Thailand (2005) and Singapore (2006).

The Australian program has been phenomenally successful. Seven workshops have been held: Albany (1988), Rottnest Island (1991; 1996), Darwin (1993 organised by AMSA NT); Houtman Abrolhos Islands (1994); Dampier (2000) and Esperance (2003). To date the results of six of the workshops have been published. A list is attached. These publications total 10 volumes and over 3,500 pages. They provide a wealth of information on the marine biology of the western half of Australia. Over 300 new species, 20 new genera and 2 new families have been described. In addition there are hundreds of range extensions, with many taxa being recorded for the first time in Australia. There is considerable information which has been used by marine managers in maintaining coral reefs, mangroves, seagrass meadows, estuaries and other habitats. For example, about a third of the papers cited in *Management of the Houtman Abrolhos System* were published in the proceedings of the Abrolhos workshop. The workshops have deliberately been held in different geographic locations to cover the three marine areas of the State: tropical north coast, temperate south coast and west coast overlap zone.

The most recent workshop was held at Esperance on the south coast in February 2003. Twenty-eight people from Western Australia, South Australia, Victoria and six overseas countries (China, France, Singapore, Thailand, United Kingdom, and United States) participated in the workshop. The field component was generously supported by SRFME.

SRFME assisted in publishing the proceedings of the 2003 Esperance workshop. The assistance provided top up funds for the publication, limited use of colour, and hard binding. While the information and printing are otherwise identical to soft bound volumes, the use of colour and hard binding considerably increased the durability and appearance of the volumes.

Objectives of the project

The goal of the workshop program was to document the flora and fauna of the area being examined. In the ease of taxonomic papers, participants were encouraged to also utilise zoological specimens held in the collections of the Western Australian Museum or botanical material held by universities. All holotypes were deposited in the WA Museum or WA Herbarium.

Other papers examined subjects such as distributional patterns, ecology of particular species, groups, or habitats, physiology, and functional morphology.

These papers develop a considerable amount of information rapidly, and cost effectively, that would not otherwise become available. In general participants pay their own way to Australia and their costs at the workshop; their home institutions pay their salary both during the workshop and the write-up phase. In addition to the workshops themselves, a number of professional partnerships have been developed which have resulted in further work, both in Western Australia and elsewhere.

Work program and publication of proceedings

The field component of the workshop was held in Esperance in February 2003. The proceedings have been published in two volumes with a total of 24 peer-reviewed papers included.

Linkages with SRFME research priorities and core projects

This project is closely linked with SRFME Core Project 2, Coastal Ecosystems and Biodiversity. SRFME generously supported part of the costs for the field component with a grant of $ 15,000, and two SRFME staff participated. The proceedings of the Esperance workshop provide considerable information on the marine biodiversity and coastal ecosystems of the Recherche Archipelago region.

Relevance to State government polices and programmes

The WA government has an active program of developing marine parks in the State. The 1994 report on a representative system of marine reserves for the Western Australia listed the Recherche Archipelago as an area worth further consideration. This work is being undertaken by CALM. In conjunction with a number of State government departments, the National Oceans Office is targeting the southwest as the first part of Western Australia to be examined for bioregional marine planning. Documentation of marine biodiversity is an integral part of the WA Museum's program in documenting the marine fauna of Western Australia. The WA Herbarium in CALM has a similar responsibility for flora and works in conjunction with the universities. The WA Department of Fisheries is actively considering options for aquaculture for the Recherche Archipelago. All of these agencies will benefit from publication of the results of the Esperance workshop.

In addition, there was a major study conducted in the Recherche Archipelago, centred at UWA. The workshop was done in close collaboration with the UWA study.

Proceedings of Previous Australian Workshops

Hanley, J.R., Caswell, G., Megeriaq D. and Larson, H.K. (Eds.) (1997), *Proceedings of the sixth international marine biological workshop: The Marine Flora and Fauna of Darwin Harbour, Northern Australia.* Northern Territory Museum, Darwin and the Australian Marine Sciences Association.

Wells, F.E., Walker, D.L, Kirkman, H., and Lethbridge, R. (Eds). (1990/91). *Proceedings of the third international marine biological workshop: The marine flora and fauna of Albany, Western Australia.* Western Australian Museum, Perth. 2 volumes, 722 pages

Wells, F.E., Walker, D.L, Kirkman, H., and Lethbridge, R. (Eds). (1993). *Proceedings of the fifth international marine biological workshop: The marine flora and fauna of Rottnest Island, Western Australia.* Western Australian Museum, Perth. 634 pages.

Wells, F. E. (Ed). (1997). *Proceedings of the seventh international marine biological workshop: The marine flora and fauna of the Houtman Abrolhos Islands, Western Australia.* Western Australian Museum, Perth. 566 pages.

Walker, D.L, and Wells, F.E. (Eds). (1999). *Proceedings of the ninth international marine biological workshop: The seagrass flora and fauna of Rottnest Island, Western Australia.* Western Australian Museum, Perth. 421 pages.

Wells, F.E., Walker, D.I., and Jones, D.S. (2003). *Proceedings of the eleventh international marine biological workshop: The marine flora and fauna of Dampier, Western Australia.* Western Australian Museum, Perth. 587 pages.

Esperance Workshop Participants

Dr Roger Bamber, Natural History Museum, London, England

Dr Ilse Bartsch, Forschungsinstitut Senckenberg, Hamburg, Germany

Dr Rudiger Bieler, Field Museum of Natural History, Chicago, Illinois, USA

Dr Anne Brearley, The University of Western Australia, Nedlands, Western Australia

Dr Marion Cambridge, The University of Western Australia, Nedlands, Western Australia

Ms Sarah Coote, The University of Western Australia, Nedlands, Western Australia

Ms Nisse Goldberg, University of Western Australia, Nedlands, Western Australia

Ms Emily Glover, Natural History Museum, London, England

Prof Carole Hickman, University of California, Berkeley, California, USA

Dr John Keesing, CSIRO Marine Research, Floreat, Western Australia

Dr Gary Kendrick, The University of Western Australia, Nedlands, Western Australia

Prof Alan Kohn, University of Washington, Seattle, Washington, USA

Mrs Marian Kohn

Mr Alan Longbottom, Honorary Associate, Western Australian Museum, Perth, Western Australia

Mrs Joy Longbottom

Dr Justin McDonald, The University of Western Australia, Nedlands, Western Australia

Mr Tim Moore, Flinders University, Adelaide, South Australia

Dr Julia Phillips, CSIRO Marine Research, Floreat, Western Australia

Mr Kitithorn Sanpanich, Institute of Marine Sciences, Burapha University, Bang Saen, Thailand

Dr S.A. Shepherd, South Australian Research and Development Institute, Adelaide, South Australia

Mrs Anna Shepherd

Dr Tan Koh Siang, National University of Singapore, Singapore

Prof John Taylor, Natural History Museum, London, England

Prof Di Walker, The University of Western Australia, Nedlands, Western Australia

Dr Hongzhu Wang, Chinese Academy of Sciences, Hubei, Wuhan, China

Dr Jan Watson, MuseumVictoria, Melbourne, Victoria

Dr Fred Wells, Western Australian Museum, Perth, Western Australia

Mr Corey Whisson, Western Australian Museum, Perth, Western Australia

Marine Flora and Fauna of Esperance, Western Australia (List not complete)

Introduction

Introduction to the marine biology of the Recherche Archipelago, Western Australia. Gary Kendrick, Euan Harvey, Justin McDonald, Fred Wells and Di Walker.

Fauna

The Tanaidaceans (Arthropoda: Crustacea: Peracarida: Tanaidacea) of Esperance, Western Australia. Roger N. Bamber.

The Pycnogonids of Esperance, Western Australia. Roger N. Bamber.

Western Australian *Werthella* (Copidognathinae: Halacaridae: Acari), description of a new and notes on related species. Ilse Bartsch.

The Australian Agauopsis fauna (Halacaridae: Acari), with description of new and known species of Western Australia. Ilse Bartsch.

The rhombognathine fauna of Australia (Rhombognathinae: Halacaridae: Acari) with notes on the fauna of Esperance, Western Australia. Ilse Bartsch.

Anatomy and morphology of *Stephapoma nucleogranosum* Verco, 1904 (Caenogastropoda: Siliquariidae) from Esperance Bay, Western Australia. Rudiger Bieler and Luiz Ricardo L. Sunone.

Checklist of marine fishes of the Recherche Archipelago and adjacent mainland waters. J. Barry Hutchins.

Anthropogenic enhancement of marine invertebrate diversity and abundance: Intertidal infaunal invertebrates along an exposure gradient at Esperance, Western Australia. Alan J. Kohn and Amanda Blahm.

Diets of the predatory gastropods *Cominella* and *Conus* at Esperance, Western Australia. Alan J. Kohn, Kaitlin M. Curran and Brenda J. Mathis.

Rhodoliths: The inside story. Brenda J. Mathis, Alan J. Kohn, and Nisse A. Goldberg.

Solitary Ascidiacea from shallow waters of the Archipelago of the Recherche, Western Australia. Justin I. McDonald.

Echinoderms of the Archipelago of the Recherche, Western Australia. Justin I. McDonald.

Ontogenetic changes in diet, feeding behaviour and activity of the western blue groper, *Achoerodus gouldii*. S.A. Shepherd.

Notes on the southern endemic southern Australian corallivorous gastropod *Coralliophila mira* (Neogastropoda: Coralliophilidae). Tan Koh-Siang.

Another bloody bivalve: anatomy and relationships of *Eucrassatella donacina* from south Western Australia (Mollusca: Bivalvia: Crassatellidae). John D. Taylor, Emily A. Glover and Suzanne T. Williams.

Hydroids of the Archipelago of the Recherche and Esperance, Western Australia: Annotated List, Redescription of Species, and Description of new Species. Jeanette E. Watson.

The marine molluscs of Esperance Bay and the Recherche Archipelago, Western Australia. Fred E. Wells, Alan F. Longbottom and Joy Longbottom.

Feeding of *Lepsiella flindersi* (Adams and Angas, 1863) on the limpet *Patelloida alticostata* (Angas, 1865), near Esperance, Western Australia. Fred E. Wells and John K. Keesing.

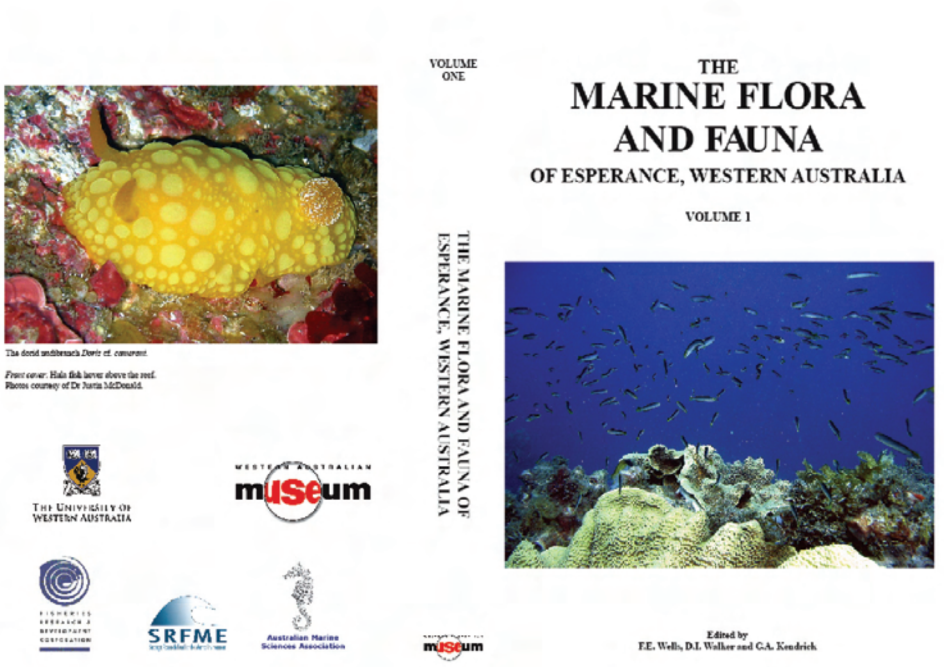
Flora

A catalogue of the marine plants found in the western islands of the Recherche Archipelago, Western Australia, with notes on their distribution in relation to island location, depth, and exposure to wave energy. N.A. Goldberg and G.A. Kendrick.

First record of tetrasporangia in *Herposiphoniella plurisegmenta* Womersley. Nisse A. Goldberg and John M. Huisman.

Variability of leaf morphology and growth in *Posidonia kirkmanii* growing in a spatially structured multispecies mosaic. Tim N. Moore, Marion L. Cambridge and Peter G. Fairweather.

Use of C:N ratios to assess the nutrient status of macroalgae growing at different depths in the Esperance region, Western Australia. Julia C. Phillips.



The dorid nudibranch *Doris* cf. *cameroni*.

Front cover: Hula fish hover above the reef.
Photos courtesy of Dr Justin McDonald.

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THE MARINE FLORA AND FAUNA OF
ESPERANCE, WESTERN AUSTRALIA

museum

THE
MARINE FLORA
AND FAUNA
OF ESPERANCE, WESTERN AUSTRALIA

VOLUME 1

Edited by
F.E. Wells, D.I. Walker and G.A. Kendrick

Fig. 4.1: Cover of *The Marine Flora and Fauna of Esperance, Western Australia*. The dorid nudibranch *Doris* cf. *cameroni*. *Front cover*: Hula fish hover above the reef. Photos courtesy of Dr Justin McDonald.

4.3.3 Assistance to staff members of the Western Australian Museum to participate in the biological cruise of the Southern Surveyor off Western Australia in 2005

Investigators / Institutions

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Western Australian Museum

Collaborating Agencies

CSIRO
Museum of Victoria, Melbourne
Australian Museum, Sydney

Introduction

Relatively little is known about the benthic biodiversity in the vast expanse of the Australian Exclusive Economic Zone (EEZ) adjacent to Western Australia. For example, a review of existing data available for the national deep water bioregionalisation shows that, in the national context, the outer continental shelf and slope of the southwest region (SWR) of Western Australia is particularly data-sparse (Last *et al.*, 2004).

Presently, there is also a selective and incomplete treatment of the taxa and taxonomic resolution of fauna used to determine bioregions. For example, the best known taxa are the fishes as they tend to be larger, more visible, and well surveyed for fisheries purposes. Many other taxa are small, less mobile, can be captured only with specialised gear, are sometimes extraordinarily diverse, but so far poorly sampled in the SWR. Such taxa could provide novel insights into bioregional structure, but a dedicated research effort is required.

The geographic extent of the project is the outer continental shelf and continental slope (~100-1000 m) between the western Great Australian Bight and the northwest coast of Western Australia (east of Albany to Dampier).

This project allowed for staff of the WA Museum to participate in the 'voyage of discovery' off Western Australia in November and December 2005. The Museum staff were involved specifically to determine the sponges, echinoderms (seastars) and molluscs collected. The sponges were thought to be one of the dominant benthic space occupying fauna at the sampling depths proposed and the molluscs and echinoderms were anticipated to be some of the dominant motile taxa found. Expertise for these three groups is in the WA Museum.

In addition, the WA Museum were to ensure that voucher specimens of each species collected would be accessioned into the State's Museum. This is critically important for building on the State's intellectual knowledge base of the marine fauna of WA, and the biological cruise was in areas that had little to no sampling at these depths, particularly the SWR. Any holotypes and a proportion of paratypes are to be lodged in the WA Museum.

Objectives of the project

The biological survey data will meet the following over-arching science objectives:

- Test hypotheses on the evolution and biogeography of Australia's biodiversity.
- Examine the biogeographic patterns exhibited by shallow water species in southern temperate Australia and determine if they are also reflected in deeper water of the SWR (cf. O'Hara & Poore, 2000).
- Examine the biogeographic patterns exhibited by tropical upper slope fauna from the

"North West Shelf" (cf. Ward & Rainer, 1988) and determine if they are also reflected in sub-tropical and temperate waters of the SWR.

- Determine if a clinal pattern in the SWR is detectable in the epibenthic invertebrate community, and in selected species-rich taxa, such as that hypothesised for fishes (cf. Williams et al., 2001).
- Determine if the high diversity associated with the continental slope and seamounts in southeastern Australia is mirrored in the SWR (cf. Poore & Wilson, 1993; Poore et al., 1994; Richer de Forges et al., 2000; Koslow et al., 2001).

The sampling allowed for the first large scale assessment of marine biodiversity at a range of depths off the shelf of WA. This will enhance broad understanding of the WA marine ecosystem and help decision making for ecologically sustainable development and conservation in the marine environment. The results of the expedition will provide managers and resource users with broad-scale information on resource distributions, hotspots of biodiversity, presence of unique fauna, correlative relationships among species and habitats, and baseline data for monitoring future change. This will build capacity in WA for bioregional marine planning and management. In particular it will benefit research being undertaken by SRFME off Jurien Bay, the proposed Ningaloo Research Program, and the Marine Futures Program in the South West.

Results

A 'physical' cruise was undertaken in July and August 2005 to map the bathymetry and seabed characteristics using swathmapping and other bioaccoustic methods. The 'biological' cruise of the Southern Surveyor began in Fremantle on 18th November and ended in Dampier on 14th December 2005. The WA Museum placed mollusc and sponge specialists on board the vessel. Preliminary identifications and sorting were undertaken on the cruise with supplementary photographic records of the species collected. Specimens were appropriately preserved for accessioning into the Museum at the end of the program. We are now in the 'post cruise' phase of the project and undertaking specimen processing and preliminary identifications.

The number of asteroid specimen lots (seastars) processed so far is 152. All these specimens have been unpacked out of field containers and placed in Museum glassware. Forty-one of the specimens have been identified to family level.

Most of the mollusc specimens collected have been sorted and identified to at least Family level. This includes approximately 1200 dead-taken and 700 live-taken specimen lots. All six molluscan classes appear to be present, and preliminary identifications indicate as many as 100 families could be represented. Several new records and range extensions of mollusc species have been proposed, as well as possible undescribed (new) species. These await investigation and confirmation. Such examples include the first record of a *Conus* species in Australia and a range extension and rare live specimen of *Austroharpa wilsoni* Rehder, 1973 (Figure 4.2).

By far the largest component of the biomass in the shallower depths sampled (100-200 metres) consisted of sponges (Porifera). In total, 550 'morphospecies' (i.e. identified in the field as distinct species but requiring taxonomic verification) were collected on the expedition. Presently the sponge processing awaits the appointment of a Technical Officer to begin work on unpacking, initiating histology and assisting with identifications.

