WESTERN AUSTRALIAN
MARINE SCIENCE
INSTITUTION

Strategic Integrated Marine Science for the Kimberley Region

New Knowledge for Better Decisions and Outcomes

WAMSI Kimberley Marine Research Program

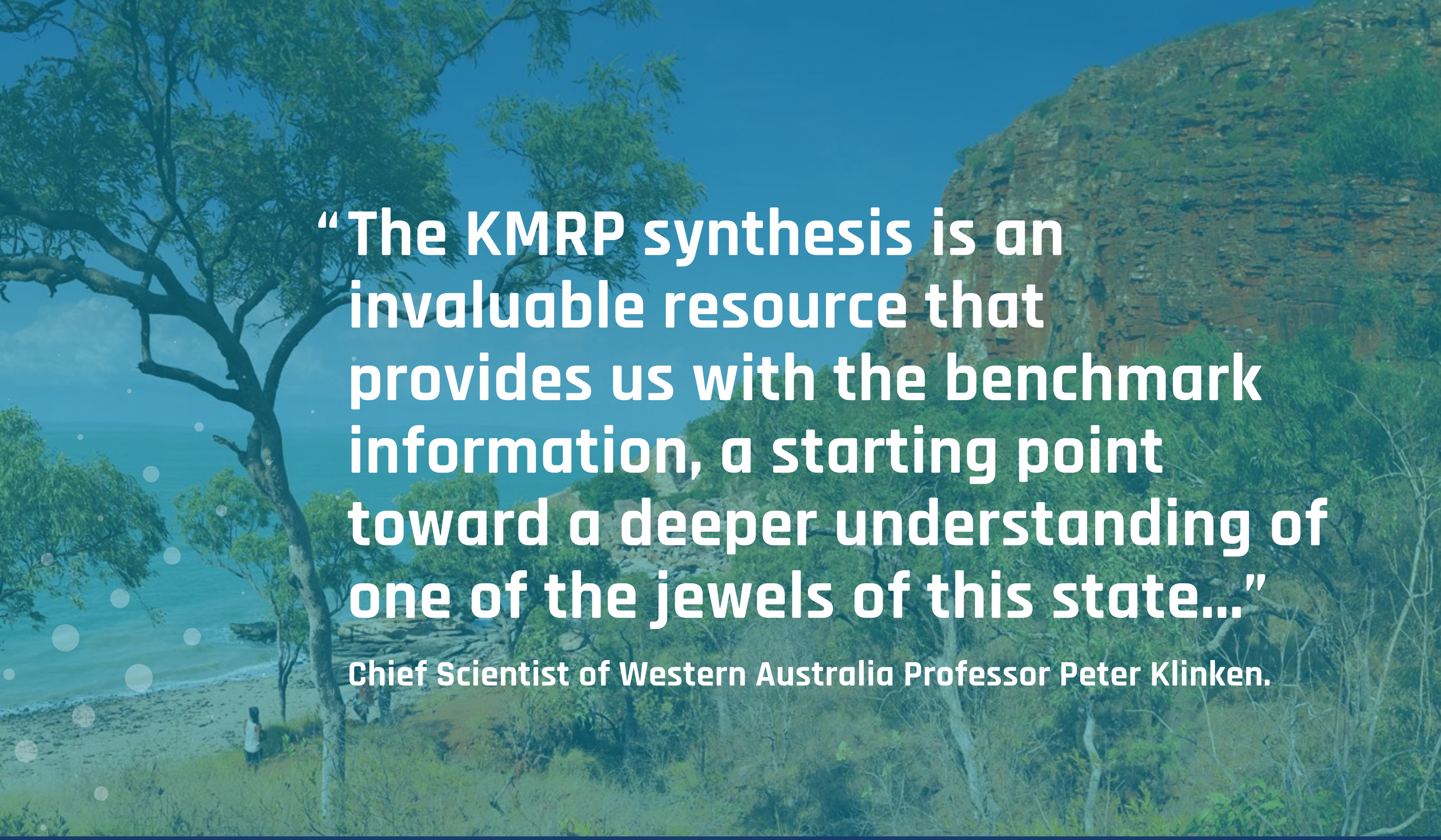
A Synthesis of Research 2012-2018

February 2019

Acknowledgements

WAMSI Kimberley Marine Research Program

Initiated with the support of the state government as part of the Kimberley Science and Conservation Strategy, the Kimberley Marine Research Program has been co-invested by the WAMSI partners to provide regional understanding and baseline knowledge about the Kimberley marine environment. The program has been created in response to the extraordinary, unspoilt wilderness value of the Kimberley and increasing pressure for development in this region. The purpose is to provide science-based information to support decision making in relation to the Kimberley marine park network, other conservation activities and future development proposals.



> "The KMRP synthesis is an invaluable resource that provides us with the benchmark information, a starting point toward a deeper understanding of one of the jewels of this state..."

Chief Scientist of Western Australia Professor Peter Klinken.

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Mark Sheridan

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Kimberley Traditional Owner agreement
This research was enabled by the Traditional Owners through their advice, participation and consent to access their traditional lands.

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Foreword

Never before has the Kimberley region been subjected to the breadth and depth of scientific investigation that is presented here in the synthesis of the Kimberley Marine Research Program (KMRP). The importance of this work cannot be underestimated as it arms us with the knowledge to better manage our northwest coast, a region that is like no other place in the world.

Until now, our science-based understanding of this marine environment has been arguably scant and yet, with looming development pressures and climate projections suggesting that the ocean temperature of the Kimberley coast will warm by more than one degree centigrade in the next 50 years, we cannot afford to ignore our responsibilities as custodians of this unique region.

The KMRP synthesis is an invaluable resource that provides us with the benchmark information, a starting point toward a deeper understanding of one of the jewels of this state, a pristine environment that has been largely untouched by anthropogenic pressures, protected up to now by its own isolation and rugged beauty.

This body of work now affords us the confidence to predict, with some certainty, that wave energy on the continental shelf will likely increase as the surface of the ocean warms, that the corals and seagrass upon which the community thrives are living precariously close to their physiological limits and that the Kimberley bioregion, and some areas within it, is largely a demographically independent system.

The science here provides quantitative evidence that traditional management practices have been effective in maintaining these ecological processes for centuries but, as interest grows in exploring this uniquely Australian environment, a mix of traditional and contemporary science-based knowledge presents itself strongly as our best chance at delivering effective solutions to manage this environment into the future.

The KMRP has brought together a veritable juggernaut of experts, more than 200 scientists, Kimberley managers, rangers, Traditional Owners and body corporates, all achieving an unrivalled cooperation and collaboration that has enhanced WA's marine science capacity as a leader in Indian Ocean marine research.

I congratulate the Western Australian Marine Science Institution for its planning, administration and management of this program of work. It is the partnership of marine science organisations, stakeholders and decision makers that we have come to rely on to provide the 'big picture' marine science for Western Australia.

As we look to the future, my hope is that new initiatives in the Kimberley region will build on the KMRP with continued collaboration and cohesion for the benefit of all Western Australians and indeed the world.

Professor Peter Klinken AC FAHMS FTSE CitWA
Chief Scientist of Western Australia

KMRP Report Overview

The tropical Kimberley region of northern Western Australia (WA) is well known for its outstanding natural features, vast and remote landscapes and Indigenous cultural significance. The inshore marine environment's rugged and dynamic coastline, characterised by tidal movements of up to 10 metres, form extensive intertidal habitats adjacent to rocky shores and headlands, islands and sandy beaches.

This physically complex inshore environment supports a diverse range of habitats that include seagrasses and coral reefs, extensive intertidal mudflats and sponge-dominated filter-feeding communities with high levels of biological diversity. The region also supports numerous large and iconic marine fauna including whales, dolphins, dugongs, turtles and estuarine crocodiles.

While aboriginal people have lived in the Kimberley for millennia and retain strong cultural connections to their Saltwater Country, this coastal and marine environment increasingly supports other activities such as tourism, commercial and recreational fishing, pearling, aquaculture and major port facilities associated with resource industries. Despite this growth in activity, anthropogenic impacts remain low compared with other parts of the WA coast and disturbance to much of the Kimberley marine environment is considered to be minor. However, the region is likely to be increasingly affected by a number of pressures including: climate change-related impacts such as coral bleaching, regional development and growth, and increased human access and use of the region. The lack of historical data available on these influences highlights the shortfall in marine biodiversity and ecological knowledge that can inform management at regional and local scales. Understanding Kimberley marine habitat connectivity in relation to regional-scale physical processes, for example, is critical to support conservation management of this region at a local scale.

The Western Australian Government's Kimberley Science and Conservation Strategy (KSCS)[1] was released in June 2011 with the intent **to recognise and conserve one of the world's last great wilderness areas**. This included investment of $12 million over six years for a research program to be administered by the Western Australian Marine Science Institution (WAMSI) to address critical knowledge gaps in the marine environment and support management of the proposed Great Kimberley Marine Park.