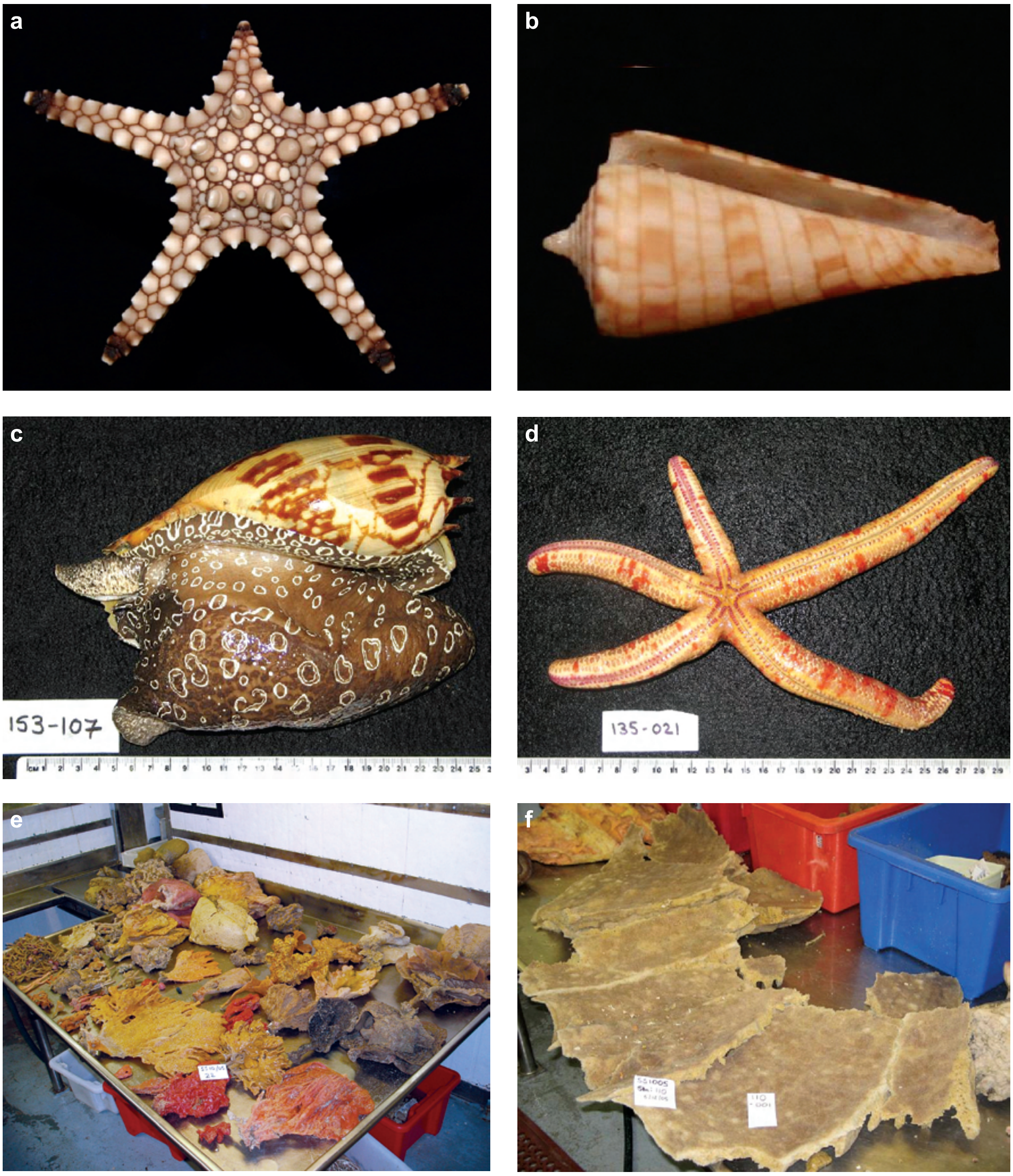

Figure 4.2: Images taken during the SS1005 *Voyage of Discovery*.

a. One of only a few WA records of the seastar *Milteliphaster regenerator* (Station 115).
b. A species of Cone Shell, *Conus* sp. not previously recorded in this area (Station 146).
c. The Bailer Shell *Melo* cf *amphora* not commonly known at this depth (Station 153).
d. A giant seastar from the family Ophidiasteridae (Station 135).
e. A selection of demosponges collected off Albany at 100m (Station 22).
f. Pieces of a large, cup-shaped demosponge collected near Shark Bay (Station 110).

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4.3.4 Assessing the Potential Benefits of Marine Protected Areas to Adjacent Fished Areas

Investigators / Institutions

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Executive Summary

I commenced this project in February 2005 and am currently in the middle of my first field season. Here I present data from the various pilot studies I have undertaken.

Currently I am assessing the feasibility of determining the potential reproductive output for coral trout (*Plectropomus leopardus*) and red-throat emperor (*Lethrinus miniatus*). The current status of the project suggests that a description of spawning aggregations and reproductive output from an aggregation within MPAs could be possible for *P. leopardus,* however, the reproductive potential for *L. miniatus* is unlikely to be established. Pilot work on the movement patterns of West Australian dhufish (*Glaucosoma hebraicum*) has had some issues with the post-operative survival of dhufish and modifications to the catch and holding procedures are currently being developed. If these are successful, then the movement patterns of dhufish can be tracked within MPAs.

Introduction

Marine Protected Areas (MPAs), often referred to as either sanctuaries, refugia, marine reserves or no – take zones, are used throughout the world to denote areas where the extraction of some or all marine organisms from an area is illegal (Newman et al. 2002, Gell and Roberts 2003, Halpern 2003). The advent of MPAs is a relatively recent management measure designed either to conserve marine biodiversity, or to serve as an additional tool in the management of fisheries stocks (Newman et al. 2002, Roberts et al. 2003).

As a fisheries management tool, MPAs create an area of increased abundance and biomass, that on average, double density, triple biomass, and increase organism size and diversity by 20 – 30% compared to adjacent unprotected areas (Gell and Roberts 2003, Halpern 2003) (Figure 4.3). Theoretically, the increased abundance and biomass of fish in MPAs provide benefits to the adjacent fishery, through the supply of larvae from increased reproductive output, and / or through spillover and the movement of post-settlement individuals of all ages from the closed area to fished grounds (Gell and Roberts 2003). Alternatively, MPAs may provide no potential benefits to the adjacent fished areas.

MPA planning and function is a contentious issue, both socially and politically. Direct evidence of export to adjacent fisheries from MPAs is crucial for their widespread understanding and acceptance. Currently there is little empirical evidence to support theoretical export functions of MPAs. In order to assess this gap in the understanding of the function of MPAs, we need to know the biology and movement patterns of key species as well as how species are affected by protection. As such the movement, biology, age and growth, as well as reproductive biology, will be compared with underwater visual census data to examine the potential export functions of MPAs.

Aims

Aim: To assess the potential benefits Marine Protected Areas to adjacent fished areas.

The specific aims are to:

1. Describe the age structure, growth rates and mortality of *Plectropomus leopardus* and *Lethrinus miniatus* in the Houtman Abrolhos Island region
2. Describe the reproductive biology of *Plectropomus leopardus* and *Lethrinus miniatus*;
3. Assess the potential reproductive output from Reef Observation Areas (ROAs) for *Plectropomus leopardus* and *Lethrinus miniatus*;
4. Investigate the movement patterns of commercially important reef fish species to relate size of home range to response to protection and potential for cross boundary movement in MPAs

Methods

Biology of *P. leopardus* and *L. miniatus*

Between 20 and 50 coral trout and red-throated emperor will be collected monthly to collect biological information. Sample collection has begun and will continue for 18 months. Samples are either whole or filleted fish. Most of the samples will be collected from fish markets with some additional research sampling for size not available in the commercial catch.

All fish will be measured (TL, FL, SL) and weighed when whole. Otoliths will be removed washed and stored in paper envelopes. Otoliths will be examined whole, and also embedded in resin and sectioned with a low speed saw to be examined microscopically. Growth zones will be counted for aging. Growth will be described through the von Bertalanffy growth equation, providing estimates of the asymptotic length (L_∞), growth coefficient (K) and theoretical age at length zero (t_o) (King 1995).The age structure of the commercial catch can then be examined as well as determining total mortality for each species.

The gonads of all fish will be weighed to the nearest 0.1g sexed and staged according to the criteria of Mackie and Lewis (2001). Gonads will then be fixed in 10% neutral buffered formalin for at least a week before being stored in 70% ethanol.

The peak spawning period for coral trout and red-throated emperor will be determined by examining the annual trends in monthly gonad stages, and average gonadosomatic index (GSI). Histological sections of ovaries will be used to determine the reproductive biology for each species i.e. examining sexual transition from female to male, and frequency of spawning in each spawning period.

Fecundity measures will be taken from a sub-sample of females collected from both inside and outside of ROAs at peak spawning period. Gonads from a wide size range of mature female fish will be weighed before being placed in Gilson's fluid to remove the connective tissue of the ovary. With mature oocytes separated from the tissues, the number of mature oocytes will be counted from three pre-weighed sub-samples. An estimate of the total number of mature eggs in the whole gonad can then be extrapolated. A relationship between fish size and fecundity can then be established through a regression analysis.

Reproductive data such as length – fecundity relationships, size and maturity and sex change will be used to assess the reproductive potential of these two species.

Reproductive Potential

To determine the reproductive potential from, *P. leopardus* and *L. miniatus*, reproductive data (see above) will be compared to length frequency data of both species inside and outside the ROAs. Initial surveys focused on locating spawning aggregations of *P. leopardus*, and preferred habitats of *L. miniatus* before broader surveying was undertaken.

Plectropomus leopardus Spawning Aggregations

To locate *P. leopardus* spawning aggregations, three 100x5m transects were used to record abundances and sizes of *P. leopardus* and other commercially important species. Sites were selected in areas where there was likely to be more water movement, as these have been shown to be areas where fish tend to aggregate for spawning (Colin et al. 2003). Small areas along or adjacent to the transect that appeared to have slightly higher numbers of *P. leopardus* were noted for later examination. As most spawning activity appears in *P. leopardus* on sunset (Samoilys 1997), those sites identified from the transects were examined at sunset to confirm if they were spawning aggregations.

Lethrinus miniatus Abundance

To assess the reproductive potential of ROAs and fished areas for *L. miniatus*, it was necessary to determine the major habitats that they occupy. To assess the distribution of *L. miniatus* in ROAs and adjacent habitats, three sites within three different habitats were surveyed for size and abundance of *L. miniatus*. These included reef slopes, inshore channels and deep drop offs. At each site, three transects of 100x5m were scored for abundances and sizes (5cm TL size classes) of *L. miniatus*.

Dhufish Movement / Acoustic tagging

Surgical Trials on three Species of Cultured fish

Initial surgical techniques were developed and refined through surgery on six individuals from three species of cultured fish; three pink snapper (*Pagrus auratus*), two mulloway (*Argyrosomus hololepidotus*) and a tarwhine (*Rabdosargus sarba*). Fish had been held in tanks at the Department of Fisheries, and were returned to the same 5000L tanks after surgery for monitoring. All fish were anaesthetised, underwent surgery and recovery. Only some were implanted with dummy acoustic tags or received OTC injections (see Table 4.1).

As the trials were successful and the surgical method was developed, we employed this technique in the field on dhufish (see below). Trials were conducted off Geographe Bay (Figure 4.5) and Fremantle (Figure 4.6). Dhufish were caught on hook and line at depths of less than 30m where possible, to reduce catch mortality (St John and Syers 2005).

On board handling protocol and Surgical Techniques

Once caught, fish were placed into a holding tank and transported to the release site if it was different to the initial capture site. Fish were then placed in a separate tank where they were anaesthetised using clove oil. A length measurement was taken prior to surgery commencing. A few lines of scales were removed from the exposed ventral side and a 3 cm incision running anteriorly was made starting at approximately 2 cm from the anus , and 2 cm laterally from the midventral line (Zeller 1999). Once the dummy tag was implanted, the wound was closed with monofilament, non-absorbable sutures and an antibiotic injection of oxytetracycline was administered intramuscularly. The fish was then transferred back into the same holding tank with air or oxygen bubbled underneath their gills and fresh seawater introduced periodically. Once the dhufish was showing signs of recovery (tail kicks or finning), a sling was used to transfer the fish from the tank to the sea cage. A wet towel was used with all handling and transfers to reduce stress and damage. The sea cage was then slowly lowered to the bottom.

Monitoring fish survival and behaviour

Divers monitored fish in the sea cages recording swimming and cage position, stress colours and other relevant behaviour. Although monitoring was planned for several time periods; immediately after release into the cage, on day one and on the day of release (either day two – four) this was not always possible due to weather and logistical constraints.

Study sites,

Houtman Abrolhos Islands

The Houtman Abrolhos Islands consists of around 122 low lying islands and associated reefs some 60 km offshore of Geraldton on the Western Australian mid west coast (Figure 4.3). These islands are concentrated into three major island groups, the Wallabi, Easter and Pelsaert groups. Each of these groups is separated by 6 – 10 km wide, 40m deep channels (Anon 2001). The islands are surrounded by the most southern coral reefs in the Indian Ocean inhabited by tropical species of fish and invertebrates. This habitat is unique because tropical reefs co-occur with temperate algae species endemic to Western Australia (Anon 1998).

The work to date on reproductive potential has been conducted primarily in the Reef Observation Area (ROA) at the Easter Group of the Houtman Abrolhos Islands (Figure 4.3). The underwater visual surveys were conducted within a range of habitats around the Leo's ROA (Figure 4.4).

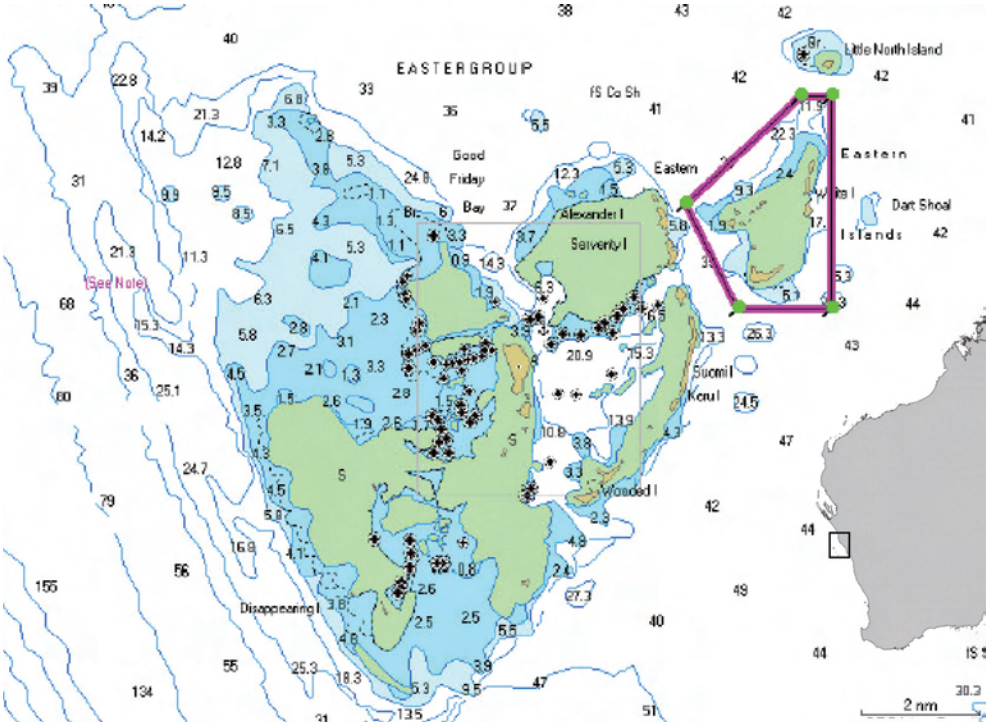

Figure 4.3: The Easter Group of the Houtman Abrolhos Islands featuring the Reef Observation Area (ROA) bordered in pink

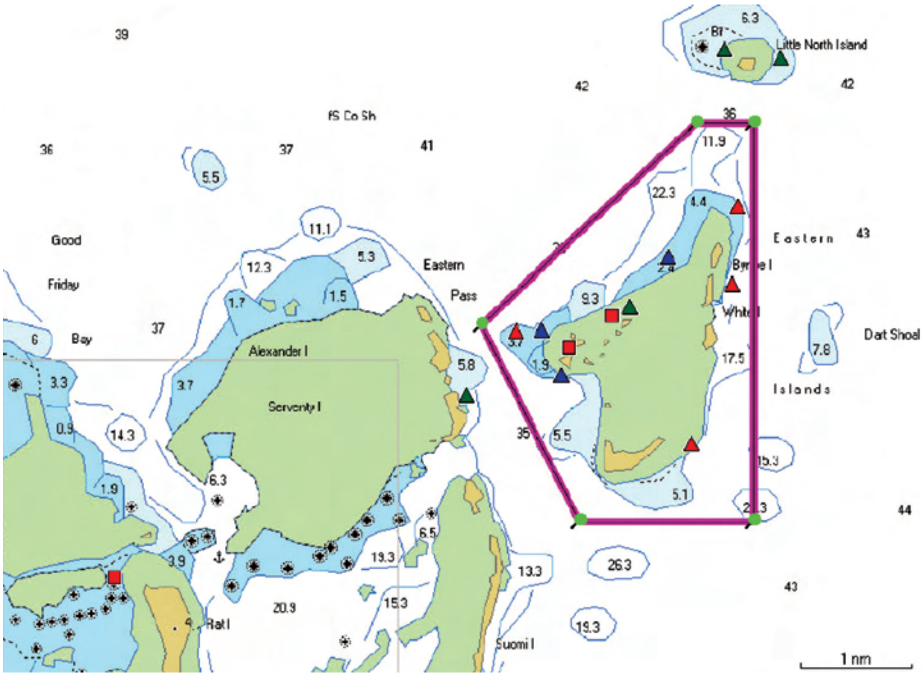

Figure 4.4: Underwater visual census of habitats around the Leo Island ROA at the Easter Group of the Houtman Abrolhos Islands. ▲ Coral Drop offs ▲ Deep Sites 🟥 Channels ▲ Snorkels

Dhufish Movement / Acoustics tagging

Initial trials of surgical techniques to implant acoustic tags into the WA dhufish were done near Meelup Bay, Geographe Bay (Figure 4.5) and the majority were done near Five Fathom Bank, Perth (Figure 4.6).