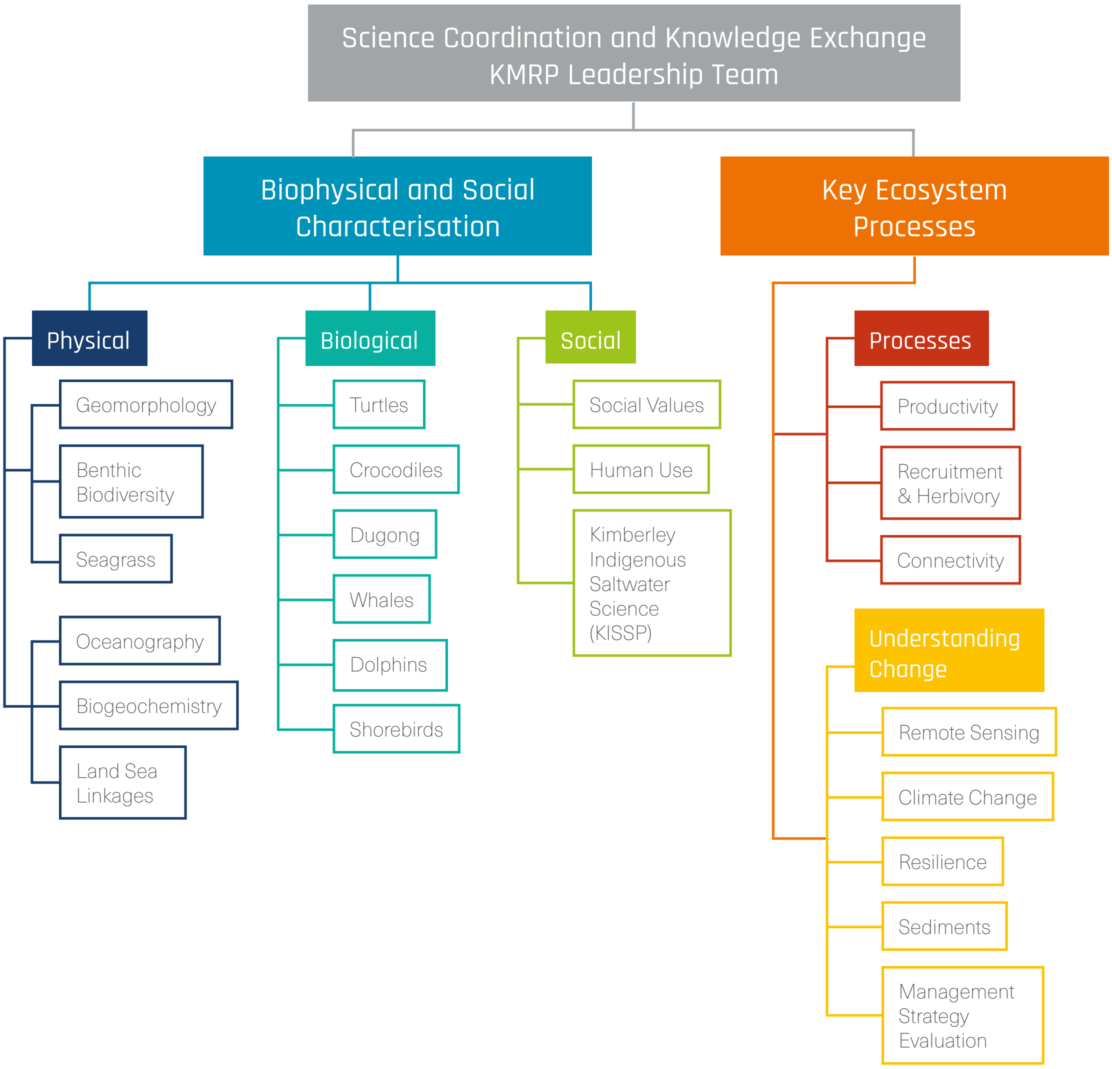
The Department of Biodiversity, Conservation and Attractions (DBCA) manages and conserves WA's terrestrial and marine biodiversity and is a key stakeholder in the Kimberley Marine Research Program (KMRP). DBCA prepared a science strategy and plan that identified critical management-related information gaps and questions to ensure that program objectives and outcomes were aligned with State and Commonwealth strategic priorities and met the needs of management. DBCA subsequently worked with WAMSI partners to develop the KMRP as a cohesive and integrated research program that would provide a regional perspective across two key themes:

1 Kimberley Science and Conservation Strategy, Government of Western Australia, May 2011.

- **A biophysical and social characterisation** of the Kimberley, through developing foundational datasets required for marine park and marine resource management and better understanding and management of current human impacts.
- **An understanding of key ecosystem processes** to provide the scientific understanding of ecosystem functioning and response to a range of potential human impacts that are likely to arise in the future, including climate change.

Co-investment from WAMSI partners and further leveraging of funds saw the initial investment of $12 million by the WA Government grow into a science program valued at more than $30 million. This expansion markedly broadened the scope and relevance of the overall program.

The full science program was developed under the direction of the DBCA leadership team in consultation with nine WAMSI partner organisations along with external scientists where additional capacity was needed. The process identified 23 research projects under the umbrella project of science coordination and knowledge exchange led by the leadership team. Research projects were planned and undertaken by multidisciplinary teams across institutions. This governance structure created a strong alignment between management questions and science objectives, to ensure the final outcomes aligned with key stakeholder needs.



Structure of the KMRP noting how the 23 research projects fit within the two themes.

Traditional Owners of Kimberley saltwater country have also been key KMRP stakeholders and participants in the science program. An important aspect of KMRP projects has been the integration of current science and Traditional Owner knowledge built from their long cultural experience and traditions as land and sea managers. DBCA and Traditional Owners are increasingly becoming joint managers of WA's conservation estate, including marine reserves in the Kimberley region. KMRP research projects have involved participation by Indigenous and marine park rangers where possible and have had an emphasis on developing tools and protocols for use in future healthy country management. In particular, the Kimberley Indigenous Saltwater Science Project (KISSP) developed guidelines for, assisting scientists to engage with Indigenous communities and understanding how to bring the two knowledge streams together, as well as a framework, toolbox and training program to support monitoring on saltwater country.

Many of the KMRP projects have created baseline data for key ecological assets and processes to develop long-term monitoring and, more broadly, to provide information to support management of the Kimberley marine reserves. This includes baseline information on; reef formation and growth; description of sea floor habitats; and the distribution of biodiversity and key environmental parameters associated with biodiversity hotspots.

Key ecological and physical processes that support the marine system are now better understood, including oceanic currents and local hydrodynamic regimes as well as the associated flow of nutrients and energy. The diversity, abundance and distribution of many species that inhabit the Kimberley, including iconic marine fauna species such as dugong, humpback whales, dolphins and marine turtles, are much better understood and baseline information and protocols for ongoing monitoring now exist.

The physical and process research has highlighted how key marine communities cope with the harsh and extreme Kimberley environment that is subject to macro tides, exposure to high temperatures and limited light penetration due to turbidity. Modelling exercises used to explore the effectiveness of current management arrangements, the consequences of alternative management actions and alternative future scenarios, have demonstrated that some species/groups are likely to benefit while others may exhibit little change or decline. The focus for management action, monitoring and research effort therefore, is on appropriate indicators of change.

The KMRP research also examined what people are doing in the marine and coastal environment and the associated potential for impacts, along with assessing what people value and their future aspirations for the region. Considerable effort has been made to ensure effective communication between research teams, the program leadership team and key stakeholders. This helped to shape final outcomes and products to maximise direct relevance to managers.

The five-year marine and coastal KMRP has generated a massive (more than 10-fold) increase in knowledge and understanding of the physical and biological environment, ecological processes, as well as the values and impacts of people that inhabit the region.

The key outcomes, specific outputs and their application to management are outlined in the following sections:

Program outcomes are linked back to the original science plan and to relevant products and tools that represent the enduring legacy of the KMRP. Importantly, we emphasise knowledge exchange that will ensure that science informs management, including communication outputs, data storage and access, and key recommendations for additional knowledge exchange products and activities.

Project summaries focus on key findings and how this information relates to the original management questions. Projects are grouped across the two key integrated themes to build a fuller picture of the Kimberley marine environment and ecosystem highlighting the knowledge shared across themes and relationships throughout the program.

How the Kimberley Marine Research Program met Expected Outcomes

The KMRP Science Plan (Simpson 2011) outlined a set of expected outcomes to direct the structure and implementation of the program of work consistent with the priorities for WA, the Commonwealth and the WAMSI joint venture partnership.

Improved capacity to plan and manage the regional network of Kimberley marine parks and reserves

Through its 23 research projects, the KMRP has increased understanding of the biodiversity and marine ecosystems of the Kimberley region tenfold. It has produced a series of foundational datasets and spatial products on the physical background, habitats and key species groups as well as current patterns of human use including; identification of biodiversity hotspots, population strongholds, critical, unique or important habitats and key species that are intricately linked to the maintenance of healthy ecosystems. The information provides the necessary understanding and regional context that is essential for planning and management of marine protected areas to ensure conservation objectives and targets are met and that current pressures are sustainable.

Enhanced capacity to identify, plan and manage current human activities (e.g. tourism, fisheries, pearling, aquaculture) and impacts and predict risks in the coastal waters of the Kimberley

Several streams of research have contributed to this outcome by quantifying and understanding human use across the Kimberley in addition to understanding the social values people attribute to the coastal and marine environment. Several projects have also provided further understanding of the future risks associated with climate change and regional development scenarios, including the potential impacts to biodiversity. Together, this information provides a sound basis on which to make decisions regarding recreational and commercial activities in coastal waters of the Kimberley, in particular with regard to management effort, infrastructure and regulation.

Communication outcomes for the Kimberley Marine Research Program

134
GENERAL AND CONFERENCE PRESENTATIONS

68
PRESENTATIONS/ MEETINGS WITH TRADITIONAL OWNERS OR THEIR REPRESENTATIVES

10
PRESENTATIONS TO THE BROOME COMMUNITY

55
PEER REVIEWED JOURNAL ARTICLES

100
MEDIA MENTIONS

40
PRESENTATIONS/ MEETINGS WITH PARKS/ MANAGEMENT

Enhanced use of Indigenous knowledge and participation in marine management

WAMSI established, as a principle, the requirement for all projects to work respectfully with Traditional Owners, recognising their responsibility as healthy country managers, to bring together western and Indigenous knowledge in ways that would enhance understanding and management of the region by joint managers. This included discussing research projects with Prescribed Body Corporates, employing Indigenous rangers to assist in field activities, taking elders back on Country, training rangers in new monitoring skills and techniques and sharing research findings with local communities through the ranger groups and schools. The KMRP has left a legacy of products and tools that can be used by Indigenous rangers and state management agencies as well as strong and collaborative relationships between scientists and Indigenous communities.

Enhanced capacity to understand, adapt to and mitigate climate change impacts in the coastal waters of the Kimberley

Several projects in the KMRP have explored the environmental processes influenced by climate change and the potential impacts to biodiversity. The knowledge generated supports best practice management of the marine parks and the region in order to minimise impacts from climate change, in particular when occurring in conjunction with other development impacts. However, further research is needed to examine the resilience of habitats, species and communities as well as the means of monitoring for change.

Increased capacity to respond to and mitigate the impacts of oil spills

New knowledge about the distribution of habitats and species that may be sensitive to the impacts of oil spills combined with enhanced understanding of oceanography in the Kimberley region provide pertinent information to inform response to oil spills or other incidents involving hazardous waste material.

Improved regional understanding of relative ecological and conservation significance of the key marine biodiversity assets of the Kimberley

A range of key marine biodiversity assets, as detailed in healthy country and marine park management plans, have been thoroughly assessed through the KMRP. A sound knowledge base of diversity, abundance and distribution of a range of taxa throughout the Kimberley is now available, including iconic megafauna, culturally important species and habitat forming taxa. This information demonstrates the clear significance of the Kimberley as a unique ecosystem of exceptional conservation significance, supporting its recognition both nationally and internationally as an iconic site.

A preliminary understanding of regional differences in the Kimberley has also been established with a clear indication that the marine environment of the north Kimberley may be markedly different to the west and south Kimberley. This is significant in relation to how the marine conservation values across the region are collectively managed and conserved.

Increased capacity to assess the environmental significance of resource development projects

The integration of information from the KMRP projects has produced a broad characterisation of the Kimberley marine ecosystem that will be useful in assessing development projects from a regional perspective. A range of spatial products and datasets that identify areas of conservation value and vulnerability have also been produced that can be used to assess the potential impacts from development. An improved understanding of physical and ecological processes similarly can be used to assess potential for impacts in changes to land use practices, infrastructure or other aspects of development.

Improved capacity for marine science knowledge transfer and uptake into policy, planning and management in WA

A key focus of WAMSI, as highlighted by its motto 'better science better decisions', is the integration of new science into decision making for, and management of, the marine environment. Throughout the KMRP process a knowledge exchange framework has been used in the development, implementation and delivery of the program to ensure that key end users have been engaged and pathways established to deliver information for policy, planning and management.

Knowledge uptake is recognised as a long-term process, extending well beyond the life of the research program. To this end, beyond the targeted body of new knowledge directed specifically to managers, the KMRP has put in place measures to ensure the information is made available over the long term and will continue to be added to with the development of additional tools, products and guidelines as detailed in the **'Pathways' to Adoption'**.

Improved knowledge base for environmental planning and management by government, industry, non-government organisations and community

The substantial body of work providing new knowledge on the Kimberley marine environment has been made available to stakeholders as foundational datasets and spatial products on key biodiversity assets including important habitats, physical features and distributions of high profile species. The information provides a valuable resource for government, Traditional Owners, non-government organisations (NGOs), industry and the wider community. It will, for example, inform environmental planning having identified important and sensitive areas as well as those recognised by the broader community as being of high value. KMRP data sets are also being used to develop secondary school teaching resources. Further, the information on social values and preferences is of high value toward future regional planning and engagement with all stakeholders.

Improved links and collaboration in marine science between state and Commonwealth agencies, universities, industry and NGOs in WA

A key principle of the WAMSI partnership is to foster collaboration within and between science institutions, NGOs, industry and government agencies. Twenty-five national and international research organisations, including nine WAMSI partners, participated in KMRP projects over five years. As a result, the experience proved to strengthen the collaborative effort between organisations with the benefits extending beyond the program, leading to ongoing collaborations, joint research proposals and new research projects.

Improved community understanding and support for government conservation and management programs in the Kimberley

WAMSI and the KMRP scientists have engaged key stakeholders and the broader community throughout the program and continue to work to raise awareness of the importance of the research program and of the findings it has produced. Communication of KMRP outcomes highlighting the unique Kimberley marine environment and how the science will be used to support its conservation include: 40 presentations/meetings with parks management, 68 presentations/meetings with Traditional Owners/representatives Aboriginal Corporations (in addition, five projects scheduled regular meetings), more than 55 peer reviewed journal articles, 100 media mentions, 134 conference and stakeholder presentations and 10 Broome community presentations.

Enhanced marine science capacity in WA

The KMRP involved and supported more than 200 scientists from 25 organisations working on 23 marine science projects in the Kimberley. The scale of the KMRP achieved a level of cooperation and collaboration that has enhanced WA's marine science capacity by providing opportunities for career development, training and research experience across the board including students, post-doctoral researchers, Traditional Owners and government staff in a range of marine science techniques, skills and understanding. The result has been a broader level of management understanding and research expertise, and an improved capacity in WA to draw on state, national and international skills and expertise.

Improved facilities and infrastructure for marine research and management in the Kimberley

The concentration of KMRP scientists in the Kimberley has acted as a catalyst to prompt the development of facilities and infrastructure that continue to support marine research in the region. State and Commonwealth government organisations, including AIMS and CSIRO, as well as Traditional Owners, recognise the importance of the region and the need for a better understanding of the environment for sustainable management in the face of change. As a result, research programs and interest across the region have expanded beyond the WAMSI program, fostering better working relationships with Indigenous communities, NGOs and industry in the area. The Kimberley Marine Research Station at Cygnet Bay has invested in facilities that can accommodate future research in the Buccaneer Archipelago and, while the main focus is aquaculture and pearling, there is a broader research interest in the health of the Kimberley marine environment.

Enhanced marine science capacity in WA

200 SCIENTISTS

25 ORGANISATIONS

23 MARINE SCIENCE PROJECTS

26 STUDENTS SUPPORTED

Overview of Research Outcomes

Improved capacity to plan and manage the regional network of Kimberley marine parks and reserves	Project
Detailed benthic habitat and assemblage distribution maps for key marine reserve areas and broader predictive regional maps. [Benthic Biodiversity]	All
Identification and maps of all reef types including those unique to the Kimberley. [Geomorphology]	
Baseline data to inform long-term monitoring of key ecological and social values of Kimberley marine and coastal regions. [Recruitment/Herbivory, Crocodiles, Turtles, Dolphins, Dugong, Seagrass, Human Use, Social Values]	
Knowledge of patterns of human use and activities across the entire inshore Kimberley. [Human Use]	
Knowledge of key physical and ecological processes and how these relate to biodiversity distribution, significance and connectivity. [Oceanography, Resilience, Land Sea Linkages, Connectivity, Benthic Biodiversity]	
A management strategy evaluation tool that provides a framework within which to consider current understanding of the Kimberley marine system under future scenarios and management regimes. [MSE]	

Enhanced capacity to identify and manage current human impacts and predict risks in the coastal waters of the Kimberley	Project
Benchmark study of spatial and temporal patterns of human use across the Kimberley coastal environment which has identified patterns of general use and nodes of relatively intense activity. This research identifies where anthropogenic pressures may be higher, requiring more targeted monitoring and on ground management. [Human Use]	Human Use Social Values Land Sea Linkages Geomorphology Climate Change Sediments MSE Connectivity Sediments Benthic Biodiversity
Improved understanding of what the community values and aspirations are for the region. This information can be used to consider human use patterns, regional development and the need for infrastructure and appropriate education strategies to target relevant audiences. [Social Values]	
Preliminary understanding of nutrient and sediment flow from terrestrial systems into marine systems, to inform the management of land-based activity that will impact on river systems and the coastal environment. [Land Sea Linkages]	
Regional assessment of coral reefs by remote sensing and GIS providing a database to assess and manage human activity related threats and risks to reefs. [Geomorphology]	
Consideration of specific human activities and their impact on the environment and biodiversity, e.g. trochus fishery, aquaculture. [Connectivity, Sediments]	
Identification of biodiversity hotspots, critical, unique or important habitats that may require a high(er) level of protection. [Benthic Biodiversity, Geomorphology]	
Enhanced predictive capacity to understand climate related changes to the marine ecosystem. [Climate Change, Sediments, MSE]	

Enhanced use of Indigenous knowledge and participation in marine management	Project
Participation of Traditional Owners, including ranger groups, in research. [Benthic Biodiversity, Recruitment/Herbivory, Connectivity, Crocodiles, Turtles, Whales, Dolphins, Dugong, KISSP, Social Values, Seagrass] Use/integration of Indigenous knowledge in research projects and interpretation. [Turtles, Dugong, KISSP] Development of a protocol for researchers to engage effectively with Traditional Owners to undertake research on Country. [KISSP] Development and/or delivery of training for Indigenous rangers in research/monitoring methods. [Benthic Biodiversity, Recruitment/Herbivory, Turtles, Crocodiles, Dolphins, Dugong, Seagrass, KISSP] Development of guidelines and tools to support "right way" science that brings Indigenous and western participants together from the outset to plan and undertake research and monitoring activities and support Indigenous rangers with training and protocols for monitoring techniques. [KISSP]	KISSP Benthic Biodiversity Recruitment/ Herbivory Connectivity Turtles Crocodiles Whales Dolphins Dugong Social Values Seagrass

Enhanced capacity to understand, adapt and mitigate climate change impacts in the coastal waters of the Kimberley	Project
A sound understanding of environmental processes associated with climate change to better predict warming events and the need to mitigate additional pressures. [Climate Change, MSE] Recognition of the extreme conditions already experienced by intertidal and coastal biodiversity in the Kimberley highlighting the potential for impacts with even minimal additional temperature increase [Resilience, Turtles, Seagrass, Productivity]. New information on oceanographic and hydrodynamic processes, used in conjunction with the biodiversity findings, will inform further research on the impacts of climate change and how best to improve resilience or to mitigate impacts. [Oceanography, Biogeochemistry, Land Sea Linkages, Productivity, Resilience, Remote Sensing] An understanding of geologically recent (Holocene) reef development provides an improved basis for climate change management, e.g. to determine if short-term ecosystem changes are a reflection of changing climate, or states through which reefs have persisted over time. [Geomorphology]	Climate Change MSE Resilience Turtles Biogeochemistry Seagrass Productivity Oceanography Land Sea Linkages Geomorphology Remote Sensing

Increased capacity to respond to and mitigate the impacts of oil spills	Project
Knowledge of physical oceanographic processes to inform oil spill trajectory modelling, particularly in complex coastal sites. [Oceanography, Land Sea Linkages] Patterns of biodiversity distribution, including key habitats and areas of high conservation value. [Benthic Biodiversity] Areas of key social/commercial value. [Social Values]	Oceanography Benthic Biodiversity Land Sea Linkages Social Values

Improved regional understanding, context and relative ecological and conservation significance of the key marine biodiversity assets of the Kimberley	Project
Benthic habitat and assemblage distribution mapping that can identify biodiversity hotspots associated with benthic formations and complexity. [Benthic Biodiversity] Confirmation of the marine biodiversity significance of the Kimberley based on species diversity including many species new to science. [Benthic Biodiversity, Connectivity] Improved understanding of the distribution, abundance and critical habitat of marine fauna species recognised as key biodiversity assets. [Crocodiles, Turtles, Dugong, Whales, Dolphins] Maps of regionally important marine and coastal habitats. [Geomorphology, Seagrass]	Benthic Biodiversity Connectivity Crocodiles Turtles Dugong Whales Dolphins Geomorphology Seagrass

Increased capacity to assess the regional environmental significance of resource development projects	Project
Identification of biodiversity hotspots, critical, unique or important habitats that may require a high(er) level of protection. [Benthic Biodiversity, Geomorphology] Better understanding of ecological processes and the habitat requirements to support biodiversity. [Recruitment/Herbivory, Connectivity] Knowledge of physical oceanographic and hydrodynamic processes and the potential for anthropogenic impacts through changed land use practices on coastal biodiversity. [Oceanography, Land Sea Linkages] A framework for assessing future impacts of development in the context of current ecological, physical and social understanding of the region. [MSE]	Benthic Biodiversity Geomorphology Recruitment/ Herbivory Connectivity Oceanography Land Sea Linkages MSE