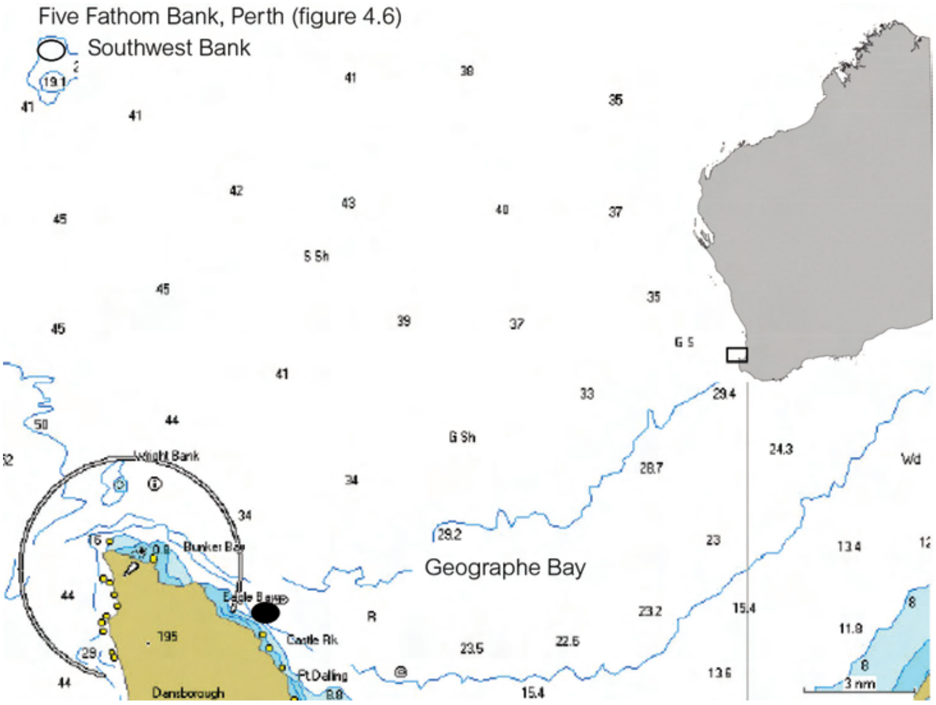

Figure 4.5: Capture location (open circle) and surgical and caging area (full circle) for initial trials on dhufish surgery in Geographe Bay, Western Australia

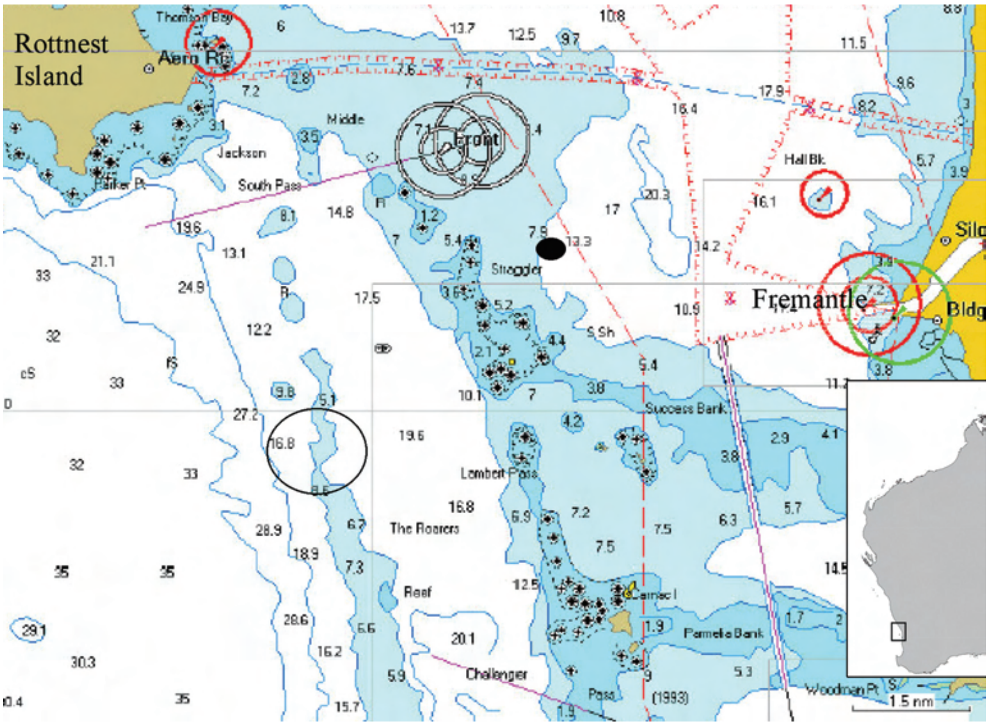

Figure 4.6: Sites were fish were caught (large open circle) for dhufish trials off Fremantle. Some fish were caged at the capture sites while others were caged in more sheltered waters (closed circle).

Results

Biology of *P. leopardus* and *L. miniatus*

259 *L. miniatus* and 100 *P. leopardus* have been processed with approximately 400 *L. miniatus* and 60 *P. leopardus* collected. However, aging and histological examination of gonads has not yet commenced.

Reproductive Potential

Plectropomus leopardus Spawning Aggregations

During the visual censuses two small areas had higher numbers of *P. leopardus* and were identified as potential aggregation sites. Both areas were drop offs on the eastern slopes of the ROA (Figure 4.4). On the 28th of February 2006 (the new moon), at 1645 – 1745, the first of these two sites was revisited and a spawning aggregation was discovered. A count of *P. leopardus* at the aggregation was done by two divers drifting side-by-side 35m through the aggregation counting every *P. leopardus* they could see (approximate visibility of 20m). 61 fish were counted. The drift was done once. Males were observed to be territorial and were displaying to males (presumably to defend their territory) as well as directly towards very gravid females.

Due to logistical constraints the site could only be snorkeled on again the next morning at 0830 and evening at 1630, and as such was unable to be quantified. Approximately 1/3 of the fish present the night before, mostly larger males with a few smaller females were still at the site. One day after the aggregation was first seen, only large males were present with two large females arriving toward the end of the snorkel.

Lethrinus miniatus Abundance

The abundance of *L. miniatus* numbers was low in all of the habitats surveyed. Of 28 transects surveyed, only six fish were recorded, averaging 0.2 fish per $500m^{-2}$. *L. miniatus* were absent from the channel habitat, and were found in the deep and drop off habitats only, in low numbers (Figure 4.7). The size of the *L. miniatus* surveyed was 34.2 cmTL (±1.5SE; range 30 – 40 cmTL).

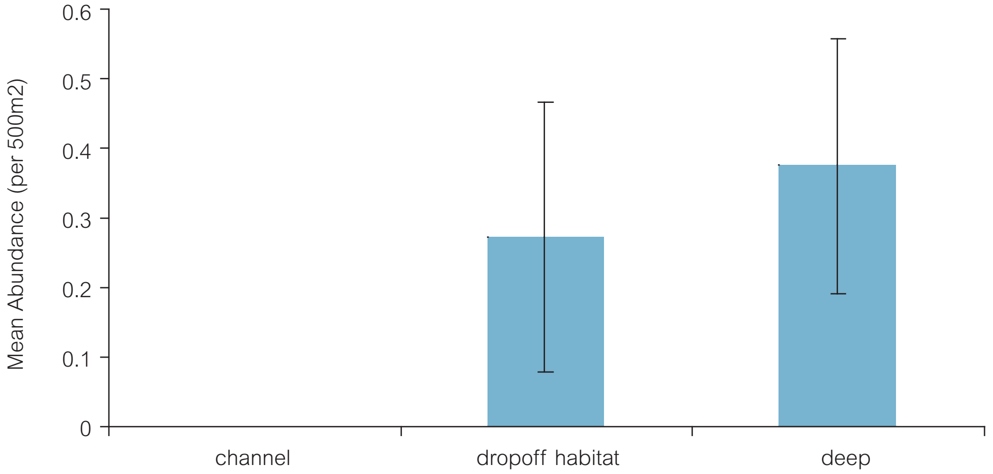

Figure 4.7: Abundance of *L. miniatus* in three habitats in the Leo ROA at the Houtman Abrolhos Islands (SE error bars).

Dhufish Movement / Acoustic Tagging

Surgical Trials on Cultured Species

Of the six cultured fish that underwent surgery half are still alive. Both of the mulloway and one pink snapper are still alive after 147-8 days. The tarwhine died after 78 days and two pink snapper died after 15 and 62 respectively.

Table 4.1. Details of surgery performed on each aquaculture reared individual

Date Operated On	Species	Dummy Tag	OTC	Died?	Days Survived
11/10/2005	Mulloway	No	No	Still Alive	148+
12/10/2005	Mulloway	Yes	Yes	Still Alive	147+
11/10/2005	Pink Snapper	No	No	12/12/2005	62
12/10/2005	Pink Snapper	Yes	Yes	Still Alive	147+
12/10/2005	Pink Snapper	Yes	Yes	27/10/2005	15
12/10/2005	Tarwhine	Yes	No	29/12/2005	78

Post mortems on the dead fish found that the first pink snapper that died after 15 days appeared to have an infection (skin was a red colour and swim bladder was very bloated, Figure 4.8a). Note that the body cavity was full of fat (Figure 4.8b), which is common for cultured fish (S. Kolkovski pers com.).

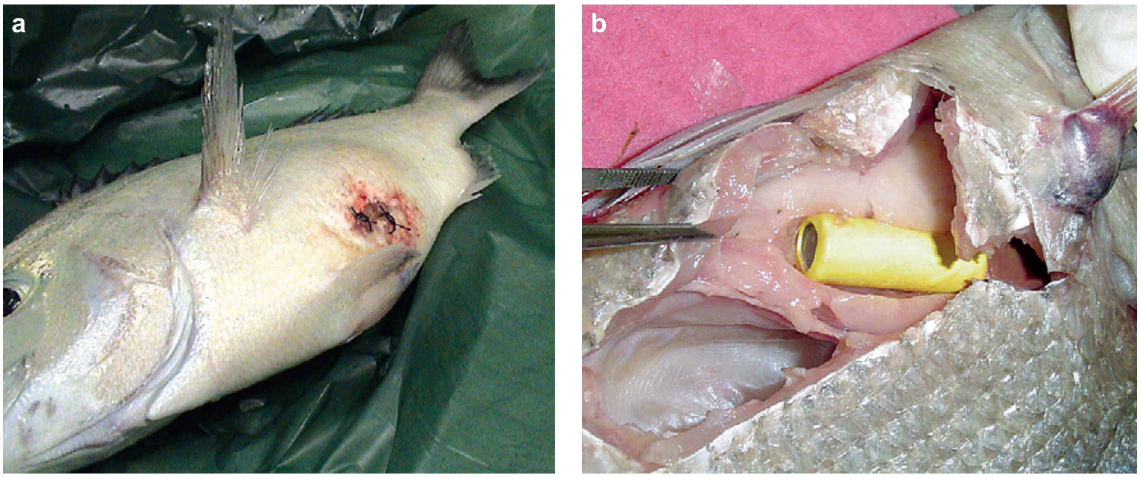

Figure 4.8: Post mortem photos of pink snapper that died after 15 days. a) showing bloated swim bladder and red skin from infection; b) position of the dummy tag in the body cavity and the large amount of fat reserves

The post mortem on the second pink snapper that died after 62 days found a different cause of death. The intestine appeared to be stitched (Figure 4.9a) and the fish had no fat reserves indicating that the stitch reduced the ability of the fish to feed and the fish died after utilising all of its existing fat stores.

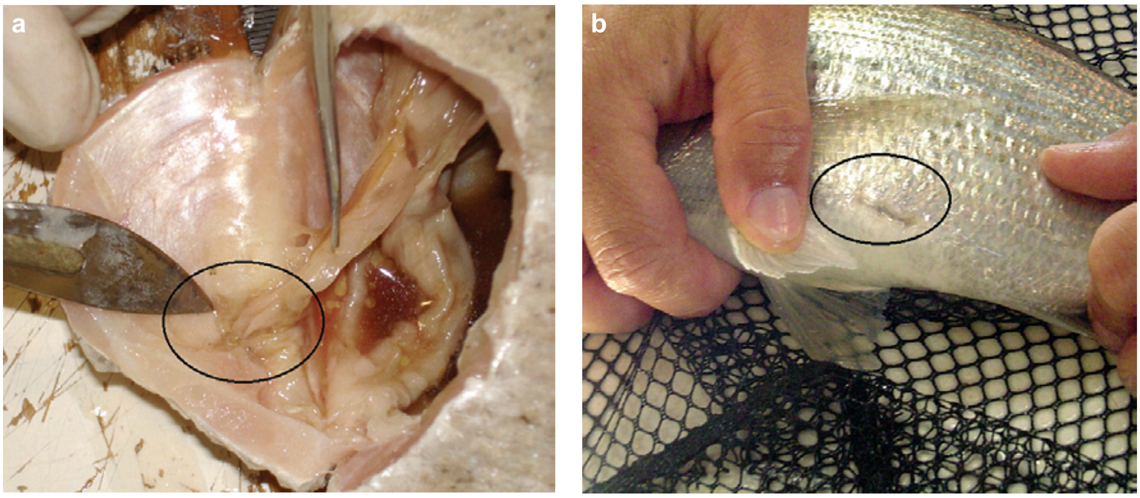

Figure 4.9: a) Intestine of pink snapper stitched to body wall; b) wound recovery in the Tarwhine (wound circled)

Of the remaining fish that died, there was no obvious cause for the death for the tarwhine after 78 days. The wound in the tarwhine showed good repair and was completely covered with a new layer of scales 40 days post surgery (Figure 4.9b). This death, therefore, may be explained by normal mortalities associated with rearing cultured fish rather than an artefact of the surgery.

Field Trials on Dhufish

Field surgery was attempted on nine dhufish. Of these, one was aborted due to the stitches pulling through the flesh on a very small fish (31cm TL). Three were in poor condition after capture and handling before surgery due to 1. being held too long in the holding tank while transporting from capture site to caging site, 2. being too small for the large tag (39cm TL) and 3. being not fully recovered (poor swimming on the surface). In these cases both surgery and/or recovery was continued to establish limits for survival, time held on boat, fish size, and degree of recovery.

Of the other five fish that were implanted with dummy tags, two survived surgery and were released either two or four days after surgery and three dhufish died with no obvious explanation. The fish that died all showed good initial recovery either on the surface or when initially dived on, however when they were to be released, (2, 3 and 4 days post surgery), were dead.

Because of survival problems in apparently healthy fish, three fish were used in control experiments to test the various stages of the process. To determine if catch mortality was responsible for some of the deaths, two fish were held on board for 6 and 18 minutes respectively, before being released back into the cage for 4 days and four hours respectively. Both fish are still alive, surviving caging, cage retrieval and transportation to the Department of Fisheries (DoF) tanks at Hillarys.

To determine the effects of the anaesthesia one fish was held on board for 6 minutes before being anaesthetised and placed in a holding tank for recovery. No surgery was done. This fish was released into a cage. On retrieval 4 days later, the fish had been stolen.

Discussion

Reproductive Potential

Plectropomus leopardus Spawning Aggregations

An aggregation was discovered off the northern tip of Bynoe Island within the Leo ROA and a preliminary survey was done, however, sizes of fish were not estimated. The aggregation appeared to be there only on the new moon night and was almost non existent the following night. Ideally a number of aggregations should be described to get a more accurate picture of spawning aggregations within ROAs at the Houtman Abrolhos Islands. Another avenue to be explored is the movement of eggs, or larvae from the aggregation site to outside the ROA as the aggregation is in an area of strong current movement, and near the northern edge of the ROA. Tracked over several days, this movement will demonstrate potential egg movement outside the ROA from an aggregation inside. The feasibility of such a project is currently being assessed.

Lethrinus miniatus Abundance

A large number of individuals is required to compare the abundance and size distribution of *L. miniatus* between areas open and closed to fishing and to compare reproductive differences between the two management areas. The pilot study on habitat preference revealed low numbers of *L. miniatus* in the habitats surveyed.

L. miniatus appear to be a deep water species and not abundant in shallow waters, although surveys were limited by depths at which SCUBA surveys could be conducted (approximately 18m). Fish processed for biological information were of a similar size of those counted in the transects. They were found to be either immature (n=12) or in a non reproductive state (n=1).

Results of the pilot study suggest that determining the reproductive potential of *L. miniatus* at the Abrolhos Islands is not possible using existing methods.

Dhufish Movement

Surgical Trials on cultured Species

Of the three cultured species that underwent surgical trials, mulloway may be best suited to coping with surgical tagging. However, all species seem to cope well with initial recovery from surgery when held in tanks and most survived for reasonable time periods in captivity. Egli and Babcock (2004) held wild caught pink snapper for an average of average 6 days (minimum of 24 hours) both pre and post surgery, before re-release at the capture location. There was no postoperative mortality during the holding time.

The results of surgical trials suggest that the surgical methods used on these individuals is a suitable technique which could be used on other wild caught fish, eg. dhufish.

Field Trials on Dhufish

The trials of the surgical methodology developed from the cultured fish were not as successful on the wild caught dhufish but there was no pattern that explained either all survivorship or mortality. It is likely that the high stress levels from capture, combined with surgery and recovery in a relatively exposed cage, may cause an accumulation of a number of sub-lethal stresses, which then culminate in the death of the fish.

Other options to reduce stress on fish are being explored, including holding them in either tanks or cages in the field before surgery is done. Initial trials show that fish survive capture and release into cages at the site and/or transport back to the mainland into holding tanks. The next stage is to ensure surgery techniques of wild caught dhufish kept in captivity are not fatal. As surgery of culture fish was mostly successful, this appears to be highly likely.

Acknowledgements

This work wouldn't have been possible without the continued support of my two supervisors Glenn Hyndes and Jill St John. The work involving pilot techniques on Dhufish movement was required extensive assistance and consultations with Mike Mackie and Paul Lewis, whose help has been invaluable. Also I need to thank the staff of the Geraldton Regional Branch of the Department of Fisheries, particularly Kim Nardi who has been instrumental in assisting organising time at the Houtman Abrolhos Islands and also providing a lot of local knowledge and advice. Also, the other members of Geraldton Fisheries who helped skippering the boat and collecting samples, namely Andy Derbyshire, Michael Nicholas and Mat Robinson. I would also like to acknowledge the volunteers that have helped or attempted to help on the field work both locally and at the islands, Lachlan MacArthur, Emily Gates, John Eyres, Michael O Brien, Nick Jarvis, Ian Keay and Miles Parsons. Sagiv Kolkovski helped with the housing and surgical techniques looking at the Dhufish pilot tagging.