Improved capacity for marine science knowledge transfer and uptake into policy, planning and management in Western Australia	Project
Knowledge exchange framework and strategy [Science Coordination] Research focussed on specific management questions and reporting on the management implications of key findings and new information. [All] Communication strategy focussed on ensuring information and data are available over the long term and known to relevant stakeholders. [Science Coordination]	All (see Pathways to Adoption)

Improved knowledge base for environmental planning and management by industry, NGOs and community	Project
Identification of biodiversity hotspots, critical, unique or important habitats that may require a high(er) level of protection. [Benthic Biodiversity, Geomorphology] Better understanding of ecological processes and the habitat requirements to support biodiversity. [Recruitment/Herbivory, Connectivity] Knowledge of physical oceanographic and hydrodynamic processes and the potential for anthropogenic impacts on coastal biodiversity. [Oceanography, Land Sea Linkages] Assessment of the values and aspirations people hold for the Kimberley marine environment and how these should be managed to meet community needs. [Social Values] A framework for assessing future impacts of development in the context of ecological, physical and social understanding of the region. [MSE]	Benthic Biodiversity Geomorphology Recruitment/ Herbivory Connectivity Oceanography Land Sea Linkages Social Values MSE

Improved links and collaboration in marine science between state and Commonwealth agencies, universities, industry and NGOs in Western Australia	Project
All projects involved multi-partner collaborations, including agencies external to WAMSI. [All] Participation by 25 research institutions, (nine WAMSI partners, five universities across Australia, six International universities, three research bodies and two consultants). [All] Cooperative relationships and information sharing between jurisdictions and agencies for current and future initiatives. [Crocodiles, Dugong, Connectivity, Productivity, Resilience, Whales, Turtles, Shorebirds, Sediments]	All

Improved community understanding and support for government conservation and management programs in the coastal waters of the Kimberley	Project
Presentations to the local community through the Roebuck Bay Working Group's Science on the Broome Coast series. [Recruitment/Herbivory, Connectivity, Turtles, Crocodiles, Whales, Dolphins, Dugong, Geomorphology, Human Use, Social Values, Productivity] Presentations to Indigenous communities and schools in the Kimberley. [Seagrass, Recruitment/Herbivory, Turtles, Connectivity, Dugong] WAMSI and KMRP symposia and lunchtime seminars in Perth [All] Landscope articles, WAMSI newsletter stories, DBCA newsletter stories, local, national and social media [All] Communication strategy with ongoing activities to share new findings and appreciation of the Kimberley marine environment [Science Coordination]	All

Enhanced marine scientific capacity (including student training) in Western Australia	Project
More than 200 scientists from 25 institutions participated in the KMRP [All] Four post-doctoral scientists and 26 post-graduate students were supported by the program. [All] Training and experience has been provided to participating scientists as well as Traditional Owners and government staff in a range of marine science techniques, skills and understanding. [All] Training has been provided to agency staff and Traditional Owners in monitoring techniques for ongoing healthy country/marine park management. [Benthic Biodiversity, Recruitment/Herbivory, Crocodiles, Turtles, Whales, Dolphins, Dugong, Seagrass, Land Sea Linkages]	All

Improved facilities and infrastructure for marine research and management in the Kimberley	Project
Ongoing investment in research by DBCA. Commitment by Kimberley Marine Research Station to invest in research facilities.	

Key Recommendations

Each project provided insight as to how the research findings could inform conservation and management, often through specific recommendations. Integration of the KMRP research findings has identified a number of recommendations that apply to the Kimberley marine ecosystem overall, while many additional recommendations are specific to particular themes and biodiversity values.

All should be taken into consideration for the conservation and management of the Kimberley marine environment. The full set of recommendations, by relevant theme and project are listed in Appendix I. Further detail on the application of research findings to management are outlined in each project summary and associated final report.

The integrated recommendations from the program as a whole for consideration in the future management of the Kimberley marine environment are:

- Integrate foundational and baseline datasets produced by projects into corporate databases, where appropriate, for future planning and management, including zoning frameworks and establishing monitoring programs.
- Incorporate spatial, georeferenced datasets into management databases to inform conservation planning. A MARXAN analysis could, for example, be undertaken with updated spatial data provided by the KMRP on biodiversity, habitats and species distribution to determine if there would be recommended revisions to the current zoning of marine reserves to better meet the three CAR principles (Comprehensive Adequate, Representative) of conservation planning.
- Hold workshops with key end-user stakeholders (Indigenous, DBCA, DPIRD, DWER) to discuss the outcomes of the KMRP and how best to ensure that information and data products are visible and incorporated into future management. This should include setting priorities for development of additional data products, tools and guidelines that have direct application to management processes.
- Promote the protocol developed for researchers to engage with Traditional Owners to science organisations and universities as best practice for research on Country and in marine parks.
- Ensure that products and tools are readily available to scientists and managers using web-based applications, where appropriate. This should include the monitoring frameworks and toolbox created by KISSP, the management strategy evaluation model and scenarios produced by MSE and training manuals and products produced by various projects.
- Undertake an evaluation of knowledge uptake from the KMRP in five years to assess the full value of the program and to provide learnings on improving knowledge exchange in large research programs.

Tools and Products

A range of tools and products have been developed that are available to managers and scientists. Some of these may benefit from further adaptation as highlighted in **Pathways to Adoption**.

Protocols for Monitoring Techniques

Many of the KMRP projects have developed and/or refined protocols and methods that can be used for long-term monitoring. These range from the identification of effective monitoring indicators and recommendations for the most appropriate sampling techniques, through to comprehensive standard operating procedures that include sample design, reference sites and clear protocols that can be adopted in monitoring.

- Standard operating procedures for spotlight surveys as a method to monitor crocodile abundance and demographics undertaken by DBCA and Indigenous rangers [Crocodiles]
- Protocol for vessel-based surveys to estimate dolphin abundance and distribution to be used by DBCA and Indigenous rangers [Dolphins]
- Basic protocol and design for ongoing vessel/satellite imagery surveys of humpback whale relative abundance at specific high use sites [Whales]
- Protocol for cliff based surveys to monitor whale density and use of specific sites [Whales]
- Standard operating procedures and manual to monitor nesting turtles to be used by marine and Indigenous rangers [Turtles]
- Protocol for aerial surveys to monitor dugong abundance and distribution to be used by marine and Indigenous rangers [Dugong]
- Standard operating procedures to monitor tropical seagrasses [Seagrass]
- Protocols for assessing fish recruitment by monitoring juvenile fishes [Recruitment/Herbivory]
- Protocols for assessing coral recruitment using settlement tiles adapted for Kimberley conditions [Recruitment/Herbivory]
- Protocols to monitor coral cover and other benthic habitats using drop-down cameras adapted for Kimberley conditions [Benthic Biodiversity]
- Protocol to design and undertake aerial surveys of human activities in coastal and nearshore areas including use of commercially available software to record data [Human Use]
- A cost-effective desktop survey method to monitor tourist visitation by expedition cruise vessels based on Kimberley coast itineraries [Human Use]
- Techniques and protocols for remote camera surveillance of vessel launches at boat ramps as an indicator of recreational vessel use [Human Use]
- Toolbox of monitoring techniques available for use by Indigenous rangers in healthy country management [KISSP]

New Tools and Techniques

- A biopsy pole and methodology for obtaining genetic samples from crocodiles [Crocodiles]
- A database app for real-time input and storage of geo-referenced data collected during crocodile spotlight surveys [Crocodiles]
- A methodology to conduct choice experiments using an online Public Participation GIS technique [Social Values]
- A cost-effective desktop survey method to monitor tourist activity from expedition cruise vessels along the Kimberley coast [Human Use]
- New methods for settlement tile placement to monitor coral recruitment for use in the Kimberley environment [Recruitment/ Herbivory]

Training Material

In addition to developing protocols and techniques for monitoring and research, some projects have provided training to Indigenous rangers and/or DBCA staff to continue with monitoring initiatives and/or have made material available for training programs.

- Indigenous and DBCA rangers trained to undertake dugong aerial surveys [Dugong]
- Indigenous and DBCA rangers trained to do vessel-based dolphin surveys [Dolphins]
- Indigenous rangers and DBCA staff trained to use drop cameras for monitoring benthic habitats [Benthic Biodiversity]
- Indigenous rangers trained to monitor tropical seagrasses [Seagrass]
- Indigenous and DBCA rangers trained to undertake crocodile spotlight surveys and genetic sampling [Crocodiles]
- Indigenous and DBCA rangers and staff trained in turtle nesting monitoring techniques [Turtles]
- Training package developed for Indigenous rangers to monitor healthy country [KISSP]
- Training manual and presentations on cliff-based monitoring of humpback whales [Whales]

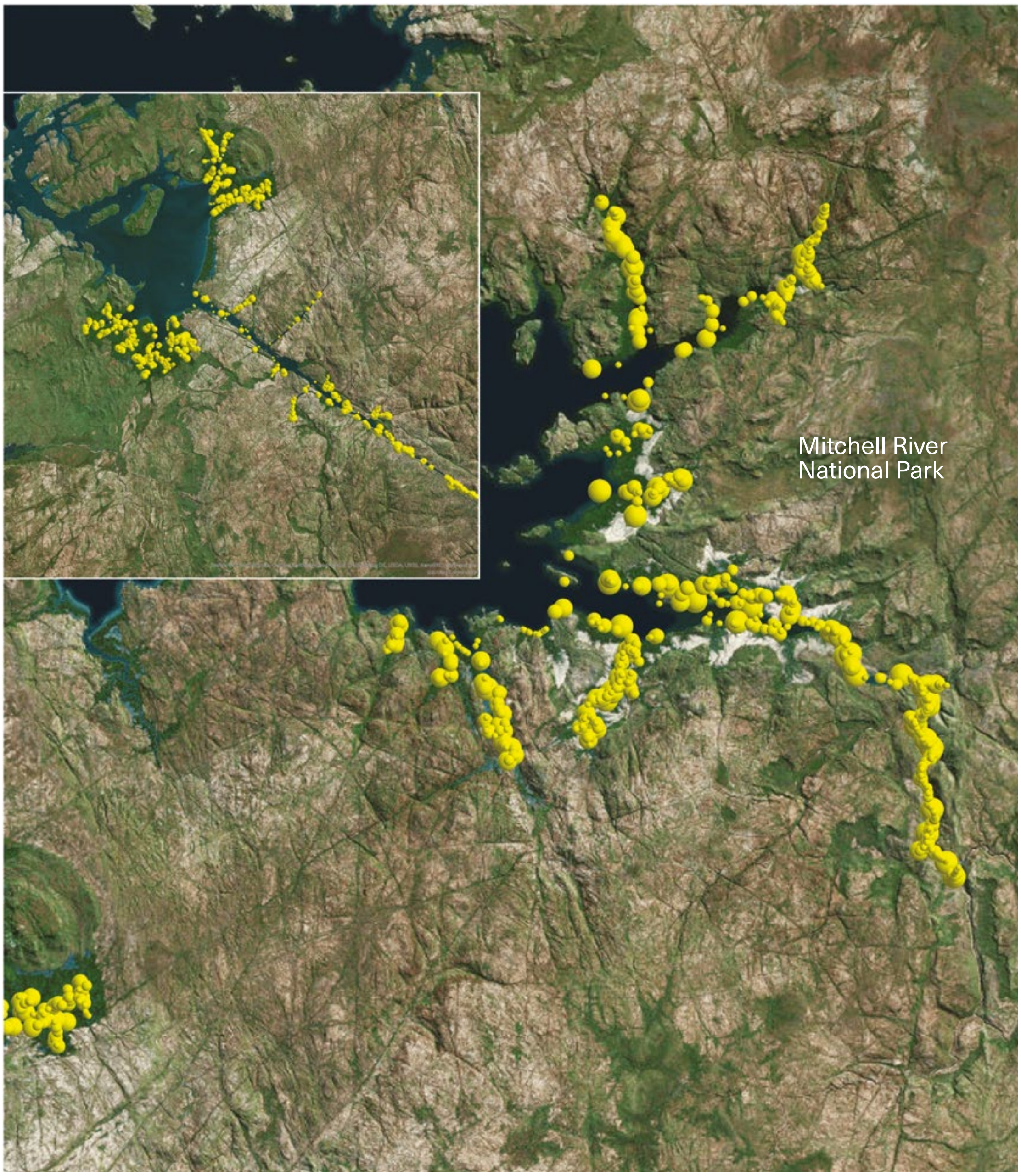
Training

Training activities undertaken during WAMSI field trips included data collection, morning track counts, hatchling success measurements, turtle measurements, turtle tagging, paper GIS, data logger excavation, weather station installation, boat surveys, morphometrics and samples from carcasses, genetic samples, satellite tracking of females, predator evaluations. [Turtles]

Major Baseline Datasets

The KMRP has produced a vast amount of new data, much of which is compiled into foundational and baseline or benchmark datasets that can be used to commence long-term monitoring and inform future planning and development. All WAMSI data is accessible and publicly available (full details in Appendix II).

- Biological and physical oceanography parameters including pelagic primary productivity, community metabolism, community and food web structure [Biogeochemistry, Oceanography, Productivity]
- An inventory and catalogue of species and assemblages, including abundance and diversity [Benthic Biodiversity]
- Spatial and temporal patterns of human use and activities along the Kimberley coast [Human Use]
- Baseline survey data of the relative abundance of key marine fauna species [Crocodiles, Dolphins, Dugong]
- Catalogue of recognisable individual dolphins from several key sites added to the statewide database (DolFIN) [Dolphins]
- Acoustic repertoire and vocalisation rates of snubfin and humpback dolphins [Dolphins]
- Characterisation of the underwater soundscape for Cygnet Bay and Roebuck Bay [Dolphins]
- Inventory of all turtle nesting beaches [Turtles]
- Inventory of all reefs and islands, including their geomorphic features [Geomorphology]
- Aggregated data from choice experiments and social values attributed to the Kimberley marine and coastal environment [Social Values]
- Improved bathymetry data for the western Kimberley from Camden Sound to Cape Bougainville [Benthic Biodiversity, Remote Sensing, Oceanography]
- Contemporary and historical coral calcification rates that provide an important baseline for evaluating how coral growth responds to changes in environmental conditions [Resilience, Geomorphology]
- Coral health surveys conducted before, during and after the first natural bleaching event in the Kimberley region in 2016 provide important baseline data on coral bleaching abundance, bleaching susceptibility, and coral community dynamics associated with disturbance-related recovery and mortality [Resilience]

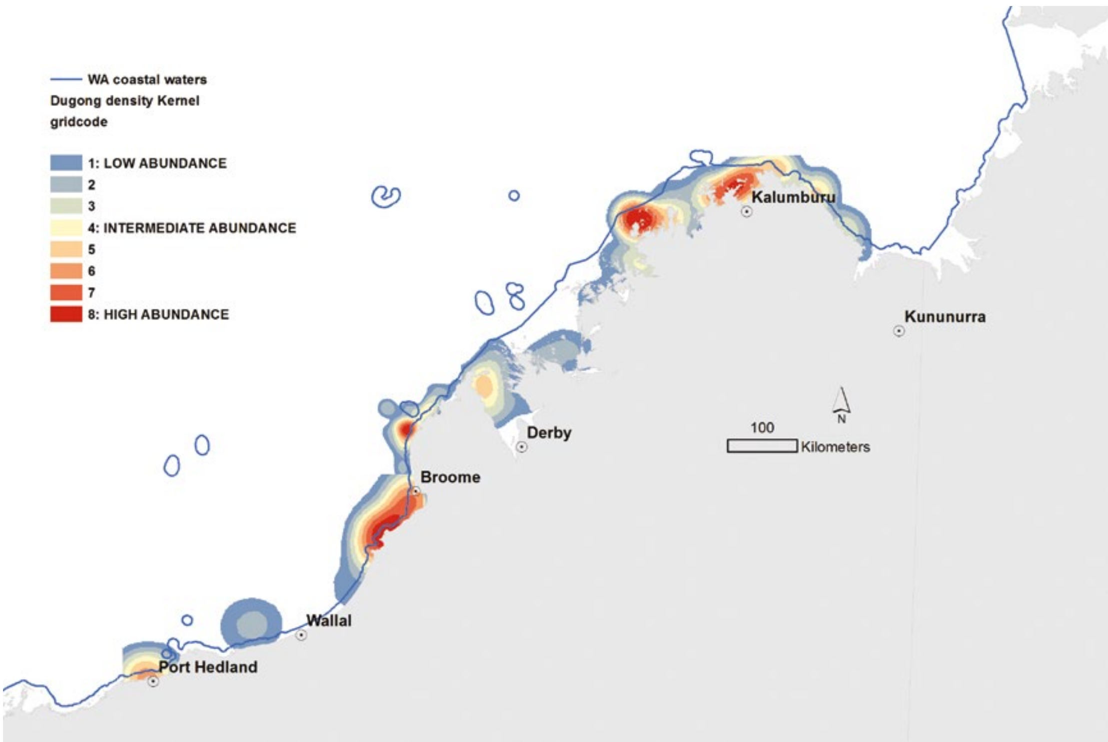


Location of crocodiles 1.5 – 2.1m in length in the Roe-Hunter River system in 2015. [Crocodiles]

Maps/spatial products

Numerous KMRP projects have produced GIS-based datasets and map products to inform management decision making for Kimberley marine reserves and assist planning for future developments across the region.

- Fine scale predictive benthic habitat maps for the western Kimberley (Camden Sound to Cape Bougainville) with associated classification accuracy maps [Benthic Biodiversity]
- Broadscale predictive benthic species assemblage maps for the western Kimberley (Camden Sound to Cape Bougainville) [Benthic Biodiversity]
- Heat map of dugong density based on aerial survey, Indigenous knowledge and seagrass habitat [Dugong]
- Geo-referenced map of all green and flatback turtle rookery beaches, noting density, winter vs summer nesting and priority ranking [Turtles]
- Distribution and density maps of humpback whale use of the Kimberley throughout the migration season [Whales]
- Map of crocodile survey sightings in two river systems [Crocodiles]
- Overview and individual point density and heat maps for social values and management preferences associated with the Kimberley coast and marine environment (derived from interviews and online Public participation GIS study) [Social Values]
- Heat maps of human use patterns at different temporal scales (monthly, seasonal, one off) for the southern, central and northern Kimberley respectively [Human Use]
- A reef classification scheme and associated GIS database of habitats, (ReefKIM) of every significant reef in the Kimberley and detailed substrate and geomorphology maps for 30 of these reefs [Geomorphology]

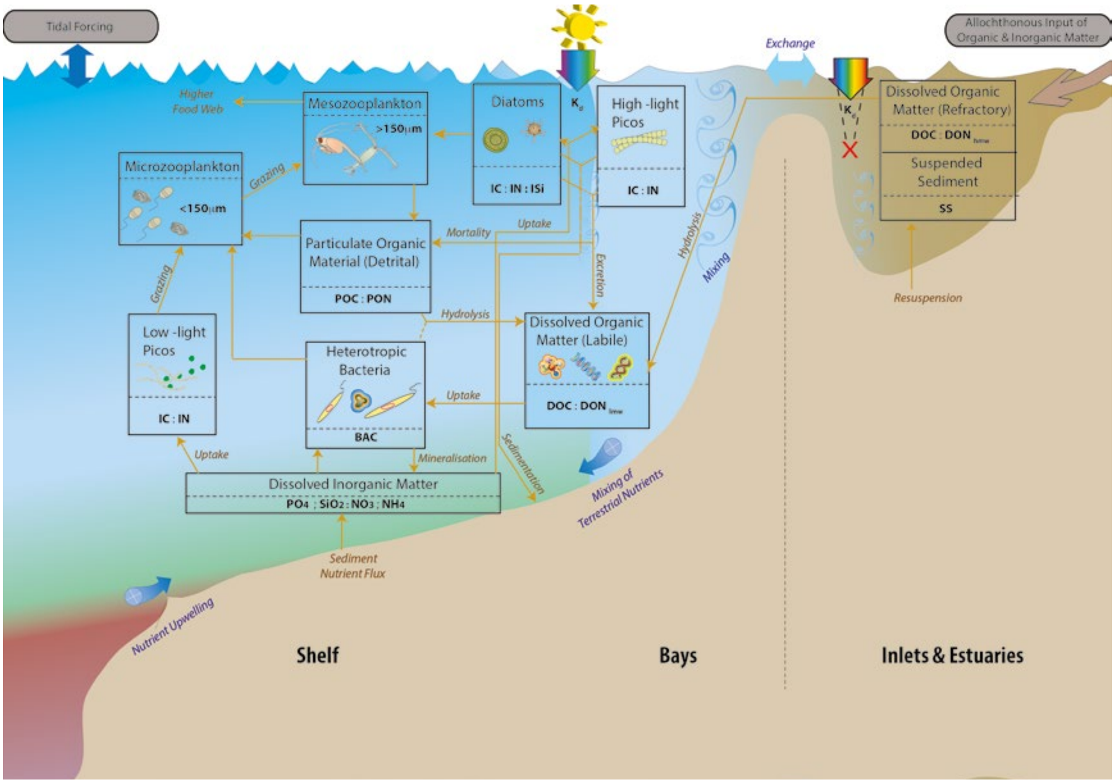


Map showing dugong abundance "hotspots". [Turtles]

Models

A range of conceptual and numerical models of the Kimberley marine environment have been developed. These models represent key ecosystem components and how they interact in a healthy functioning environment. Further detail on the management questions leading to the model and application to sustainable management are outlined in the project summaries.