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Conference attendance and presentations

Conferences Attended:

International Marine Protected Areas Congress; Geelong 2005

Other Presentations:

Proposal Seminar, Department of Fisheries October 2005

Spawning Aggregation Workshop; Department of Fisheries W.A., September 2005

Proposal Seminar, Edith Cowan University, September 2005

AMSA Student Workshop; Rottnest Island, June 2005

4.3.5 Baseline biodiversity monitoring in the proposed Jurien Bay Marine Park, Survey 3

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Introduction

Concurrent with the implementation of a network of Marine Protected Areas (MPAs) in Western Australia is the need for effective monitoring programs to assess the ability of MPAs to achieve management aims. Only by studying changes that occur in MPAs following protection can we assess the true value of MPAs as baseline reference areas for quantifying ecosystem effects of fishing in the coastal zone, and the success of current conservation and fisheries management strategies. Potential benefits of MPAs include those related to protection of spawner biomass and conservation of critical habitats.

In order to properly determine whether changes observed within MPAs are the result of protection rather than natural variation in space and time, scientifically-credible baseline surveys within and adjacent to proposed MPAs are needed prior to protection from fishing, with subsequent survey of locations at biologically meaningful time intervals. Ideally, baseline surveys should be conducted over several years to assess the scale of inter-annual variability before the MPA is declared.

In the present project, we undertook quantitative surveys of fishes, macroinvertebrates and algae on reefs in the Jurien Bay Marine Park (JBMP) in October/November 2003. These surveys represent a baseline data set, given that JBMP was declared on 31 August 2003 but fishing restrictions had not been gazetted nor sanctuary or scientific reference zones marked in the field in 2003.

The JBMP area surveyed is centred around the towns of Jurien and Cervantes and extends for approximately 80 km of coastline to a distance of 5 km offshore. The MPA is characterised by an extensive offshore development of limestone pavement, structured reef, seagrass beds, sand banks and islands that provide a protective barrier from the prevailing swells and seas. Wave height generally declines substantially eastward of a series of reefs running north-south at a distance of 5-7 km offshore. The inner three kilometres of coastal waters essentially form a protected lagoon with water depths <5 m and isolated structured reefs outcrop from sand and seagrass. The most highly protected management zones within the MPA comprise 7 sanctuary zones (4% of the area) and 3 scientific reference areas where commercial lobster fishing and shore-based line fishing are allowed but other extractive activities prohibited (17% of the area).

Underwater visual censuses of fish, large mobile invertebrates and macroalgae were undertaken at 7 to 9 sites within each of the major management zone types (general use, sanctuary and scientific reference area). Surveys utilised similar techniques to those currently used for MPA monitoring in Tasmania, New South Wales and Victoria as part of a continental-scale study of the effectiveness of marine protected areas (MPAs). The survey methodology covers several assemblage types, having been designed to maximise quantitative information collected on a variety of species in the limited diving time available. This methodology should not only detect changes in heavily exploited species, but also any cascading ecosystem effects of fishing as well as patterns of long-term change in the region.

Aims/objectives

The objective of the project was to provide baseline data on the biodiversity of marine habitats within various management zones in the proposed Jurien Bay Marine Park. This information will be consistent with and supplement biodiversity information collected in two previous surveys undertaken by the University of Tasmania's survey team.

Discussion

Baseline surveys conducted in the Jurien Bay Marine Park have provided a broad-scale description of inter-site and inter-annual variation in communities of reef fishes, large mobile invertebrates and cover-forming plants and animals. The selection of 7-9 sites within each management zone should be sufficient to detect biologically meaningful change for the species examined – a doubling in population numbers for common species or an increase of ≈3 species in number of species richness per transect. From the results of the Tasmanian MPA study (Edgar and Barrett, 1999), and a workshop examining MPA monitoring techniques (Barrett and Buxton, 2002), it appears that six sites would be the accepted minimum number of "replicates" per treatment for an effective monitoring program.

Nevertheless, the sampling design could be improved by increasing the number of sites investigated in sanctuary zones. We recommend that two additional sites in sanctuary zones be monitored in future surveys to provide a fully balanced design with nine sites in each zone. The relatively low number of sites currently sampled in sanctuary zones reflects a slight change in zone boundaries from those proposed when the initial survey was undertaken. Additional sites would best be located in the large sanctuary zone block immediately south of Jurien Bay township, providing that reefs of sufficient depth and extent can be found amongst the predominance of shallow sand and seagrass in this block. Given the importance of following trends in rock lobster abundance, we also recommend that the total area surveyed for rock lobsters in future years is doubled by counting animals present on both sides rather than one side of the transect line.

Ideally, surveys should be repeated each year following enforcement of the MPA zoning scheme, at least for the first few years until population responses start to stabilise. In addition to its MPA value, a long-term data set possesses a variety of other uses, including as a tool for tracking regional changes in biodiversity associated with climate change or invasive species. Because a wide range of species have been surveyed, the experimental design should have sufficient power to detect ecosystem shifts as well as changes in the abundance of target fishery species.

Comparison of the overall relationship between sites based on assemblage data indicates that, while there is some degree of variation between sites within each zone category, the management zones broadly overlap and therefore future comparisons between zones are valid using current sites and experimental design. Our surveys were confined to moderately-sheltered inshore reefs of the region because sanctuary zones are all located in this ecosystem type. We note that, because sanctuary zones do not encompass any offshore reef habitat, the full range of ecosystem types within the JBMP remains to be adequately protected. We therefore recommend that a sanctuary zone be extended to include the outer reef, and that the monitoring program is extended to at least three outer reef sites in different zones.

Summary and Conclusions

Quantitative data are now available on densities of fishes, macroinvertebrates and plants on lagoonal reefs in the Jurien Bay Marine Park. Relative to variation between sites, the flora and fauna at different sites generally exhibited a low level of change between years for sites with data collected previously. With the exception of somewhat anomalous sites in the north near Fishermans Island, the biotic composition of sites was interspersed with respect to the three major MPA management zones – sanctuary, scientific reference and general use, with no zone possessing a predominance of one particular biotic assemblage type. Thus, data collected encompassed the range of variability within zones, allowing rigorous comparative analysis of change through time. Because a wide range of species have been examined, ecosystem shifts as well as changes in the abundance of target species should be detectable following the protection of areas from fishing.

The selection of between 7 and 9 sites within each management zone appears to provide sufficient replication to detect biologically meaningful change for the species examined. Nevertheless, to restore a fully balanced design following slight changes to the management zone locations originally proposed, we suggest that an additional two sites in sanctuary zones are monitored in future. Additional sites should be located in the large sanctuary zone immediately south of Jurien Bay if reefs of sufficient size to encompass 200 m long transect lines can be found in that area, which is presently unmonitored. We also recommend that (i) at least one sanctuary zone should be extended to the outer reef region to protect the full range of biodiversity within JBMP, (ii) monitoring should be undertaken at sites on the outer reef, and (iii) the number of 50 m x 1 m transect blocks monitored per site be increased from 4 to 8 for rock lobsters.

Analysis of the baseline data set indicated no significant differences between zones in number of fishes, macro-invertebrate or plant taxa per 50 m transect. Once fishing restrictions pertaining to different management zones are adequately enforced, surveys should be repeated on an annual basis until differences between zones stabilise. Such a monitoring scheme would provide time-series information on trends in the abundance of species of interest in different management zones, information on indirect impacts of both rock lobster fishing and general recreational and commercial fishing on ecosystems, and regional changes associated with such factors as climate change.

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List of publications and/or outcomes to date

Edgar, G., Barrett, N., and Bancroft, K. (2003) Baseline surveys for ecosystem monitoring within the Jurien Bay Marine Park 1999-2003. Tasmanian Aquaculture and Fisheries Institute Internal Report, Hobart, 29 pp.

4.3.6 Providing marine algal taxonomic expertise to *Coastal Ecosystem* and *Biodiversity in Western Australia*, a core CSIRO work priority area, and preparation of an interactive key to the seagrass epiphytes

Principal Investigator / Institution

Dr John Huisman	Murdoch University

Co-Principal Investigators / Institutions

Dr Russ Babcock	Project Manager, CSIRO Marine and Atmospheric Research
Dr Julia Phillips	Marine Ecologist, CSIRO Marine and Atmospheric Research
Dr Chris Simpson	Project Manager, Department of Conservation and Land Management
Dr Neville Marchant	WA Herbarium, Department of Conservation and Land Management

Introduction

Benthic plants (algae and seagrasses) are a dominant component of most inshore marine ecosystems in Western Australia, and several CSIRO projects presently underway incorporate macroalgal surveys to establish baseline community structure. One of SRFME's core research projects, *Coastal Ecosystem and Biodiversity in Western Australia* has as a primary objective the 'provision of representative baseline assessments'. It is imperative that these surveys be based on reliable and consistent taxonomic information if they are to provide meaningful habitat and community characterizations. This project uses the taxonomic expertise of John Huisman to ensure consistent and accurate identifications of the macroalgae. In addition to the benefits to CSIRO core research, this project will contribute to 'FloraBase', a CALM endeavour to document information regarding Western Australia's plant life. This information is web-based and, in part, made available to the public.

Aims/Objectives

This project has several objectives. The first is to provide taxonomic expertise to SRFME core research projects, the results of which will enhance our knowledge of Western Australia's marine flora and will be used to provide information to establish and update CALM's 'FloraBase', the web-based repository of information pertaining to Western Australia's plants. The second objective is to construct an interactive key to the algal epiphytes occurring on seagrasses. This key will use the program LUCID and will be an extremely valuable resource for monitoring the health of Western Australia's seagrasses, as epiphyte composition and load is regarded as a key indicator of ecosystem health.

Results

Work on this project began in mid January 2005 at 20% time (one day per week) and is due to be completed late in 2006. Since commencement the backlog of unidentified/tentatively identified specimens has been cleared, most being named to species level. These names have been incorporated into the 'Coastal Ecosystem' project. Many of the specimens represent range extensions for the species and are therefore of value in establishing accurate distributions. Once these specimens have been curated they will be lodged with the WA Herbarium and their details entered into FloraBase. The Jurien Bay specimens will partly form the basis of an annotated checklist being compiled for the region.

As a result of this work, the extremely rare red alga *Gelidiella ramellosa* (Kützing) Feldmann & Hamel has been recognized in the Perth specimens. This species was originally described from collections made over 150 years ago from Western Australia (Kützing 1843) and has not been found in the region since that time (Womersley 1994). Materials have been sent to Dr Wilson Freshwater (University of North Carolina) for DNA sequence analyses and a collaborative paper is being prepared. Dr Freshwater is the acknowledged expert in the Gelidiales, the red algal order to which *Gelidiella* belongs.

Two other collaborative projects are underway. One is to produce a small booklet on the common marine plants of the Perth Region. This will be co-authored by John Huisman, Julia Phillips, and Cheryl Parker (CALM, State Herbarium) and is due to be completed in April, publication following shortly thereafter.

A second project ties in with the Jurien Bay coastal ecosystem project and a current project by Huisman at the State Herbarium to verify all extant collections of marine algae from the Jurien Bay region. All records will be collated and published as an authoritative checklist for the region, providing a detailed summary of the flora of this important region.

With regard to the 'Seagrass Epiphyte Interactive Key', John Huisman attended a CALM workshop on using LUCID for developing interactive keys and purchased the updated version of the software, which is now usable on the web. A list of known epiphytes has been compiled (over 200 species) and the major portion of the key has been built. At present it includes some 57 characters ('Features'), and 200 character states ('States') for 204 species ('Entities'). A large portion of the final product will be the species descriptions and images for confirmation of identification. Many of these are 'in house' and the remainder will be acquired before the end of the project (late 2006). We envisage that the final product will appear as a self-contained CD, complete with interactive key, descriptions, and images. Example photographs and pages are included (Figs 4.10, 4.11).

Summary

This project has made significant advances towards recognition of the Western Australian marine flora, having already added new distributional data and rediscovered an extremely rare species. In addition, considerable progress has been made toward building the interactive key to the seagrass epiphytes.

References

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Womersley, H. B. S. (1994). *The Marine Benthic Flora of Southern Australia. Part IIIA.* Australian Biological Resources Survey, Canberra.

Publications

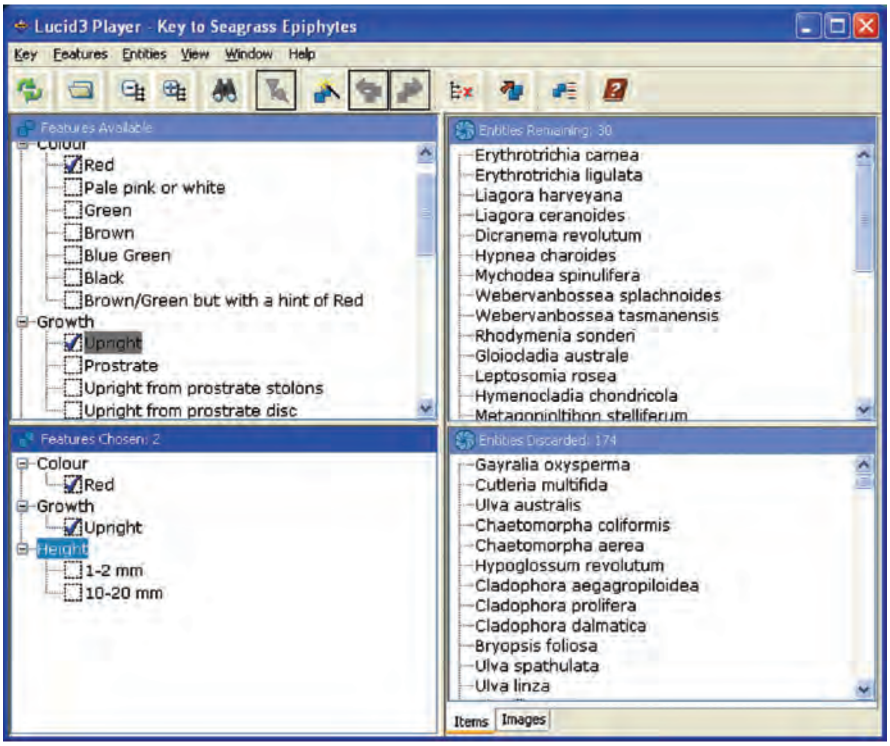
Two manuscripts, a booklet, and a CD are being prepared:

a. The rediscovery of *Gelidiella ramellosa*.

b. Annotated checklist of the marine alga of Jurien Bay.

c. Seaweeds of the Perth Region (booklet).

d. Seagrass Epiphytes: Interactive Key and Identification Guide (CD).



Features Available:

- ☑ Red
- ☐ Pale pink or white
- ☐ Green
- ☐ Brown
- ☐ Blue Green
- ☐ Black
- ☐ Brown/Green but with a hint of Red

Growth
- ☑ Upright
- ☐ Prostrate
- ☐ Upright from prostrate stolons
- ☐ Upright from prostrate disc

Entities Remaining: 30

- Erythrotrichia carnea
- Erythrotrichia ligulata
- Liagora harveyana
- Liagora ceranoides
- Dicranema revolutum
- Hypnea charoides
- Mychodea spinulifera
- Webervanbossea splachnoides
- Webervanbossea tasmanensis
- Rhodymenia sonderi
- Gloiocladia australe
- Leptosomia rosea
- Hymenocladia chondricola
- Metagoniolithon stelliferum

Features Chosen: 2

Colour
- ☑ Red

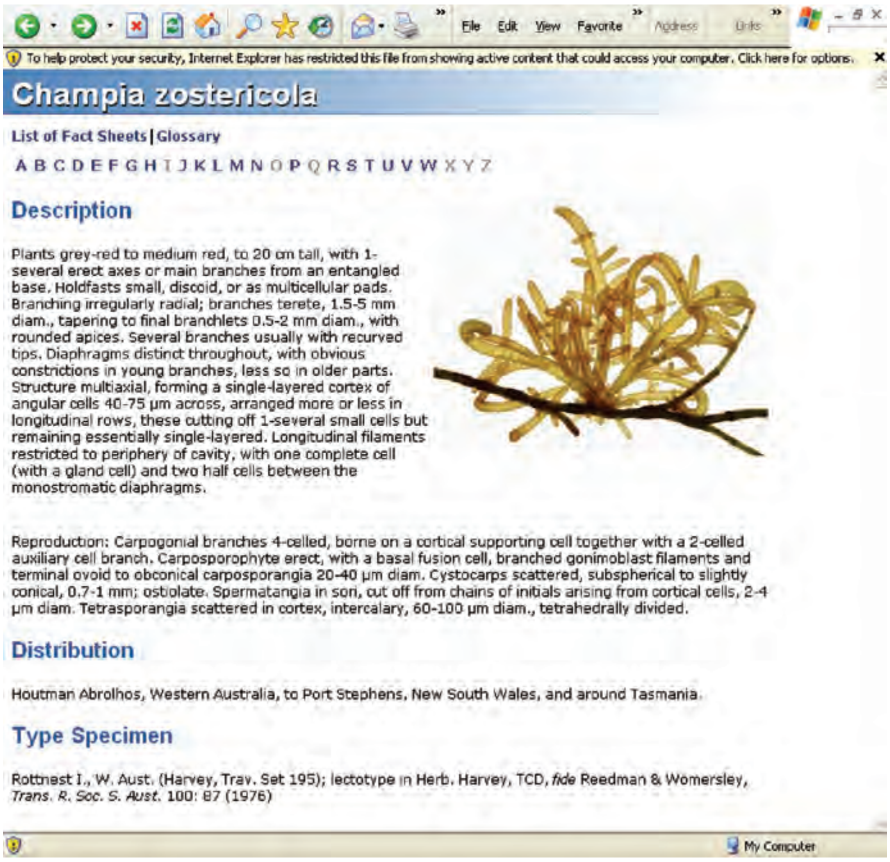
Growth
- ☑ Upright

Height
- ☐ 1-2 mm
- ☐ 10-20 mm

Entities Discarded: 174

- Gayralia oxysperma
- Cutleria multifida
- Ulva australis
- Chaetomorpha coliformis
- Chaetomorpha aerea
- Hypoglossum revolutum
- Cladophora aegagropiloidea
- Cladophora prolifera
- Cladophora dalmatica
- Bryopsis foliosa
- Ulva spathulata
- Ulva linza

Figure 4.10: Example Screen from Interactive Key to Seagrass Epiphytes



Champia zostericola

List of Fact Sheets | Glossary

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

Description

Plants grey-red to medium red, to 20 cm tall, with 1-several erect axes or main branches from an entangled base. Holdfasts small, discoid, or as multicellular pads. Branching irregularly radial; branches terete, 1.5-5 mm diam., tapering to final branchlets 0.5-2 mm diam., with rounded apices. Several branches usually with recurved tips. Diaphragms distinct throughout, with obvious constrictions in young branches, less so in older parts. Structure multiaxial, forming a single-layered cortex of angular cells 40-75 µm across, arranged more or less in longitudinal rows, these cutting off 1-several small cells but remaining essentially single-layered. Longitudinal filaments restricted to periphery of cavity, with one complete cell (with a gland cell) and two half cells between the monostromatic diaphragms.