- Numerical 3D coastal scale ROMS hydrodynamic model [Oceanography]
- Conceptual model of nutrient flow in the marine system from continental shelf to shore, including coastal embayments [Biogeochemistry]
- A validated numerical *ROMS-BGC* shelf-scale simulation model of nutrient flow from upwelling onto the shelf and into the coastal zone with riverine and catchment inputs [Biogeochemistry]
- A validated numerical *TUFLOW-FV – AED2* custom biogeochemical/ecological configuration model, including locally relevant model for nutrient and productivity pathways in complex coastline/islands and inlets [Biogeochemistry]
- A numerical model of terrestrial inputs and flow into the coastal environment at Walcott Inlet and Collier Bay including detailed hydrodynamic understanding of the nature of the bay [Land Sea Linkages]
- A numerical ROMS shelf model nested within the OFAM model outputs, to simulate the coastal circulation off the Kimberley [Climate Change]
- A numerical model of terrestrial land use and landscape dynamics that are relevant to the interface between terrestrial and marine ecosystems in the Kimberley [MSE]
- A numerical model that characterises the trophic structure, ecosystem attributes and impact of human uses and climate change in the marine environment of the region [MSE]
- A conceptual representation of the links between land, coastal and marine systems in the Kimberley [MSE]
- Spatial predictive models of mixed benthic assemblages, showing the probable distribution of various mixed benthic habitat classes [Benthic Biodiversity]



Conceptual model depicting main flow of carbon and nitrogen in Kimberley waters, considering the gradient in conditions from the coastal inlets to the shelf-edge. [Biogeochemistry]

Genetic samples

Genetic samples were collected from a range of taxa across the Kimberley to better understand connectivity and species population structure.

- Snubfin and humpback dolphins [Dolphins]
- Green and flatback turtles [Turtles]
- Dugong [Dugong]
- Two fish species – *Pomacentrus milleri* and *Lutjanus carponotatus* [Connectivity]
- One gastropod - *Tectus niloticus* [Connectivity]
- Two seagrass species - *Halophila ovalis* and *Thalassia hemprichii* [Connectivity]
- Two coral species - *Isopora brueggmanni* and *Acropora aspera* [Connectivity]
- Zooxanthellae - *Symbiodinium* [Resilience]

Guidelines

- Guideline for collaborative knowledge between Indigenous and western scientists [KISSP]
- Guideline and protocol for researchers to engage with Indigenous people in collaborative science on country [KISSP]

Simplified stages of the Collaborative Research Cycle described within the Collaborative Science on Kimberley Saltwater Country - A Guide for Researchers – [KISSP].

Tools and Products

Project	Monitoring Protocol	Research Technique	Training Material	Baseline Dataset	Spatial products (maps)	Model	Genetic samples	Guidelines
Geomorphology				✓	✓			
Benthic Biodiversity	✓	✓	✓	✓	✓	✓		
Seagrass	✓	✓	✓	✓	✓			
Oceanography				✓	✓	✓		
Biogeochemistry				✓	✓	✓		
Land Sea Linkages				✓	✓	✓		
Turtles	✓	✓	✓	✓	✓		✓	
Crocodiles	✓	✓		✓	✓		✓	
Dugong	✓		✓	✓	✓		✓	
Whales	✓	✓			✓			
Dolphins	✓		✓	✓			✓	
Shorebirds								
Social Values		✓		✓	✓			
Human Use	✓			✓	✓			
KISSP		✓	✓					✓
Productivity		✓		✓	✓			
Recruitment/Herbivory	✓	✓		✓				
Connectivity		✓			✓		✓	
Remote Sensing				✓				
Climate Change					✓	✓		
Resilience		✓					✓	
Sediments				✓				
MSE						✓		

Integrating Science into Conservation

The integration of science into conservation management decisions and actions remains a significant challenge in the marine environment. WAMSI addresses this need through a collaborative approach to research program development and delivery established to maximise science impact through a knowledge exchange process.

Knowledge exchange refers to the interpretation, movement, uptake and use of research outcomes by various stakeholders and relies on the two-way exchange of information between researchers and end users. WAMSI leads and guides this process through open and ongoing dialogue between scientists and end-users, mediated by the Program leadership team which takes on a knowledge broker role between science and management.

The end result is the integration of research findings across the program and provision of information and products relevant to manager needs. For the KMRP these have included, for example, spatial and baseline datasets for regional planning and resource management, protocols and reference sites for long-term monitoring programs and new information for community education programs.

The knowledge exchange framework and outcome management strategy approach used by WAMSI ensures its research programs are both aligned with, and delivering on, management objectives in a format suitable for both the immediate use of new information and long-term access to information for future needs.

There are a number of steps in the framework, starting with identifying the key stakeholders and their need for a program of research, developing a clear research strategy that outlines critical information gaps and questions, through to ensuring research projects are targeted and findings are available, explained in a meaningful way and used by the relevant stakeholders. Implicit in this approach is the overarching importance of both communication and data management.

Key steps in the WAMSI knowledge exchange framework

1. Identify end-users, their information needs and priorities.
2. Focus research on agreed management questions expressed in a science plan.
3. Implementation of projects in the science plan.
4. Determine application to management strategies.
5. Develop and implement a delivery plan that will enhance uptake (products and tools).
6. Post program engagement to bed down decision-making tools and products.

Governance | Communication | Interpretation | Data Management

Bardi Jawi ranger measuring seagrass growth.

The key steps in WAMSI's knowledge exchange framework are outlined on the previous page including their application under the overarching elements of governance, communication and data management that support the framework for the KMRP.

Research Program Conduct and Governance

WAMSI provides a clear governance structure for its research programs, including oversight of program design to meet identified priorities and partner capacities as well as research quality and delivery.

Program leadership is determined based on the key end-user to ensure the strongest links between research and application. Given the management focus of the KMRP is to inform marine reserve planning and joint management with Traditional Owners in the Kimberley, the significant end-users were identified as the WA government (primarily DBCA) and Traditional Owners of Saltwater Country in the Kimberley, with additional stakeholders including other state agencies, NGOs and industry with an interest in resource management and regional development in the Kimberley.

The resulting KMRP Leadership Team appointed by the WAMSI Board, consisted of scientists from DBCA, charged with the development and delivery of the research program and managing knowledge exchange with scientists, managers and other stakeholders.

An advisory group was formed to support the Leadership Team and maintain the dialogue between scientists and managers, including key representatives from DBCA regional staff and planners, Traditional Owners and the Department of Primary Industries and Regional Development (DPIRD).

WAMSI provided guidance and additional governance to ensure science quality and delivery through a science review panel that undertook periodic, independent and expert review of the research.

Research Program Design and Development

Step 01 Identify end users, information needs and priorities

Step 02 Focus science plan on agreed management questions

Designing a focused research program relies on the development of a clear science plan with priority management questions, scope and direction that captures the needs of relevant end-users. The plan should be unambiguous to both managers and scientists and contain achievable research goals.

Engagement with end users in the early stage ensures that management's needs are recognised and there is some ownership over the information sought and its anticipated use. Similarly, science participants need a clear understanding of the issues of concern and of the current state of knowledge to ensure research is well planned, cost effective and targeted.

The need for the KMRP was articulated through the KSCS, which recognised the need for improved knowledge to support conservation planning and decision making for the Kimberley marine environment.

An initial gap analysis was conducted through WAMSI and presented in 'A Turning of the Tide' (Wood and Mills 2008). These information needs, combined with direction from government, led to the development of a KMRP Strategy and Science Plan (Simpson 2011a, 2011b) that set out the key objectives of the KMRP, the research areas that would achieve these and the anticipated outcomes.

Collaboration amongst WAMSI partners, along with discussion with the KMRP Leadership Team, led to the development of 23 project plans, each focused on specific and agreed management questions, that comprised the KMRP.

All projects were reviewed by an independent science panel, with careful consideration given to program integration and overall value to conservation and management.

Science and Outcomes

Step 03 Science implementation

Step 04 Application to management

The next step in knowledge exchange is research project implementation, with a clear focus on aligning with the agreed plan to meet management needs. The research results then need to be considered with regard to how best they can be interpreted for management.

The KMRP was implemented over five years with projects teams providing regular updates on research activities and findings to ensure they remained focussed on relevant research questions.

At the conclusion of each project, the results were presented to managers and discussed with specific attention to the original management questions and consideration for data products or tools that could be used directly by key stakeholders. Feedback has been incorporated into final reports and recommendations for ongoing application to management.

KISSP Project Leader Dean Matthews (Senior Project Leader Yawuru) presents KISSP results to marine park managers at DBCA, Kensington.

Science Delivery

Step 05 Delivery plan

The delivery plan is designed to enhance the impact of research findings with recognition that conservation science is often a long-term game rather than one that causes immediate change. The delivery plan should support the adoption of recommendations into policy and operational actions and development of appropriate guidelines, tools and data products that will enhance the legacy left by new knowledge as well as ensuring visibility and availability of data and key findings.

Science delivery for the KMRP has included production of final reports, provision of datasets, associated metadata and publication of manuscripts.

The KMRP has approached the need to enhance knowledge exchange through long-term delivery with the development of a Communication Strategy and Plan extending into the post-KMRP period that addresses multi-focussed needs for communication between the scientists, end-users and to the broader community.