Reproduction: Carpogonial branches 4-celled, borne on a cortical supporting cell together with a 2-celled auxiliary cell branch. Carposporophyte erect, with a basal fusion cell, branched gonimoblast filaments and terminal ovoid to obconical carposporangia 20-40 µm diam. Cystocarps scattered, subspherical to slightly conical, 0.7-1 mm; ostiolate. Spermatangia in sori, cut off from chains of initials arising from cortical cells, 2-4 µm diam. Tetrasporangia scattered in cortex, intercalary, 60-100 µm diam., tetrahedrally divided.

Distribution

Houtman Abrolhos, Western Australia, to Port Stephens, New South Wales, and around Tasmania.

Type Specimen

Rottnest I., W. Aust. (Harvey, Trav. Set 195); lectotype in Herb. Harvey, TCD, *fide* Reedman & Womersley, *Trans. R. Soc. S. Aust.* 100: 87 (1976)

Figure 4.11: Example Screen from Species Fact Sheets

4.3.7 Establishing Reference and Monitoring Sites to Assess a Key Indicator of Ecosystem Health (Seagrass Health) on the central west Coast of Western Australia

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Executive Summary

Seagrasses are key elements of shallow marine ecosystems that require protection from human influences in Western Australia (WA). To protect WA's marine environment from the effects of waste discharges, an Environmental Quality Management Framework (EQMF), which explicitly includes seagrass, is being implemented. For physicochemical stressors and biological indicators, operation of the EQMF is based on the collection of monitoring data and the evaluation of these data against criteria that are established from data collected at suitable reference sites. In this study we examine natural spatial and temporal variability in *Posidonia sinuosa* shoot density and use resulting data to evaluate the potential for transferability of criteria established in one region to monitoring data gathered in another. During this study six new *P. sinuosa* seagrass reference sites were established at three depths at two locations within two protected areas of the Jurien Bay Marine Park and seagrass health data were collected on three occasions over the period 2003 to 2005. A 3-way ANOVA (year, location, depth) indicates that the overall structure of *P. sinuosa* meadows measured in terms of shoot density varies significantly among locations and depths. Significant interaction factors in the ANOVA model suggest that factors driving shoot density are likely to be complex and additional to those considered here. Based on comparisons among various percentiles of shoot density data performed here, the transfer of seagrass shoot density criteria derived from one region to monitoring sites in another region may be possible, but will need to give serious consideration to the inter-site variability in shoot densities. Discussions have taken place between the Department of Environment and SRFME researchers to strengthen collaboration by exploring opportunities to investigate potential influence of wave energy on *P. sinuosa* meadows at Jurien. We also discuss the potential implications of strengthening seagrass health criteria if this need was to arise.

Introduction

Seagrasses are key elements of shallow marine ecosystems off the south and west coasts of Western Australia (WA) that require protection from human influences. Impact of human activities on seagrasses can be direct (eg. physical removal by dredging) and/or indirect (eg. marine discharge of nutrient-enriched waste, turbidity generated by dredging). Direct impacts are generally managed though good project planning to avoid losses. To protect the marine environment, explicitly including seagrasses, from the indirect effects of waste discharges, the Department of Environment (DoE) is implementing an Environmental Quality Management Framework (EQMF), which is consistent with the *National Water Quality Management Strategy* documentation (ANZECC and ARMCANZ, 2000). The WA Government has set a mandate to progressively implement the EQMF throughout State waters on a priority basis (Govt of WA, 2003).

In general terms, the operation of the EQMF is based around targeted collection of monitoring data, with these data being evaluated against benchmarks called Environmental Quality Criteria (EQC). For physio-chemical stressors and biological indicators such as seagrass health, the EQC are pre-determined percentiles calculated from data collected at suitable reference sites. As part of the EQMF being given effect in Cockburn Sound through a whole-of-Government *State Environmental Policy* (Govt of WA, 2005), the primary indicator of *Posidonia sinuosa* health is shoot density. Work has been undertaken in SRFME to show that shoot density is a robust early warning indicator of *P. sinuosa* meadow health (Collier, 2005, and Sec. 2.2.1). Part of the EQC for *P. sinuosa* health is met for a 'high level of protection' if the calculated median shoot density at a monitoring site is greater than or equal to the 20th percentile of shoot density measured at a suitable reference site in two consecutive years. Conversely, the EQC would not be met if the median of monitoring site data is less that the 20th percentile of reference site data, and a management response aimed at improving environmental conditions for seagrass must be implemented.

Underlying the above approach is the need for reference sites to be as similar as possible to the monitoring sites, except that they are not influenced by the anthropogenic pressures that the monitoring sites are exposed to. In this context, the reference sites are designed to disentangle anthropogenic and natural changes. It is well established that *P. sinuosa* shoot density is influenced by depth (Collier, 2005). The influence of depth on seagrass shoot density is accounted for in the EQMF by ensuring that reference sites are established in water depths comparable to depths at the monitoring sites. To date it has been assumed that reference sites should ideally be as close to monitoring sites as possible to minimise the introduction of variation that may arise from natural differences between regions. For example, the percentile-based seagrass shoot density EQC applied in Cockburn Sound are established from data collected each year at reference sites located in the adjacent Warnbro Sound. Currently, little is currently known about variability in shoot density over regional scales, and hence the implications for seagrass health assessments if reference sites are located at varying distances from monitoring sites (e.g. kilometres to 100's of km).

In addition to ensuring that reference sites are established in water depths similar to depths at the monitoring sites, it is desirable to locate reference sites in areas that are afforded long-term protection from the effects of discharges and deposits. Sanctuary and other high protection zones within marine conservation reserves meet this desired objective. The Jurien Bay Marine Park (JBMP) has been selected as the focal point for this study because it includes high protection zones (Sanctuary zones and Special Purpose zones), has a statutory management plan, and contains representative elements of the mid-west coast marine environment. Moreover, land adjacent to the JBMP and areas to the south and north are predicted to come under increasing human-use pressure in the future through urban expansion and port development. Accordingly, forward-looking baseline data acquisition and implementation of the EQMF is a high priority to guide decision-making and to ensure management is effective in protecting the environmental quality and conservation values of the JBMP.

In this study we establish six new seagrass health reference sites in the JBMP, monitor them over three consecutive summers and utilise the resultant data to investigate the potential transferability of seagrass health criteria established from a reference site in one region to 'test' sites nearby (kilometres apart) and in another geographic region (~2° latitude and some 220 km away). This project provides an important information base for setting EQC for seagrass health off the central west coast of WA, further development of seagrass health assessment techniques and future performance evaluation of the JBMP.

Study objectives

The objectives of the project are to:

- quantify the natural spatial and inter-annual variability in proposed seagrass health indicators on the central west coast of WA for a period of three years;
- enable comparisons to be made between natural variability in seagrass health indicators at sites in the vicinity of the JBMP and in Perth's southern metropolitan coastal waters;
- provide an information base to make an assessment of the transferability of proposed seagrass health indicators and criteria from the central west coast and other temperate coastal waters in WA;
- enable Government agencies to broaden the geographic coverage of the environmental quality management framework currently being implemented in Perth's coastal waters; and
- enhance strong collaboration between university researchers, key Government natural resource management agencies and SRFME researchers.

Study sites and methods

Study sites

This study focused on the Jurien Bay Marine Park (JBMP). The township of Jurien is located centrally along the length of the Park and is approximately 200 km north of Perth, Western Australia. As part of the data analyses we also utilised *P. sinuosa* shoot density data collected from reference sites located in Warnbro Sound, about 20 km south of Perth (Lavery and Westera, 2003, 2004, 2005).

A pilot survey was undertaken in late March 2003 to locate *P. sinuosa* meadows at suitable depths in proposed protected areas of the JBMP. Reference sites were subsequently established in large *P. sinuosa*-dominated meadows at two locations in the JBMP, hereafter referred to as Boullanger Island (Is.) and Fisherman's Is. The Boullanger Is. is located near the Jurien township in a Special Purpose (*Puerulus*) Zone, while the Fisherman's Is. location is approximately 17 km north of Jurien and is within the Fisherman's Island Sanctuary Zone (Figure 4.12).

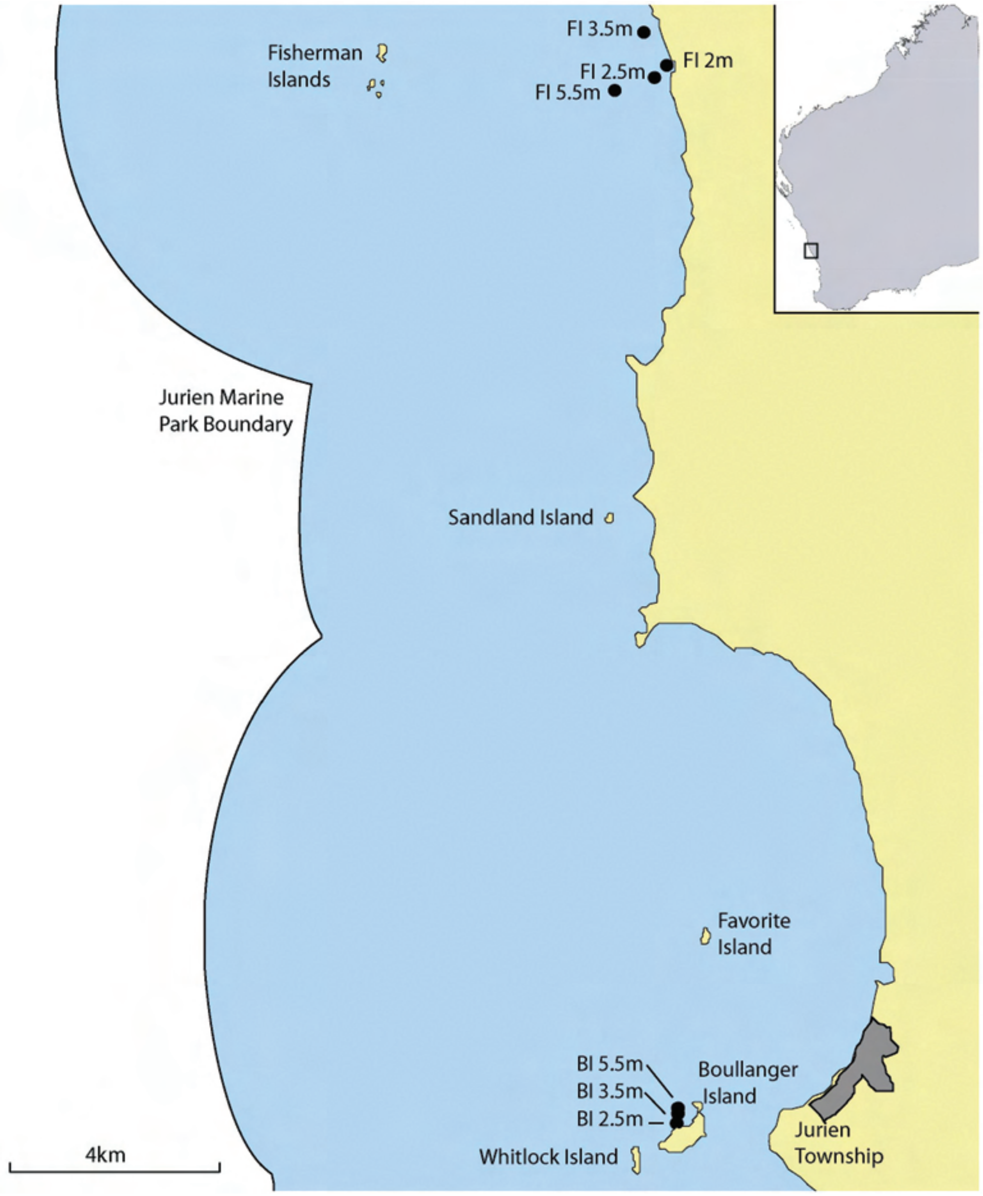

Figure 4.12: Location of sampling sites within the Jurien Bay Marine Park.

At each location, reference sites were established at approximately 2.5 m, 3.5 m and 5.5 m water depth over the period 1-3 April 2003. These depths were selected to correspond to water depths at the reference sites located in Warnbro Sound. Following subsequent spatial analysis, it was found that a 2.0 m deep site at Fisherman's Is. fell just outside the gazetted Fisherman's Islands sanctuary zone. To maximise the long-term protection of the site, a new site was established and sampled within the Fisherman's Is. sanctuary zone in 2004, in a water depth of 2.5 m. The site outside the sanctuary zone still contains permanently marked quadrats, but has not been re-sampled since 2003. The Global Positioning System coordinates for each reference site in the JBMP are shown in Table 4.2.

Table 4.2. Global Positioning System coordinates for seagrass health reference sites in the Jurien Bay Marine Park

Location	Depth	UTM Coordinates (WGS84 datum)		Comment
		East	North	
Fisherman's Is.	2.0 m	307408	6664795	2003 site–not sampled 2004-05
	2.5 m	307146	6664594	Replaces 2.0m site in 2004
	3.5 m	306940	6665428	
	5.5 m	306417	6664328	
Boullanger Is.	2.5 m	307929	6644723	
	3.5 m	307955	6644916	
	5.5 m	307971	6645019	
Warnbro Sound	2.5m	378957	6423948	
	3.2m	378967	6423933	
	5.5m	378938	6423789	

Methods

The reference sites were established, and sampled each year, using methods described by Lavery and Westera (2003) and outlined below.

At the 'centre' of each site, a star picket was driven into the sediment to locate the site. Four transects were then randomly located by assigning compass bearings from the central star picket to a start point of each transect. Each transect then continued along the same bearing for a length of 10 meters. A depth measurement was made at the end of each transect to ensure it was within the allowable depth limits for that site (±0.2m of the assigned depth for that site). If the depth at the end of the transect was outside the allowable depth limits the end of the transect was rotated until it satisfied the minimum depth requirements.

Six 20 x 20 cm quadrats were established at random distances along each 10 m transect. Stainless steel pegs were driven into the seabed in each corner of the six randomly allocated 20 x 20 cm quadrats to aid relocation on subsequent sampling occasions. Once set in place, each permanent relocatable quadrat was sampled for shoot density, percentage cover, maximum and average shoot height. For those quadrats where the randomly assigned position was either on bare sand (ie. no shoots) or contained other seagrass species other than *P. sinuosa*, the quadrat was moved until it contained shoots of only *P. sinuosa*. This process was carried out at each of the seven sites established at Jurien. A total of 24 permanent quadrats were sampled at each site on 3 occasions: 1-3 April 2003; 27-28 February 2004; and 11 and 24 January 2005.

Data were collected as follows.

Shoot Density

On each sampling occasion, the number of *P. sinuosa* shoots within each 20 x 20 cm quadrat was recorded by a diver on SCUBA. The measured shoot density in each quadrat was then expressed as a density of shoots per square meter (m^{-2}).

Maximum Shoot Height

The maximum shoot height was recorded by placing a one metre rule on the seabed and measuring the tallest leaf inside each 20 x 20 cm quadrat.

Average Shoot Height

The average shoot height was recorded by placing a one meter rule on the seabed and measuring the height above the sea floor of 80% of the seagrass leaves inside the 20 x 20 cm quadrat (i.e. the tallest 20% of leaves are ignored; as per Duarte & Kirkman, 2001). The 80th percentile was estimated visually by a diver on SCUBA.

Percentage Cover

Within each 20 x 20 cm quadrat leaves were stood upright and an estimate of the percentage of the quadrat containing seagrass was made the divers.

Light measurement

Submersible Odyssey data loggers with 2π light sensors were deployed to measure photosynthetically active radiation (PAR) in the field. Two PAR loggers, each with automatic wiper units to minimise sensor fouling, were deployed in an arrangement to enable continuous assessment of light attenuation at the 5.5 m sites at Fisherman's and Boullanger Islands. Another logger was deployed at a shore station at the CALM District office in Jurien to measure ambient surface PAR.

Data analysis

Spatial and inter-annual variability in seagrass shoot density among the JBMP and Warnbro Sound reference sites was analysed by a 3-way ANOVA model in which Location, Depth and Year were fixed factors. Seagrass shoot data from the 2.0 m Fisherman's Is. site established in 2003 were omitted from the ANOVA.

To assess potential transferability of seagrass health indicators and numerical EQC between Perth and the central west coast and other areas of WA, a series of comparisons were made to determine the effect of using each site as a reference for the other two sites. This was done using seagrass shoot density data collected at Fisherman's Is., Boullanger Is. and Warnbro Sound. For each test, two sites were chosen to represent 'test' sites. The 50th percentile of shoot density was calculated for these sites and compared against the 20th percentile of the chosen 'reference' site. The comparisons between percentile values are similar to those used to test the health of seagrass at monitoring sites in Cockburn Sound against reference site data collected in Warnbro Sound (EPA, 2005a&b). Percentile values were calculated from the total data sets for all years at each site to maximize size of the data set (n=72) and minimize the interpolation necessary to calculate the percentiles. Due to the relocation of the Fisherman's Is. 2.5 m site in 2004 and because the comparison of percentiles relies on data collected from the same site over time, the 20th and 50th percentiles of shoot density at this site were calculated using 2004 and 2005 data only (n=48). Tests were made for all combinations of 'test' and 'reference' sites.

Results

Spatial and temporal variation in *P. sinuosa* shoot density

Over the three years of this study and across the three depths sampled, average *P. sinuosa* shoot density ranged from 727 to 973 shoots m^{-2} at Boullanger Is. and 734 to 1511 shoots m^{-2} at Fisherman's Is. (Table 4.3). Average shoot density at reference sites in Warnbro Sound varied over the same three years and at similar depths from 738 to 1100 shoots m^{-2} (Table 4.3).

Table 4.3. Mean shoot densities (±standard error) for each region, year and depth.

Year	Depth 2.5m	Depth 3.5m	Depth 5.5m
	Boullanger Island		
2003	866 (64)	861 (74)	727 (49)
2004	950 (78)	974 (95)	838 (65)
2005	878 (58)	805 (86)	797 (51)
	Fisherman's Island		
2003	1116 (50)	735 (60)	9188 (54)
2004	1511 (92)	794 (63)	934 (68)
2005	1275 (81)	734 (53)	1061 (74)
	Warnbro Sound		
2003	980 (80)	1100 (132)	860 (55)
2004	958 (68)	917 (118)	781 (43)
2005	1100 (84)	833 (81)	738 (61)

Spatial and temporal patterns in mean *P. sinuosa* shoot densities at the sites monitored are illustrated in Figure 4.13. Mean shoot density was higher at the 2.5 m Fisherman's Is. site than at any of the other sites (Figure 4.13). Mean shoot densities at Boullanger Is. and Fisherman's Is. show similar patterns of inter-annual variation, which is characterised by an increase in 2004 compared with 2003, and then followed by a slight reduction in 2005. This pattern did not hold for sites at Warnbro Sound, where mean shoot densities were generally highest in 2003 and declined in 2004 and 2005, particularly at the 3.5 m site and less so at 5.5 m (Figure 4.13).

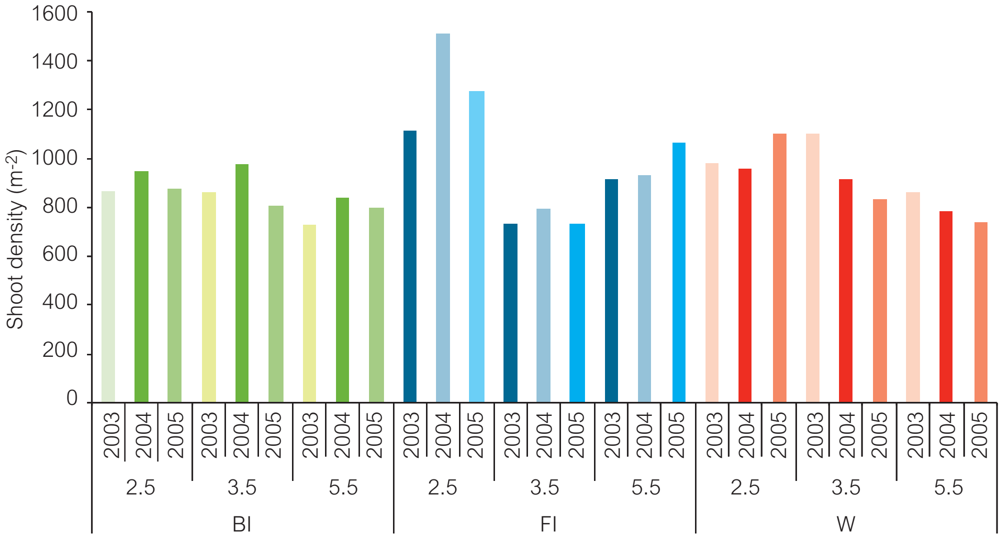

Figure 4.13: Mean shoot densities (m^{-2}) of *Posidonia sinuosa* at Boullanger Is. (BI), Fisherman's Is. (FI) and Warnbro Sound (W) at different depth in 2003-05.

Results of 3-way ANOVA indicate that location and depth both significantly affected *P. sinuosa* shoot density at the sites surveyed over the 3 years sampled (Table 4.4). The significant interactions between Year and Location, and Location and Depth suggest that the differences in shoot density among locations were only statistically significant at some depths and in some years. The interaction of Location and Depth was driven by a minimal change in shoot density over depth at Boullanger Is., but more significant among-depth differences at the other two sites, particularly Fisherman's Is. where shoot density at the 3.5 m site was considerably less than at the 2.5 m site. As noted earlier, Boullanger Is. and Fisherman's Is. sites showed similar patterns of inter-annual variation in shoot density, while at the Warnbro Sound sites, the three-year inter-annual variation was generally quite different.

Table 4.4. Results of 3-way ANOVA testing for effects of Year, Region and Depth on *P. sinuosa* shoot density.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	31882.263(a)	26	1226.241	6.089	.000
Intercept	869800.858	1	869800.858	4319.05	.000
YEAR	599.681	2	299.841	1.489	.226
LOCATION	4105.124	2	2052.562	10.192	.000
DEPTH	10413.794	2	5206.897	25.855	.000
YEAR * LOCATION	2155.394	4	538.848	2.676	.031
YEAR * DEPTH	1660.055	4	415.014	2.061	.084
LOCATION * DEPTH	10391.707	4	2597.927	12.900	.000
YEAR * LOCATION * DEPTH	2169.613	8	271.202	1.347	.217
Error	122443.145	608	201.387		
Total	1027641.000	635			
Corrected Total	154325.408	634			

a R Squared = .207 (Adjusted R Squared = .173)

The overall shoot density structure of *P. sinuosa* meadows was also examined by evaluating the between-location variation in the estimates of selected percentiles. There were differences in the percentile values calculated for each site at any given depth (Table 4.5). The maximum divergence in the estimates of percentile values tended to occur at the 2.5 m depth where the 50th, 20th, 5th, and 1st percentiles at Boullanger Is. were 59%, 67%, 52% and 26% of the maximum estimates for corresponding percentiles, which were all calculated for Fisherman's Is. In absolute terms, these maximum discrepancies equate to between 320 and 430 shoots m^{-2}. Greater discrepancy among sites also tended to occur for the smaller percentiles (i.e. 1st and 5th), particularly at 2.5 m and, to a lesser degree, the 3.5 m sites.

Table 4.5. Variation in estimates of percentile values for shoot density, expressed as a proportion of the maximum percentile value, for combined 2003-05 data at each depth at Boullanger Is. (BI), Fisherman's Is. (FI) and Warnbro Sound (W).

		Percentile			
Depth	Site	50th	20th	5th	1st
2.5 m	BI	0.59	0.67	0.52	0.26
	FI	1.00	1.00	1.00	1.00
	W	0.69	0.72	0.64	0.47
3.5 m	BI	0.89	0.95	0.63	0.40
	FI	0.78	1.00	1.00	1.00
	W	1.00	0.83	0.53	0.54
5.5 m	BI	0.83	0.79	0.76	0.71
	FI	1.00	1.00	1.00	0.90
	W	0.80	0.77	0.97	1.00

Potential transferability of indicators and criteria

Figure 4.14 shows multiple comparisons of median seagrass shoot densities verses 20th percentiles for all combinations of location and depth. In all cases but one, median seagrass shoot densities for the selected 'test' sites were greater than the 20th percentile calculated for selected 'reference' site. The median seagrass shoot density for Boullanger Is. 2.5 m (863 shoots m^{-2}) was the only median less than a 20th percentile value (<975 shoots m^{-2}, Fisherman's Is. 2.5m). The Boullanger Is. 2.5 m median was greater than the 5th percentile of Fisherman's Is. 2.5m data (734 shoots m^{-2}).

2.5 m	655 (B)		975 (F)		700(W)	
Ref (20th%ile)	<1450	<1000	>863	<1000	<863	<1450
Test (median)	(F)	(W)	(B)	(W)	(B)	(F)
3.5 m	500 (B)		525 (F)		435 (W)	
Ref (20th%ile)	<775	<1000	<888	<1000	<888	<775
Test (median)	(F)	(W)	(B)	(W)	(B)	(F)
5.5 m	575 (B)		725 (F)		555 (W)	
Ref (20th%ile)	<950	<762	<788	<762	<788	<950
Test (median)	(F)	(W)	(B)	(W)	(B)	(F)

Notes:
< signifies 'compliance' of the median test site seagrass shoot density against the 20th percentile of the selected reference site data.
> signifies 'non compliance' with the above test.

Figure 4.14: Multiple comparisons of medians verses 20th percentiles for all combinations of sites at Jurien Bay Marine Park and Warnbro Sound. (Ref = 'reference site', Test = 'test' site, F = Fisherman's Island, B = Boulanger Island, W = Warnbro Sound).

Other indicators

Posidonia sinuosa shoot height was measured along with shoot density. At each depth, shoots were longer at Boullanger Is. than at Fisherman Is. (Figure 4.15). This pattern was particularly strong at the 2.5 m and 5.5 m sites. Shoot density was strongly negatively related to shoot height at the same depths. A similar relationship between shoot height and shoot density at the two locations was not observed at 3.5m.

Odyssey PAR data loggers were deployed at the Boullanger Is. and Fisherman's Is. 5.5 m sites on two occasions. The loggers either failed to record or logged erroneous and unstable data on both occasions. Accordingly, we have not been able to investigate the variability of PAR among the reference sites in Jurien or Perth.

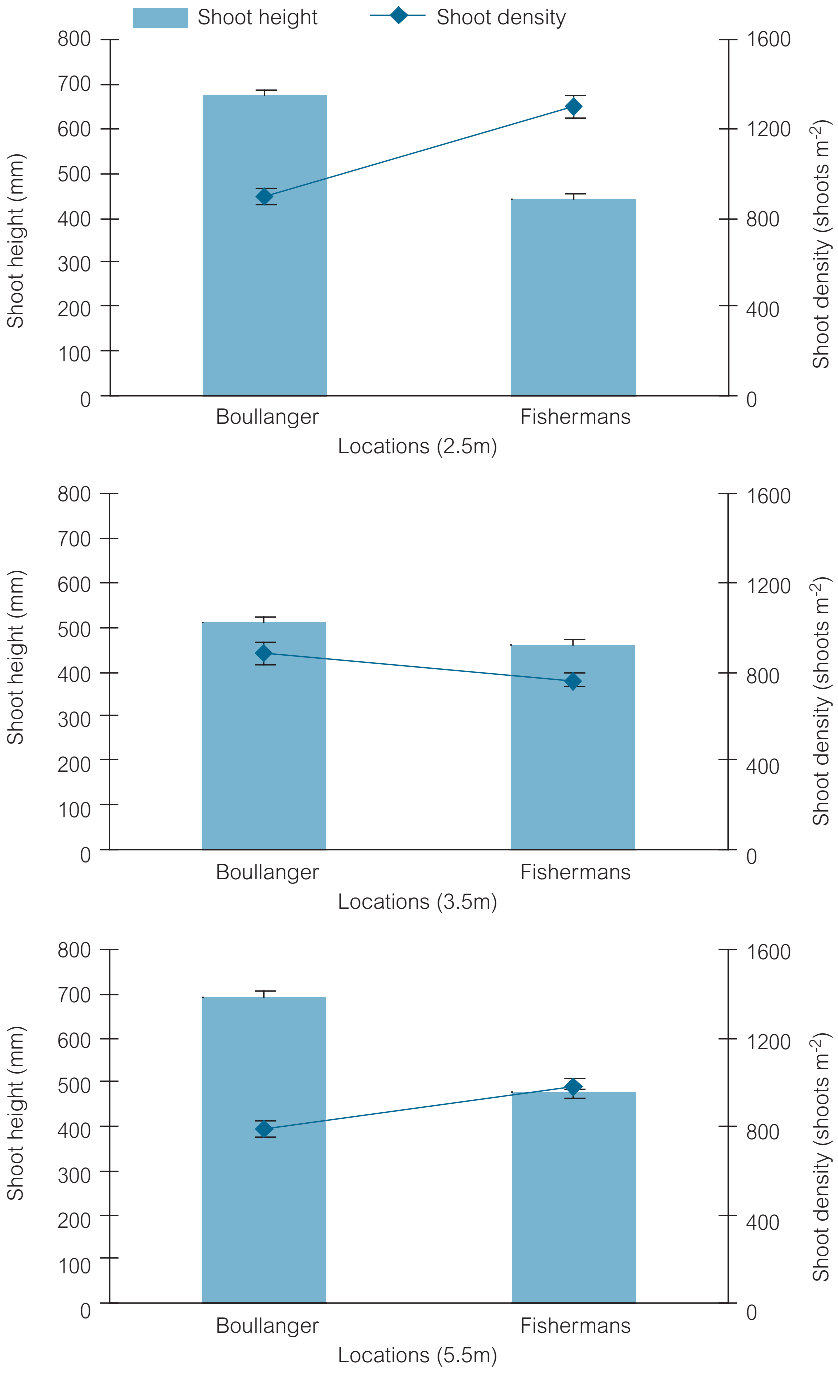

Figure 4.15: Average *P. sinuosa* shoot height and shoot density at 2.5 m, 3.5 and 5.5 m sites at Boullanger Is. and Fisherman's Is.

Discussion

Establishing six new seagrass health reference sites in protected areas of the Jurien Bay Marine Park and monitoring them over three summers has improved understanding of the natural spatial and temporal variation in overall shoot density structure of *Posidonia sinuosa* meadows off the mid-west coast and near Perth, and increased confidence in the approach being taken to assess seagrass health.

The results of statistical analysis performed here suggest that the overall shoot density structure of *P. sinuosa* meadows in the JBMP and Warnbro Sound varied significantly among the locations and depths monitored during this study. Interactions among the main factors in the ANOVA model also suggest that variability in overall meadow shoot density structure is complex and is probably driven by a variety of environmental factors, including depth (Collier, 2005), but possibly also including hydrodynamics, exposure to wave energy, and sediment type and depth.

Variation among estimates of percentiles of shoot density also provide insight into the overall structure of seagrass meadows at the sites monitored. Most variation among locations occurred for small percentiles and at 2.5 m deep sites. It is likely that a contributor of variation among small percentiles of *P. sinuosa* shoot density was sample size. In this study we calculated percentiles from three years of shoot density data (n=72, except Fisherman Is. 2.5 m were n=48). It is worth noting that to maximise confidence in calculated 1st and 5th percentiles, the Standard Operating Procedures for monitoring in Cockburn Sound (EPA, 2005b) recommend using a minimum of five years data (n=120). A minimum of 20 samples should be used to calculate the 20th percentile (ANZECC/ARMCANZ, 2000). It is also possible that seagrass inhabiting extremes of the depth range (e.g. very shallow or very deep water) may exhibit greater variability than seagrass inhabiting mid-range depths. While it is beyond the scope of this work to address this possibility, additional research could be designed and undertaken to test the applicability of the intermediate disturbance hypothesis in the context of *P. sinuosa* meadow structure using the reference sites established in the JBMP.

The finding based on analyses performed here that the three reference locations examined (Fisherman's Is., Boullanger Is. and Warnbro) were assessed as being as 'healthy' as each other has important management implications. Firstly, this suggests that the transfer of seagrass shoot density criteria derived from one region to monitoring sites in another region may be possible, but will need to give serious consideration to the inter-site variability in shoot densities. For example our data indicate that shoot density structure of *P. sinuosa* meadows at Fisherman's Is. sites, particularly the 2.5 m site, is different to that observed at Boulanger Is. and Warnbro Sound.

Fisherman's Is. is geo-morphologically most distinct from the other two sites, being located on a wide tombola-like structure formed in the shelter of the offshore islands. Fisherman's Is. sites are exposed to winds waves and swells from most directions. It has a thin veneer of sand over hard limestone. Boullanger Is. site is in a sheltered embayment on deeper sands, protected from southerly winds and swells and, while still differing in some important respects, is more similar to Warnbro Sound than is Fisherman's Is. The fact that the outcomes for Warnbro Sound and Boullanger Is. were similar, despite some significant differences in the degree of exposure and depth gradients, indicates a potential to apply reference site data from one geographical region to a monitoring site in another region.

It is probably the case that the particular habitat conditions at any given site are more crucial to the shoot density of a seagrass meadow than the general location. It is well known that light is a major determinant of shoot density, but the influence of other factors that can vary among sites, such as sediment depth and type and hydrodynamic conditions, is less clearly understood. In order to determine whether a site is suitable as a reference against a monitoring site, it would be important to determine that the sites were comparable with respect to key non-anthropogenic factors that can affect shoot density. Further investigations are required to be conducted into the factors that affect shoot density at sites not influenced by anthropogenic disturbance in order to determine which characteristics should determine the comparability of monitoring and reference sites. Research undertaken by SRFME scientists has revealed that reef algal diversity is correlated with orbital velocity generated by waves. Discussion with the SRFME ecological modeller has taken place to explore opportunities for collaboration to broaden this existing SRFME work to investigate whether correlations exist between orbital wave velocity and the seagrass meadow variables measured during this study.

A second and related key finding is that the assessments of Warnbro Sound against Fisherman's and Boullanger Islands reference sites confirm that Warnbro is 'healthy' according to the criteria applied and, from this perspective, is therefore an appropriate reference site.

Thirdly, the data gathered during this study provide an opportunity to examine the effect of strengthening the seagrass shoot density criteria to provide greater protection should the need arise in the future. Figure 4.16 provides an indication of the sensitivity of the seagrass health assessment methodology to strengthening the criteria in order to provide greater protection to the environment. If Warnbro Sound or Boullanger Is. sites are used as reference sites, the median values for the other two 'test' sites are consistently higher than the 35th percentile of the selected reference site (Figure 4.16). This suggests that, for these sites, the methods applied are robust enough to accommodate a strengthening of the EQC by reducing the allowable departure from a reference condition. The median values of selected 'tests' sites is more likely to be less than the nominal 35th percentile of reference site data if Fisherman Is. sites are the reference sites. This is most likely due to shoot densities at the 2.5 m and 5.5 m Fisherman's Is. sites being high relative to shoot densities measured in similar depths at the other locations. These findings, while promising, also point to the need for work into what are the most important factors that drive comparability of reference and monitoring sites.

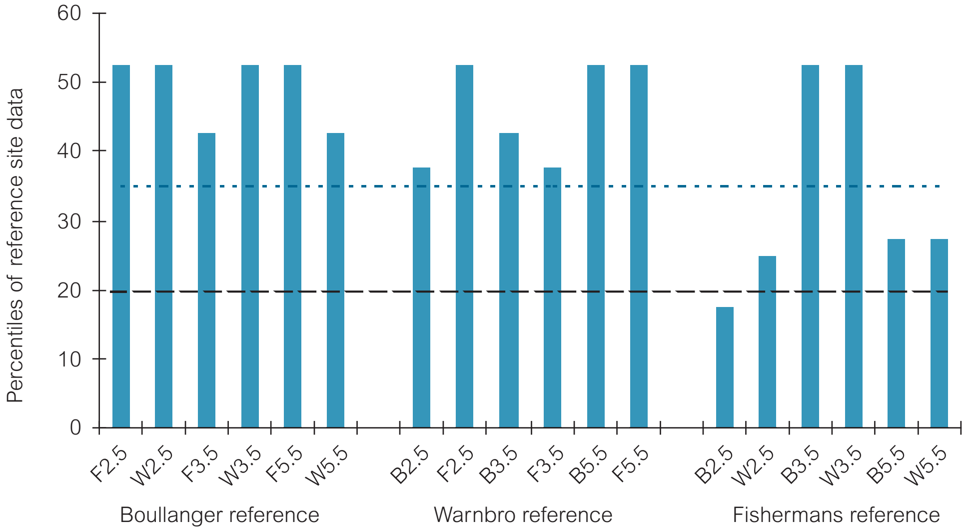

Figure 4.16: Estimates of median seagrass shoot density at as percentiles of three selected reference sites. The 35th percentile is marked as the horizontal line.