While communication activities during the research stage of the program focussed on identifying new findings and keeping end users engaged in the science process, the main emphasis during final delivery is on integration of information developed through the KMRP, its interpretation and potential translation into tools and products that stakeholders will be able to use, and ensuring these products and information are readily accessible. This includes synthesis and integration of research findings from the various projects into a regional picture and broader understanding of the Kimberley marine environment, the pressures upon it and the need for sustainable management. This stage also recognises and seeks to enhance the KMRP legacy by identifying new opportunities to extend existing projects, collaborations and the development of new research.

Supporting the Framework - Communication and Data Management

Effective knowledge exchange relies on strong communication throughout the entire program. The KMRP Communication Strategy was specifically planned to overcome some of the known barriers to knowledge exchange. For example, managers may feel that they have articulated their questions early on, yet have not received support or information to aid decision making without recognising the often longer timeframe needed for data collection, analysis and delivery, particularly for complex systems requiring multiple datasets and complex interpretation.

Staff turnover can also mean that the relationships and dialogue established early on, are no longer present at the conclusion of a program when findings are being delivered, leading to a disconnect or less personal investment in the outcomes from end-users.

Issues and politics can also change during a five-year project leading to initial research planning being perceived as less relevant.

The KMRP has worked to circumvent these barriers by making a concerted effort to engage early on with all stakeholders and consistently throughout the research program.

The communication and science delivery activities employed during the KMRP have maintained relationships between end-users and scientists, supported knowledge exchange and engaged the general community with new science.

Ongoing communication maintains awareness of the value provided by the KMRP and ensures that resources continue to be recognised and used.

The Communication Strategy includes plans for future initiatives that will showcase the achievements of the KMRP and present an integrated understanding of the Kimberley marine environment.

Communication and Science Delivery Activities

Activity	Description	Participants
Regional Workshops	Regular workshops to share research findings and discuss management application and emerging issues.	KMRP Leadership Team and DBCA regional staff
Conference Presentations	Presentations of key science findings at professional conferences and at two KMRP conferences.	KMRP scientists and Leadership Team as presenters
Public Presentations	Community presentations in Broome and Perth to engage the wider community in Kimberley science.	KMRP scientists and Leadership Team as presenters
Lunchtime Seminars	Presentations at the conclusion of each project held at DBCA to share key findings and their application with KMRP Advisory group and other stakeholders.	KMRP scientists, Leadership Team, Kimberley Advisory Group
Presentations to Aboriginal PBCs	Presentations to share findings and discuss application to healthy country management with relevant Indigenous ranger groups, PBCs and community members.	KMRP scientists, Leadership Team
KMRP Reports	All KMRP reports on the WAMSI website (www.wamsi.org.au).	KMRP scientists, WAMSI Communications Officer
Project Summaries	Summaries providing a brief non-technical description of each KMRP project including purpose, key findings and implications for management on the WAMSI website (www.wamsi.org.au/kmrp/kimberley-marine-research-node-projects).	KMRP scientists, Leadership Team, WAMSI Communications Officer
Science Stories	Brief written stories and videos directed toward a general audience posted in WAMSI Bulletins, on the WAMSI website and social media. Fieldwork and results stories also pitched to TV, press and online media outlets.	WAMSI Communications Officer
North West Atlas	Data and stories posted on The North West Atlas online forum for visualising data and sharing information and data links.	WAMSI Communications Officer and Data Management Officer
Data and Information Management Plan	Developed data and information management plan with detailed metadata logged with WAMSI.	WAMSI Data Management Officer, KMRP scientists

Current uptake – evidence of adoption

The KMRP has created a wealth of new information, data products and management tools that will be invaluable for the ongoing management of the Kimberley marine environment. In addition, a number of partnerships and collaborations have been developed between scientists, managers and Indigenous communities that will continue into the future. The legacy of this research program will be realised in many ways over the years to come. Initially there will be the extension of research projects and collaborations into new research questions and the passive use of new information, data and protocols in management activities including:

- Extension of the dugong aerial survey for distribution and abundance estimates to include Roebuck Bay to Eighty Mile Beach (funded by DBCA region);
- Using sediment cores to understand the potential influence of historical bushfire and/or cattle grazing pressures on the marine environment (pilot project funded by DBCA region);
- Continuation of the Saltwater Country Working Group formed through KISSP to continue to address priorities and issues relevant across Country (seed funding by WAMSI and Northwest Shelf Flatback Turtle Conservation Program (NWSFTCP);
- Support for WA Museum field trip to the Maret Islands to build on established relationships with Indigenous groups;
- Provision of datasets to Education Services Australia to develop Science, Technology, Engineering and Maths (STEM) modules for schools; and
- Ongoing research initiatives by CSIRO and AIMS, in partnership with Traditional Owners.

The Kimberley marine environment will continue to be recognised as a unique and remote wilderness area and a hotspot for biodiversity. The new WA Museum, to be opened in 2020, will promote it further with a marine filter feeder habitat display using samples of the large sponge, soft coral and sea fan specimens collected during WAMSI expeditions in the Kimberley, representing the first time this type of habitat has been described and displayed for educational purposes.

There are also examples of direct adoption of KMRP outputs into management including a number of the monitoring protocols highlighted under Tools and Products that have been adopted by DBCA in their monitoring program and by Indigenous ranger groups in their healthy country programs. DBCA is also incorporating KMRP datasets into its corporate data.

Example of Adoption – Incorporating KMRP Datasets into DBCA Corporate Data

The KMRP produced a number of important spatial datasets that describe the Kimberley marine environment and its biodiversity. Taking spatial data already produced by good science, and making it accessible through the DBCA Corporate GIS system is an effective way of facilitating access to data to determine management priorities, create visual products and use it in decision making processes and action.

Forty-seven datasets identified from the KMRP have been migrated into DBCA's corporate system for management purposes including; reef geomorphology, benthic biodiversity, human use, social values, seagrass and species distribution (dugong, crocodiles, dolphins, whales).

The availability of these datasets will enable habitat risk assessment for specific marine fauna, provide essential baseline understanding of the Kimberley to assist the development of long-term marine monitoring programs and assist in planning for the proposed Buccaneer Archipelago marine reserve.

Availability of this spatial information on board DBCA and joint manager vessels will also assist in safe navigation of the marine parks as well as in-situ planning and communication with joint managers.

Conservation science as a long-term game - adoption into the future

Step 06 Post program engagement to bed down decision-making tools and products

The uptake aspect of knowledge exchange should be recognised, particularly in conservation science, as a long-term aim. The information and findings are not only important in the short-term for decision making, but also in the long-term for monitoring programs, future development assessments and reviews of management plans and programs. There may also be future uses for the data that have not yet been developed. Ensuring the data is available, accessible and in a useful format on an ongoing basis is therefore a key element recognised by WAMSI through its data management protocols and plans.

While the delivery of science has provided the means to share the new knowledge created, to enhance the long-term conservation outcomes, a critical element of the knowledge exchange process will be post-program engagement with stakeholders to discuss their needs relative to research outcomes and to understand the decision-making tools and products that may be required for them to apply these findings to their activities.

The next step in the framework, is to hold workshops with key stakeholders including regional and Perth based DBCA staff and Traditional Owners in the Kimberley, as well as with stakeholders from other agencies. A key outcome of these workshops will be agreement on communication and decision-making products that will enhance the uptake of the science along with some indication of priority, based on value. WAMSI can then allocate resources and work in partnership with end-users to develop priority products.

Conclusion

It is clear that the focus and effort devoted to knowledge exchange moves through the life of the research program from development through to science and outcomes delivery, decision-making tools and communication products. While opening the dialogue early on and creating awareness of the research program and its delivery potential is important in the planning and project implementation phase, greater participation and input from end-users and other stakeholders is needed in the later stages, when research projects near completion. Both the integration of research findings and the interpretation of findings into management application and useful tools will rely on ongoing interaction between scientists and end-users after the research program has finished.

The focus on knowledge exchange improves the impact of the science and leaves a strong KMRP legacy. The development of lasting partnerships that will foster ongoing collaborations with future research opportunities and the delivery of products and tools for managers demonstrates the broader and lasting value on investment in the KMRP.

The knowledge exchange will be more clearly realised over time. To best understand the full impact of the KMRP and the success of its framework, an assessment should be undertaken in five years (2024) to evaluate the uptake of the science and the shift in community attitudes towards management of the Kimberley marine environment. The measure of success can be used to inform the conduct and governance of future research programs.

Program Synthesis and Outcomes Delivery - Products

Title	Description	Status; leader	Audience
Database of KMRP research projects	An information matrix of all KMRP research projects including project objectives, management questions, outputs, data products, published resources and potential application to management actions and initiatives.	In progress, DBCA internal	DBCA staff, regional and head office
Information resources	This may include posters, fact sheets and other communication resources that can be used in community education.	Ongoing; WAMSI	Broader community
Web-based tools	Several KMRP projects have initiated web-based tools for models and products (e.g. KISSP protocol for researchers and monitoring framework and toolkit, MSE scenario based model). These can be refined and made available on the WAMSI or other website.	Ongoing based on KISSP delivery; WAMSI	Indigenous rangers, resource managers
GIS data layers	A number of the projects have produced spatial data on species distribution patterns, habitat characterisation and maps and physical features such as bathymetry. These data layers can be made visible and accessible to planners and managers for current and future use in operational management, planning and marine park review exercises.	In progress, DBCA	DBCA staff, regional and head office
Compendium of monitoring protocols for long-term monitoring of key biodiversity assets.	A number of projects developed benchmark data, along with indicators and protocols for monitoring, as a key output. A framework identifying the indicators and protocols could be developed in consultation with DBCA scientists and managers to ensure they can be adapted into the WA Marine Monitoring Program. Associated SOPs and specific protocols will be developed as relevant and where resources are available.	In progress based on KMRP project outputs. Requires priorities and resources to complete; KMRP science coordinator and DBCA	DBCA, joint managers, Indigenous rangers
Training package in research and monitoring protocols and techniques	KISSP developed training package specific to setting up a monitoring program for the assets identified in Healthy Country Plans. Additional training packages could be developed based on the monitoring toolkit where resources are available.	In progress based on KISSP product, requires priorities for additional modules; requires leader	Indigenous rangers
Policy guidelines	To address specific issues stemming from KMRP project recommendations (e.g. marine park design relative to connectivity). These products would be developed jointly with managers and relevant scientists.	Requires direction on priorities; KMRP science coordinator	Natural resource managers
Integration workshops leading to publications or management products: • Overview of the Kimberley marine ecosystem and drivers • Regional bathymetry • Predictive seagrass map • Conceptual model of the Kimberley	There are a number of themes where the integration of project findings lead to deeper understanding of the Kimberley region and how it works. Workshops could be used to bring information sources together and identify cross-cutting issues relevant to sustainable management. These will require a champion to drive them and to produce an agreed upon product.	Each theme requires a champion and resources to undertake	Scientists, managers

Critical Gaps in the Understanding of the Kimberley Marine Environment

K Waples, S Field, C Cvitanovic, S Wilson

A key strength of strategic, management-focused research programs like the KMRP managed by WAMSI is that the planning involves scientists and managers to ensure that the research aligns with priorities and leads to improved, evidence-based decision making.