In addition to providing a critical scientific information base from which to broaden the geographic coverage of the EQMF, the outcomes of this work provide a basis for establishing a seagrass health baseline and longer-term data set. This information has direct utility for gauging the performance of the JBMP against long-term targets set out in the Park's Management Plan and also could inform broader-scale assessment of the condition of WA's marine environment through processes such as State of Environment reporting.

Acknowledgements

The investigators thank the SRFME Joint Venture Management Committee for agreeing to support this project. We are also grateful to Prof. Paul Lavery and Mr Jason Howe for their guidance and advice, analysis of the seagrass shoot density data and preparation of annual and final data reports which informed the preparation of this report.

Thanks are also due to the skipper of the DoE vessel, Mr Tim Daly and staff and students of the ECU School of Ecosystem Management who assisted in the field. We also acknowledge the local assistance and advice provided by Mr Keith Hockey and Mr Kevin Crane (CALM Jurien District).

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CHAPTER 5

5. SRFME CORE PROJECTS

Following are concise summaries of the scientific outcomes of the three Core SRFME projects: Biophysical Oceanography off Western Australia, Coastal Ecosystems and Biodiversity, and Integrated Modelling. The comprehensive details of the Core projects can be found in Volume Two of this SRFME Final Report.

5.1 Concise Summaries of SRFME CORE Projects

5.1.1 Biophysical Oceanography off Western Australia

Biophysical Oceanography off Western Australia: Biological Communities, Pattern, Process, and Ecosystem Dynamics across the Continental Shelf and Slope

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Executive summary

A significant aim of SRFME was to characterize the continental shelf/slope pelagic ecosystem off southwestern WA: to describe the plankton communities and their dominant patterns of spatial and temporal variability, to assess the physical, chemical and biological processes driving this variability, and to collaborate with the other SRFME projects to develop a quantitative, integrated understanding of the biogeochemical and ecosystem dynamics. To achieve this, we undertook monthly sampling from 2002 – 2004 along an onshore-offshore transect off Two Rocks from nearshore to the outer continental shelf (100 m water depth), which we extended quarterly to offshore waters (1000 m depth). Cruise sampling was combined with satellite observations of sea-surface temperature (SST), ocean colour and altimetry, and subsurface measurements of currents and temperature from moorings. The program involved six core research components:

1) The physical structure and nutrient dynamics within the water column
2) Phytoplankton community composition, biomass and productivity
3) Microzooplankton communities and their grazing dynamics
4) Mesozooplankton communities and their grazing dynamics
5) Ichthyoplankton community composition and ecology
6) Spatial structure of zooplankton and micronekton communities

Standard sampling protocols included: meteorological (wind, air temperature) observations from coastal stations; vertical CTD (conductivity-temperature-depth) casts with concurrent measurement of in situ fluorescence, dissolved oxygen and subsurface irradiance; discrete water column samples for analysis of salinity, dissolved nutrients (nitrate+nitrite, ammonium, phosphate and silicate), chlorophyll a, HPLC pigments, particulate organic carbon, phytoplankton and microzooplankton species composition and abundance, primary production, and microzooplankton grazing; bongo net samples for mesozooplankton biomass, species composition, grazing rates and secondary production; low-frequency acoustic transects, and high-frequency acoustic vertical profiles in combination with targeted water column zooplankton sampling.

Summer conditions on the shelf and offshore were oligotrophic, characterized by a shallow upper mixed layer, with a strong thermocline and well stratified water column. Surface waters were nitrate-depleted and generally contained low phytoplankton biomass levels (< 0.2 mg m-3), overlying a deep chlorophyll maximum (DCM) layer located between the 0.1% and 1.0% light levels. The DCM was frequently associated with a deep nitracline (100 m water depth). In contrast, in late autumn and winter, the upper mixed layer deepened and stratification weakened, leading to shoaling of the nitracline and DCM. Except for the lagoon environment, where no clear seasonal cycle was observed, phytoplankton biomass integrated through the water column was generally twice as high from April – September as in the spring and summer (October – February). Satellite observations indicate that the late autumn/early winter bloom over the shelf and slope is a coherent feature from approximately the Abrolhos Islands to Cape Leeuwin and coincides with the seasonal intensification of the Leeuwin Current. This leads us to hypothesize that the enhanced meander and eddy activity along the shelf break may spin-up nutrients, which are then exchanged across the shelf. Alternatively the intensified Leeuwin may entrain nutrients in the north, where the nutricline is shallower, and advect them southward. The seasonal breakdown in stratification may also facilitate vertical convective mixing of nutrients into the euphotic zone. These nutrients could have regenerated within the water column below the nutricline in deeper water or within the sediments on the continental shelf and exchanged with the overlying water column. These hypotheses remain to be tested.

Phytoplankton biomass and production integrated over the water column were generally several-fold higher offshore, although maximum volumetric chlorophyll concentrations were observed inshore. Integrated chlorophyll concentrations on the shelf and offshore generally ranged from 20 – 40 mg chl a m-2, compared to 5 – 15 mg chl a m-2 inshore. This difference was considerably reduced in spring and summer, because the seasonal cycle was less clear in the lagoon environment. Annual phytoplankton production over the study period was 46 g C.m-2.yr-1 inshore and about 115 g C.m-2.yr-1 on the shelf and offshore—relatively oligotrophic for a coastal environment. Not unexpectedly, given the nutrient depleted conditions generally observed in the euphotic zone, biomass and production were far greater in the small phytoplankton size fraction (< 5 um): the median percentage of biomass and primary productivity in the small size fraction was 5 and 12%, respectively. Based on analysis of HPLC pigments, distinct phytoplankton assemblages were observed on the inner shelf and further offshore, and between summer and winter. The outer shelf and offshore stations were characterised by high prochlorophyte and unicellular cyanobacteria populations. Small flagellates were most prevalent on the shelf, and periodic blooms of larger diatoms dominated inshore waters. Small haptophytes were ubiquitous.

Zooplankton biomass was also generally greatest in late autumn and winter. The assemblages differed significantly in nearshore and shelf/offshore waters and between winter and other seasons, following patterns among species groups observed elsewhere in coastal waters. Diversity was generally higher on the shelf and offshore than inshore.

The grazing of mesozooplankton was examined using a modified experimental and analytical design, which enabled the impact on both the microzooplankton and phytoplankton to be examined using a single set of experiments. Their direct grazing impact on the phytoplankton was generally low, but their impact on the microzooplankton increased with distance offshore. Increased densities of mesozooplankton grazed down an increasing proportion of the microzooplankton secondary production, which led to a decrease in the proportion of primary production grazed — a trophic cascade observed in our experimental chambers, as least.

Experiments were carried out to assess zooplankton secondary production based on copepod egg production, and the results were compared with a new enzyme assay and simple models based primarily on body size and temperature, which assume that production is not food-limited. The results of the copepod egg production method were generally lower, a possible indication of food limitation in our region. Levels of copepod egg production (0.4 – 10 mg C m-2 d-1) were comparable to levels observed in the North West Cape region but were considerably lower than the levels reported from more productive shelf regions in the world ocean. No significant relationships were found between secondary production based on the enzyme or copepod egg production methods and either total or large phytoplankton primary production.

Acoustics was used to examine the distribution of mesozooplankton (copepod-sized organisms) vertically through the water column using TAPS, an instrument with 6 frequencies from 256 kHz – 3 mHz, whereas larger macrozooplankton (e.g. krill) and micronekton (e.g. small fish) were acoustically sampled along the onshore-offshore transect during quarterly cruises with a three-frequency (70, 120 and 200 kHz) acoustic system. A pump sampler was deployed in conjunction with TAPS. Initial results indicate a good relationship between copepod abundance and acoustic backscatter at the higher frequencies (> 420 kHz). The regression relationships show that the instrument is limited by its signal-to-noise ratio, due to the relatively low abundance of zooplankton in WA waters.

Principal component analysis was used to examine spatial and seasonal patterns in the cross-shelf distribution of acoustic backscattering at lower frequencies (70 - 200 kHz) integrated through the water column. Two patterns explained 50% of the variance in the data from 8 cruises. The first component (31% of variance explained) was based on a pattern of very high inshore biomass in the autumn with the opposite being found in winter. The second component identified a summer pattern in which the highest acoustic backscattering was found in the inner shelf in summer.

Mixing frequencies appears promising as a means to separate major groups, and to assess relationships between topography and water mass features and the broad-scale distribution of large zooplankton and nekton. Non-gas bladdered organisms (e.g. euphausiids) have particularly high reflectivity at 200 kHz, so it is possible to distinguish a layer of krill from a layer of, say, small fish. However further ground-truthing is still required to assess these relationships.

The project also integrates two postgraduate projects that characterized the microzooplankton and ichthyoplankton assemblages in the region, as well as the role of microzooplankton grazing. Particularly clear onshore-offshore and seasonal assemblages were seen in the ichthyoplankton, which were related to water mass structure and the seasonal characteristics of spawning in the region. The inshore region was characterized by reef fishes, e.g. gobies, clinids, blennies and tripterygiids, whereas pelagic fishes, such as clupeids and carangids dominated over the shelf. Oceanic fishes, such as myctophids, phosichthyids and gonostomatids dominated the ichthyoplankton at the shelf break and over the slope. However the changing seasonal dynamics of the Leeuwin and Capes Currents were clearly seen in the ichthyofauna assemblages.

Microzooplankton biomass peaked in winter, consistent with the winter peak in chlorophyll. Species richness was significantly higher on the shelf and offshore than nearshore, which was ascribed to the generally less stable inshore environment. Dilution experiments indicated that the microzooplankton consumed on average 60% of primary production. Growth of the picoplankton was particularly closely coupled with microzooplankton grazing.

Key areas for future research include:

1. The mechanisms underlying the late autumn bloom. Several hypotheses have been identified, which will be further examined during a cruise of the Southern Surveyor in May 2007.
2. Remote sensing of the WA marine environment. Remotely sensed data will be used to further examine patterns of productivity in the region and their inter-annual variability. Using SRFME and other data sets, the ability to predict primary productivity (and possibly nutrient content) from ocean colour nd SST data will be tested.
3. Coupling between pelagic and benthic components of the lagoon and shelf ecosystems. Benthic regeneration of nutrients to the water column will be further examined along a depth gradient, as will the relative role of benthic and pelagic grazers in consuming pelagic production.

5.1.2 Coastal Ecosystems and Biodiversity

Investigators / Institutions

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Executive Summary

Western Australia is unusual in possessing high-biomass, high-productivity benthic ecosystems despite the relatively low-nutrient waters of this coastal region that result from the low-rainfall climate and the influence of the Leeuwin current. The drivers of productivity and spatial distribution of WA's coastal ecosystems are poorly understood, and there is increasing need for improved information on fundamental aspects of benthic community structure and variability in the wake of increasing pressures resulting from population growth and development. Improved understanding of benthic ecosystems can support efforts to manage growing human impacts, will better enable us to determine their likely response to human influences, and will help ensure their future health and sustainability.

The SRFME study focused on improving understanding of one major habitat type –coastal rocky reefs – that had previously received relatively little attention. Rocky reefs are an important habitat type in nearshore coastal waters, supporting a diverse assemblage of benthic macroalgae and associated fish and invertebrates. Aside from the biodiversity associated with rocky reef communities, they are also a key component of coastal productivity, provide habitat and food for marine fauna, contribute to biogeochemical cycles, and can exert influence over nearby habitats such as seagrass meadows. Despite their recognised importance, comparatively little is known of the ecology of rocky reef habitats along the lower west coast of Western Australia. As a consequence, the SRFME benthic ecology program sought to address this gap in current knowledge of the mechanisms structuring rocky reef communities.

SRFME research on benthic ecosystem dynamics incorporated the first quantitative, broad-scale investigations of the effects of several key ecological processes on the reef benthos of south-western Australia. Major findings were that spatial gradients in wave exposure were significantly correlated with spatial patterns in the species richness and composition of macroalgae, that the rates of some ecological processes (e.g. algal productivity) and the abundances of both mobile and sessile fauna vary significantly between inshore and offshore reefs, and that consumers (including humans) might exert a significant influence on some reef-associated biota.

The approach taken in the SRFME coastal benthic ecology program was to build a foundation for future research through providing a clear understanding of the distribution and abundance of major ecological components in the coastal ecosystem. This includes the description of key ecological patterns and their inter-correlations in space and time as well as research on the dynamics of interactions between physical and biological processes, and of ecological interactions. The understanding of both pattern and process is essential to the achieving the ultimate goal of modelling the coastal ecosystem and gaining the ability to predict ecosystem behaviour. The program involved the following core research components:

1) Correlate biological/ecological patterns with physical environmental variables (e.g. light, nutrients, wave energy, transport)
2) Describe biogeographic patterns in benthic community structure
3) Quantify seasonal and inter-annual variability at key sites
4) Determine the effects of nutrient availability in benthic reef communities
5) Describe patterns in community structure determined by ecological interactions

The SRFME study found a strong seasonal signal in algal biomass in all regions, however processes underlying this pattern varied for different locations, or for particular sites within locations depending on the dominant algal habitat type. Most locations showed lowest biomass in winter (e.g. Jurien Bay, Marmion, Two Rocks and Bunbury) but others showed summer minima, where the majority of sites were dominated by *Sargassum*. The proximal factors that drive these variations also differ among locations. Erosion of biomass is most likely to be the factor driving changes in *Ecklonia* dominated sites (Marmion, Two Rocks, Perth) while light limitation is likely to be a major factor at Bunbury, most likely due to seasonal re-suspension of particulate matter and sediment in eastern Geographe Bay by winter and spring storm events and long-period swells. In the case of Bunbury these effects appear to occur across the entire algal community which is largely made up of foliose red and brown algae. Where *Sargassum* dominates sites (Green Head), algal phenology can explain reduced algal biomass in summer. In contrast to the pattern for biomass, algal community structure showed no seasonal trend, which was also the case for invertebrates.

Among the study regions the overall number of algal species recorded was similar. While variations in number were not large, there were more species recorded at the lower latitude sites, and fewer recorded in the Perth region. In this regard it is worth noting that this may be explained by variation in the relative dominance of large brown algae in the different regions. In all the regions, by far the largest contribution to overall species diversity was made by the red algae. The highest densities of *Ecklonia* were found at reefs in the Perth region and since there is an inverse relationship between *Ecklonia* biomass and that of red algae, it is possible that this explains why fewer species were recorded around Perth. There is potential for anthropogenic nitrogen sources in the Perth region to enhance the growth of macroalgae a possibility worthy of further investigation. Nutrient levels offshore from Perth seem to be elevated and to carry a high level of 15N, a sign of terrestrial effluent origins for this nitrogen. Other Laminarian algae are known to be nitrogen limited however it is not known if this is actually the case for *Ecklonia* on the WA coast.

Macroalgal community structure varied at all the spatial scales we examined, but was strongest at the site level. In fact, at the site level, the differences among sites, even within locations, was greater than the differences between sites at the most widely separated regions. This strongly suggests that for algal community structure, processes operating or varying across relatively small scales may be responsible for much of the variation observed on west coast reefs. Assemblages not dominated by *Ecklonia* or other canopy species were most often composed of a diverse mixture of medium to small sized foliose algae, mainly red and brown algae, though green algae were occasionally dominant. Our study has shown that for the study area these habitats can on average form almost 50% of all algal communities, and are likely to be of greater importance than previously assumed in WA.

Since the nature of this variation was often associated with clear qualitative differences in community structure, e.g. presence or absence of a canopy, we developed a method to classify algal communities based on a semi-quantitative mix of structural and taxonomic attributes. The system was accurate in 75% of cases and offers a means of classifying algal assemblages for use in higher level analysis of patterns at the landscape scale and as a rapid system for visual quantification of habitats for mapping, ground-truthing etc. (e.g. hyperspectral mapping).

A statistical model relating algal assemblage structure to physical environmental variables in the Jurien region showed that the two factors most strongly associated with community structure were seabed roughness at the 1 m and 10 m scales, and modelled seabed orbital velocity. Wave generated water movement across the seabed and small scale seabed topography are likely to interact very strongly, further reinforcing the conclusion that small scale variations in ecological processes are likely to be of prime importance in determining the structure of benthic reef assemblages. Processes controlled by interactions of topography and water motion include physical disturbance (dislodgement), diffusive processes (gas and nutrient exchange) and sediment transport (scour and burial). It is important for us to understand the implications of this small scale variation in algal assemblages in order to lay the basis for future work and for scaling up our results to larger areas.

For invertebrates weaker patterns in community structure were present, particularly for the algal-associated epifauna. Some pattern was present in the larger sessile and solitary fauna, but levels of similarity/dissimilarity did not vary markedly across scales. The lack of pattern suggests that the spatial scales encompassed in the sampling (regions, locations, sites), which was designed primarily to quantify algal assemblages, was not adequately capturing variation in the invertebrate assemblages.

When examined at different spatial scales however, informative patterns did emerge. Species number varied according to the algal habitat type with epifuanal invertebrate species richness (at the scale of 0.25 m2 quadrats) higher for turf habitats, followed by *Caulerpa*, *Ecklonia* forest, *Sargassum*, low algae, red foliose and mixed brown habitats. A higher number of solitary and sessile invertebrates (1 m^2 quadrat) were found to be associated with low algae and red foliose habitats, followed by mixed brown, turf, *Sargassum*, *Ecklonia* forest and *Caulerpa* habitats. As for the algae, the highest number of invertebrate species was recorded at Jurien, and Perth had the lowest numbers of species although numbers were only marginally greater at Geographe Bay. While the magnitude of the differences is relatively small, it is once again interesting that the region with the most *Ecklonia* dominated sites had the lowest number of species.

For larger sessile invertebrates, belt transects revealed strong trends for coral and sponge abundance, within low algae and red foliose algal habitat types. Brown algal dominated habitats totalled 53% of habitats covered by transects at Marmion, yet within these transects only 22% of sponges and 7% of corals were recorded. These patterns essentially reflect algal habitat structure and coverage, and its patchiness or variability not just at the site level but within sites. Interestingly one of the coral species (*Plesiastrea*) was one of the taxa most responsible for dissimilarity among sessile and solitary invertebrate assemblages at the site level. Sessile invertebrates such as corals and sponges may achieve a higher larval settlement rate and/or higher subsequent survival and growth in habitat that is lower and more sparsely covered by algae, in comparison to the typically dense, canopy forming brown algae species.

At the scale of individual quadrats there were significant patterns in the overall abundance of mobile invertebrates, particularly molluscs and crustaceans. Most of these animals are relatively small and likely to be key contributors to secondary production in the reef ecosystem. Interestingly this pattern resulted from a significant negative correlation between invertebrate abundance and the biomass of *Ecklonia radiata*, which in this case turns out to have a key indirect influence on invertebrate assemblages.

Fish assemblages showed a contrasting pattern to those of algae and invertebrates, with a high level of variation among assemblages at the regional level and virtually none at the location level. However at the site level there was once again significant variation in fish assemblages. We attribute this consistent variation at the site level to the association of fish assemblages with definable algal habitat types that tend to dominate at particular sites. While large brown algal assemblages dominated at just over half the sites, nearly as many sites were instead characterized by a diverse assemblages of foliose and filamentous red and brown algae.

At small scales across all three major groups we have studied, algae, invertebrates and fish, we see the importance, even dominance, of processes operating at distances of meters to tens of meters for structuring variation in benthic assemblages. This variation has important implications for understanding which ecological processes structure these communities. Analysis of algal community structure strongly suggests that some aspect of wave action, coupled with the nature of the substratum, interacts to determine the characteristics of the algal community. The characteristics of the algal community in turn appear to strongly determine the nature of invertebrate assemblages. For fish, these aspects of habitat also appear to be important, although in their case there may also be stronger large-scale biogeographic factors influencing distribution across the west coast region. At the regional level some locations have physical characteristics that mean larger scale processes play a more important role. Variation in water quality in eastern Geographe Bay creates conditions that result in a seasonal change in algal biomass quite distinct from other parts of the west coast. The implications of this unusual pattern merit further exploration. It is possible that elevated nitrogen levels in Perth metropolitan waters are linked in some way to the abundance of *Ecklonia* dominated habitats at Marmion. For most of the coast smaller scale studies focused on the way in which environmental factors impact at the site or even quadrat scale are likely to lead to a broader general understanding of key ecological processes. This small-scale understanding will have to be applied from the bottom-up to larger scale pictures of ecological processes across the coastal ecosystem as a whole. The role of such small scale processes, and of nutrient in coastal reef systems, will be explored as part of WAMSI Node 1 programs beginning in 2006.

Using a model-based index of disturbance by wave action, we found evidence that biodiversity in assemblages of reef algae might be related to wave disturbance. Quadrat-level species diversity was highly correlated with orbital wave energy, and much of the variance in species composition could be explained by orbital wave energy. Wave energy decreases as waves are attenuated and diffracted by reefs, and this relationship provides another key explanatory variable that we used to test some aspects of assemblage structure. Importantly, accumulated wave exposure over an 8 year period provided a significantly better explanation of species richness patterns than wave energy over a single year (P. England unpublished data). This suggests that species richness of macroalgae might be the result of integration of processes occurring over years, rather than the result of short-term responses to disturbance.

The consequences of wave action for an individual alga include detachment from the substrate on which it grows. Our research showed that, once detached, kelps may drift for many kilometres. Substantial accumulations of detached reef algae occurred at an inshore reef, coinciding with high densities of sea urchins, which mainly eat detached fragments of algae.

Analyses of the morphology of individual kelps at this location indicate that a large proportion originate from the reefs several kilometres further offshore. These results indicate that there are large-scale trophic linkages across the lagoon that are a result of wave action.

Trophic linkages such as these are likely to have profound implications for how WA's coastal ecosystems function at broad scales. For example, differences between inshore and offshore reefs were observed for densities of sea urchins (higher densities inshore) and grazing on drift kelp by sea urchins (higher inshore). This overall trend might be a result of the gradient in wave action, and gradients in ecological processes that occur due to physical disturbance by waves, such as detachment and export of reef algae. Our measurements of rates of recruitment to collectors indicated that while rates were higher inshore, they were highly variable. This suggests that densities of adult urchins inshore did not seem to be due to higher recruitment, but to the higher availability of food (drifting fragments of algae).

Trends for primary productivity of *Ecklonia* showed that productivity was greater at Jurien than in the Perth Region. In addition productivity was higher offshore at Jurien, but not in the Perth Region. These results suggest that nitrogen per se might not be limiting for growth of macroalgae on this coast since these productivity patterns are directly opposite to the C:N trends found in *Ecklonia* plants from these sites. The C:N values were far lower at Perth, than at Jurien — yet production was higher at Jurien. In addition, C:N ratios of kelps from both regions were lower inshore than offshore — yet production tended to be higher offshore, at least at Jurien. The most common paradigm for marine algae of all types is that their growth is nitrogen limited, yet our data contradict this assumption. The idea that availability of nitrogen might not be limiting growth of macroalgae requires investigation, and other potential influences on the rate of N uptake, such as light availability, and the role of wave-driven turbulence, must also be investigated.

Little of the *Ecklonia* primary productivity was directly consumed. The only direct grazing was by herbivorous fish, however, densities of herbivorous fish, and rates of grazing by herbivorous fishes, varied from reef to reef, and showed no broad trends. The highest rates of consumption of tethered kelps were on drifting fragments, and this was mainly due to sea urchins. This suggests that detached macroalgae play a key role in sustaining reef food webs. Together with observations that detached macroalgae are important in seagrass and intertidal habitats in the region which reinforces the importance of detached macroalgae in sustaining coastal food webs is ubiquitous on this coast.

Humans can exert a strong influence on the structure of communities through harvesting of key species. For example, in several parts of the world, hunting and fishing has reduced predators of sea urchins to ecologically trivial abundances, resulting in increases in sea urchin abundance, followed by landscape-scale decreases in canopy-forming primary producers due to grazing. Similar processes are possible in WA, and are a potential explanation for variation in the structure of assemblages of reef algae. SRFME research included the first assessment of the effects of a 16-year fishing closure (the Kingston Sanctuary at Rottnest Island) on assemblages of fish and invertebrates. Researchers found that the overall abundance of fish, abundance of predatory fish and western rock lobster (*Panulirus cygnus*) was higher inside the Kingston Sanctuary than at adjacent fished reefs. For fish the research found significant differences for two popular angling species and four by-catch species, while some bycatch species showed opposite patterns.

These differences in abundances of predatory fishes and lobsters were reflected by patterns of predation on small and medium size invertebrates. The intensity of predation on tethered sea urchins was higher in the sanctuary. However, there were no simple trends in the abundances of prey: the abundance of one species of sea urchin (*Heliocidaris erythrogramma*) was lower in the area protected from fishing, consistent with the pattern predicted if predation was a strong influence, but the abundance of a second species (*Centrostephanus tenuispinus*) was higher in the area protected from fishing. Consistent with this finding, there was no evidence of trophic cascade effects occurring outside the protected area as a result of lower abundances of predators, with assemblages of macroalgae showing no difference in structure between the sanctuary and fished areas.

The correlation between wave energy and both algal diversity, and community structure plus the patchy nature of macroalgal assemblages suggests that physical disturbance may have much more pervasive and important influences on benthic communities of WA coastal reefs than do top down effects resulting from variations in predation. Curiously, bottom-up effects (supply of nutrients) also appear to have less influence on the structure of benthic assemblages than might be predicted for what has been assumed to be a nutrient limited coastal ecosystem. The dynamics of patches and the influence of varying nutrient availability require more detailed investigation before we can be certain of how these factors interact with the dynamics of WA coastal ecosystems.

5.1.3 Integrated Modelling

Investigators / Institutions

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Executive Summary

The health and diversity of southwestern Australia's marine ecosystems depend on ocean phenomena from small to very large scales. They are directly, and measurably, affected by scales from the circulation in the Pacific and Indian Oceans, down to turbulence from individual waves crossing the reefs. Time-scales range from the seconds associated with breaking waves up to the decades associated with climate change. Capturing and describing these scales involves a diversity of data sets collected from ships, moorings, satellites, and generated by models.

At decadal to century time-scales, the water temperature at coastal stations in the region has risen by around 0.017 ºC per year over the last 50 years, consistent with the global temperature rise attributed to climate change. At the same time, salinity off the WA coast has also increased. Sea-level at Fremantle is rising at about 1.5 mm per year. There is also a clear suggestion of a lengthening warm season.

The southward-flowing Leeuwin Current conveys much of the large-scale parameters to the coast. The Fremantle sea-level is an indicator of the strength of the Leeuwin Current on time-scales from days to years. The average flow rate of the current, estimated from long-term, ship-based measurements, is about 3.4 x 106 m3s-1. An increase in the flow rate of 1 million m3s-1 is reflected by an increased Fremantle sea-level of about 7.5 cm. The strength of the current varies by about a factor of 2 over the year, being weakest in summer, when it is opposed by southerly winds, and strongest in winter. It is also about 40% stronger during a La Nina year than during an El Nino. The La Nina-El Nino oscillation is principally based in the Pacific Ocean, with a time-scale of several years. The Southern Oscillation Index, an indicator of the La Nina-El Nino cycle is highly correlated (0.6-0.7) with Fremantle sea-level. The Leeuwin Current responds as well to a smaller signal called the Pacific Decadal Oscillation, which can also be monitored by the Fremantle sea-level.

During the winter, the Leeuwin Current turns east past Cape Leeuwin, and can be tracked, in satellite images of surface temperature and height, all the way to southern Tasmania, a distance of 5500 km from NorthWest Cape. Its name changes to the South Australian Current, and then the Zeehan Current, on this journey.

Eddies form south of the Abrolhos Islands (29ºS) from meanders of the Leeuwin Current. The eddies are studied primarily from satellite altimetry, and are more intense when the Leeuwin Current is strongest, in the winter and in La Nina years. Warm-core eddies drift from the shelf offshore and may persist for months. Approximately six warm-core eddies form each year, carrying a total volume of water roughly equivalent to flushing the southern shelf twice per year. The eddies are believed to carry nutrients and phytoplankton from inshore waters, significantly enhancing offshore primary production, and probably play a significant role in the advection of larvae.

Near-surface chlorophyll-*a*, an indicator of phytoplankton biomass, can be inferred from ocean-colour sensors mounted on satellites. Over the continental shelf, phytoplankton production appears to peak during the late autumn and early winter, corresponding to the seasonal strengthening of the Leeuwin Current and its eddy field. Further offshore, the phytoplankton biomass peaks in late winter, assisted by the eddies' transport of both nutrients and phytoplankton from the shelf. Deeper mixing during winter is also likely to enhance nutrient levels. The offshore flux of phytoplankton biomass by the warm-core eddies is estimated as equivalent to about 4 ×105 tonne of carbon.

A relatively simple, one-dimensional, biophysical model has been developed to demonstrate the importance of spinup over the shelf for warm-core eddies. The model represents an eddy as a trapped body of water and follows it as it detaches from the Leeuwin current and moves offshore. Given appropriate density and nutrient properties during eddy formation, the model successfully distinguishes between the productivity of the warm and cold-core eddies as they evolve. Cold-core eddies tend to spin up on the low-nutrient, seaward side of the Leeuwin Current.

The Leeuwin Current is apparent in images of both sea-surface temperature and sea-surface height. An accurate numerical (hydrodynamic) model of the Leeuwin Current has been developed, at 10 km horizontal resolution, by forcing it with the surface observations, and using the model equations to calculate the 3-dimensional current and density fields. The model has been validated against ship-based observations of eddies, and inshore moorings.

Three moorings were maintained for a year out from the coast at Two Rocks, at water depths of 20 m, 40 m and 100 m, primarily recording currents and water temperature. At the innermost mooring (approx. 5 km offshore), the currents follow the wind direction, principally north in the summer and south in the winter, with the water speed close to 3% of the wind speed. At the 100 m mooring, about 50 km offshore, surface waters tend to follow the wind direction, while waters below 50 m flow south under the influence of the Leeuwin Current. Water temperatures are warmer, and saltier, inshore during the summer, but during the winter the Leeuwin Current keeps the offshore water warmer. In summer, the surface water in 100 m is about 2 ºC warmer than the bottom, but the water is well-mixed during the winter.

The main role of the hydrodynamic model is to provide the ocean forcing for a 3-dimensional biogeochemical model. The biogeochemical model simulates the cycling of carbon, nitrogen and oxygen through the water column and sediments. Its primary output is phytoplankton biomass, and its key initial challenge is to represent the seasonal cycle of phytoplankton productivity as observed from satellites and the Two Rocks transect. The model appears to simulate the large-scale variability, with low productivity in the summer and blooms in the late autumn and winter. However, it does not reproduce the high inshore productivity visible in satellite images for autumn and winter.

Nutrient sources remain a significant unknown for the biogeochemical modelling. The inshore productivity is assumed due to onshore or nearshore sources that are not available to the model. Nutrients will also be stored in coastal and shelf sediments, and presumably released during high wave and swell conditions. Sensitivity tests with the model indicate the potential importance of nutrient storage in the sediments, but the magnitude of the store is unquantified. Further, the large-scale nutrient distribution, required for both initialising the model, and for its open boundary conditions, is not well established. The hydrodynamic model currently uses temperature and salinity fields predicted from synTS, a technique which, given the surface height and temperature, derives T and S profiles from historical data sets. The model can also access CSIRO's global BLUElink model for initial and open boundary conditions. Equivalent fields for nutrients do not yet exist.

Along the Two Rocks transect, over the outer shelf and upper slope, surface waters are very low in nutrients, while the nutricline, signalling a transition to high nutrient levels, is at a depth of 100 to 150 m. High nutrient water below the nutricline is not considered to contribute directly to the shelf, because the Leeuwin Current inhibits upwelling. However, vertical mixing, associated both with storms and the increased intensity of the Leeuwin Current, is thought to bring nutrients locally towards the surface, into the photic zone, during autumn and winter.

The role of vertical mixing on the biogeochemistry was tested with a simplified one-dimensional version of the biogeochemical model. The model was set up to simulate the upper 200 m at station E, the outermost station on the transect, 85 km offshore and in 1000 m of water, for the year 2003. Vertical mixing due to atmospheric conditions and the Leeuwin Current was simulated by forcing ("relaxing") the vertical temperature and salinity profiles to synTS.

There were only 5 transects during 2003, providing limited data for comparison. The model appears to predict well (given only 5 comparison points) the measured seasonal cycle of temperature. It predicts the stable summertime nutrient situation with a deep (100 m) chlorophyll maximum, and the transition to a surface bloom in autumn. It failed to predict the deep chlorophyll maximum observed in late winter. The winter observation corresponded to an exceptional cold event (2 °C cooler at 100 m depth), relative to synTS predictions, and may have been associated with an eastward migration of the Leeuwin Current, obviously beyond the scope of a 1-d model.

Towards the coastline, the seabed falls within the photic layer, and macrophyte productivity begins to dominate phytoplankton productivity. In these shallower waters, the water movement is increasingly dominated by the effect of surface waves. The 10-m mooring included a pressure sensor to measure waves, and an acoustic doppler current profiler, which could be be used to infer the sediment suspended from the seabed by the waves. The data were used to calibrate a sediment-transport model. They show that, at this inshore location, the waves are sufficiently energetic to keep the sand mobile all of the time.

South and north of Perth, the sediment mobility was examined by nesting a local wave model (SWAN) inside a global model (WAVEWATCH 3). The modelling suggests high levels of sand mobility (>60% of the time) in Geographe Bay throughout the year, with an increase (to 80%) in the winter. There is a small area in the lee of Cape Naturaliste where the mobility is much reduced. Mobility rates are similar off Geraldton, although the high-mobility region is more limited in area during the summer.

In December 2005, 4 acoustic doppler velocimeters, capable of measuring wave orbital velocities, were deployed across the Marmion reef to measure the cross-shore change in wave signature. The amplitude diminished by up to 1/3 as the waves travelled 1500 m across the reef. This behaviour was reproduced by a standard wave model (SWAN), but with enhanced bottom friction attributed to the reef roughness.

Exposure to waves is expected to affect the distribution of macroalgal species on the reefs. For Jurien Bay, the wave model was used to estimate exposure to large wave events at the 26 sites sampled during the benthic field program. The species diversity at the sites was positively correlated with wave disturbance; that is, the more exposed the site to large wave events, the higher the diversity. Presumably, the breakage and removal of plants by big waves increases opprtunities for new species to establish. There is a suggestion that, at the highest exposure, diversity begins to diminish again, presumably because only the hardiest species survive under the most extreme conditions. This increase, and subsequent decrease in species diversity with increasing disturbance rate is a well-documented phenomenon, generally known as the intermediate disturbance hypothesis.

As already noted, surface waves are also likely to enhance the release of nutrients from sediments, particularly during storms and large swell events in the winter. In addition, wave motion is believed to increase an alga's access to nutrients, by reducing the thickness of the viscous boundary-layer on the fronds. Thus, algae in an exposed location will suffer the competing impacts of faster nutrient uptake, but more severe disturbance. The interaction of waves and habitat will receive increased attention in WAMSI.

SRFME data access

The SRFME field and model data have been stored in standard formats (mostly NetCDF and ASCII column-files) in a data repository that is accessible for visualisation by the software DIVE (Data Interrogation and Visualistion Environment). DIVE enables data in up to 4 dimensions, and from different sources (such as models, vessels, moorings and diving), to be overlaid and compared. The DIVE software has been supplied to State Agencies to give them direct access to the SRFME data set.

DIVE is supplemented by other software tools developed during SRFME. WebOLIVE is a web-based visualisation program for regularly gridded data such as model output and the climatology CARS (CSIRO Atlas of Regional Seas). WebOLIVE is installed on the SRFME wesite. Aus-Connie (The Australian Connectivity Interface, http://www.per.marine.csiro.au/aus-connie) allows users to investigate the large-scale patterns of spatial connectivity around Australia. It provides estimates of the probability that any two regions are connected by ocean circulation. Meanwhile, the Argo website (http://www.per.marine.csiro.au/argo) provides an interactive data explorer to display tracks and vertical profiles from over 100 Argo vertical profiling floats which have been deployed in the Indian and Southern Oceans.

CHAPTER 6

6. PUBLICATIONS

Publications arising from SRFME funded research and related activites

This is the list of publications and reports arising from SRFME funded research projects or other allied research activities. It includes unpublished reports as well as journal publications. It also includes some as yet unpublished manuscripts which are either submitted or in preparation. It does not include a significant number of conference presentations and milestone reports. Some of these are referred to in the main body of the SRFME Final Report.

Anon. (2001). Report of the Joint Venture Management Committee on the Research Portfolio for the Strategic Research Fund for the Marine Environment. CSIRO Marine Research Unpublished Report.

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ISBN 1 921061 89 8

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