Over five years the KMRP has produced a wealth of information on the Kimberley marine environment that can be applied to improving our understanding and management of the unique ecological and social values of this region. However, numerous management-related questions and knowledge gaps remain for this vast and poorly understood area, along with emerging issues to consider for sustainable management.

It is critical that an open dialogue continues between researchers and managers to identify information gaps of greatest need so that future research can remain focussed on priority issues.

As a final outcome for the KMRP, researchers and managers have been engaged (both natural resource managers from state government agencies and healthy country or Indigenous protected area (IPA) managers) to identify critical gaps in knowledge that will need to be filled to continue the sustainable management of the Kimberley marine environment and human activity across the region.

This process was also undertaken to understand the similarities and differences in research priorities between academics and the joint land managers in the Kimberley that can be used to develop stronger partnerships and open communication.

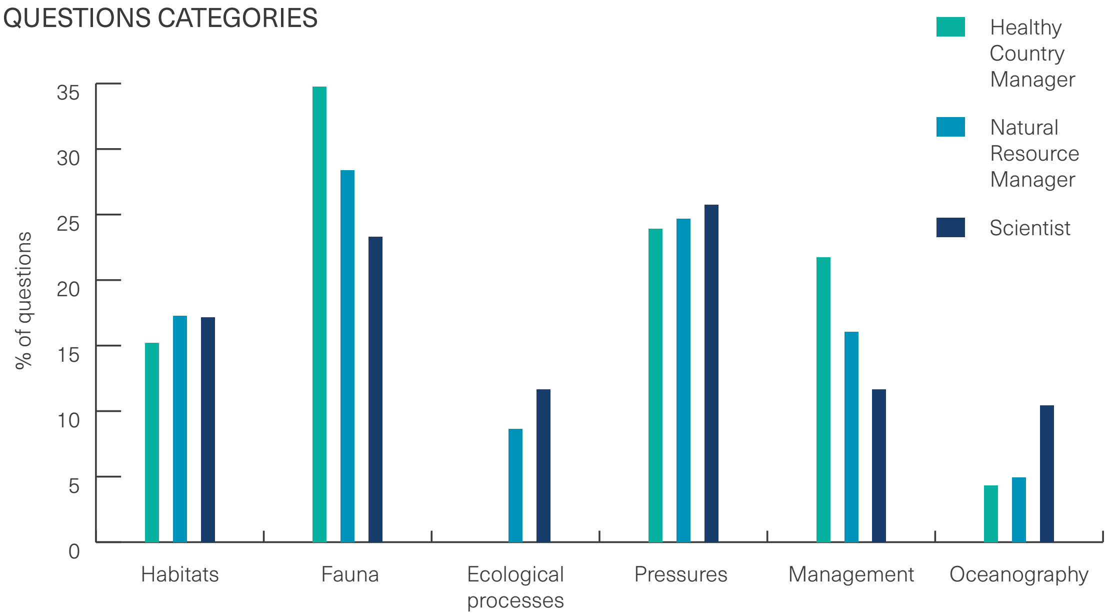
Nineteen scientists, 10 natural resource managers and six healthy country managers responded by providing their top five priority research questions.

Removing duplication produced 184 questions (Appendix III) that are a priority for research in the region. These questions cover a range of themes and provide an extensive list of information needs for the Kimberley that can be used to guide discussion on future research prioritisation at a local level and across the region.

All research questions were classified into six broad themes, comprising habitats, fauna, ecological processes, pressures, management and oceanography, to determine if there were differences in the frequency with which scientists, natural resource managers and healthy country managers posed questions on particular values or topics.

The themes were further refined for habitats (coral, mangrove, seagrass), fauna (cetaceans, dugong, turtles, crocodiles, seabirds, sea snakes, sharks, fish, invertebrates), pressures and processes (connectivity, recruitment, productivity, resilience, hydrodynamics, climate change, fishing) and management questions (Indigenous issues, monitoring, Marine Protected Areas (MPA), fisheries).

Initial analysis on the distribution of questions among themes and participants found that there were differences in the types of questions posed by scientists and managers. For example, natural resource and Indigenous managers raised



Per cent of questions posed by each group under the broad research categories.

priority questions spread relatively evenly across fauna, pressures, management and habitats, with the natural resource managers also prioritising questions on ecological processes.

In contrast, scientists provided questions across all six themes, with the main emphasis on pressures, fauna and habitats and consistent focus on processes, management and oceanography.

When delving further into the detail of these categories additional differences were noted. For example, within the habitat category scientists posed a high proportion of questions on corals compared to both natural resource and Indigenous managers who focussed on seagrass and mangroves.

In relation to specific fauna groups, both scientists and resource managers posed questions across most of the nine fauna groups, with an emphasis on fish, dugong and cetaceans, whereas Indigenous managers focussed their questions on fauna that are typically subject to traditional harvest (e.g. turtles, dugong, fish and invertebrates).

These findings demonstrate that, while individuals and groups bring their own area of expertise and interest to gap analyses, there is still much common ground on which to base future collaborative work.

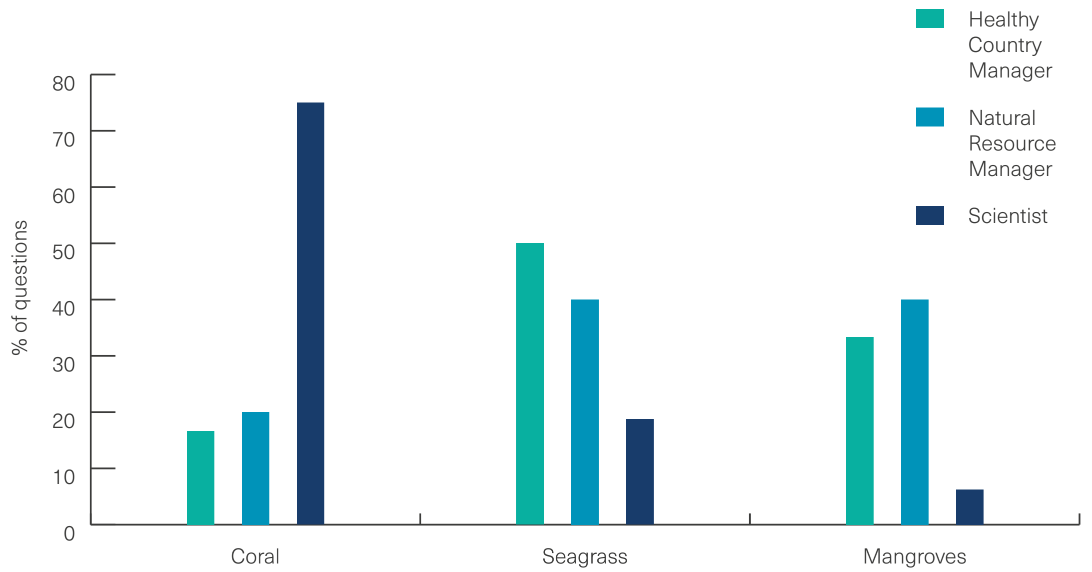
Therefore, the list of questions identified through this project may serve as a starting point for discussions between scientists and managers in the Kimberley when developing and implementing management and science plans for ongoing research and monitoring activity that may lead to collaborations between joint managers and science partners.

Aspects of this study, which is in the process of being refined, may further enhance commitment to joint research by developing a better understanding of priority questions and themes within this lengthy list.

All those who participated in the first step have been asked to rank each of the compiled 184 questions based on whether it is: achievable; a priority requiring urgent attention; and a key knowledge gap (i.e. whether existing information could adequately answer the question). This analysis will be used to explore relative priorities across broad and specific categories and to understand the common ground between the three groups that can identify potential areas of collaboration.

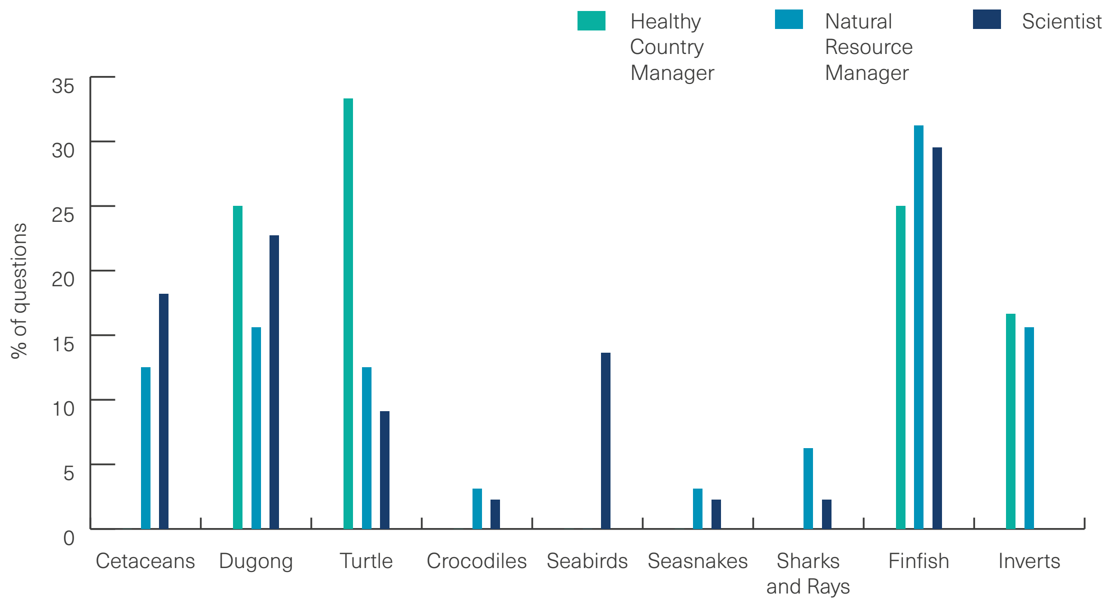
The extension study, led by University of Tasmania, CSIRO and DBCA staff, will result in a publication on similarities and differences in identifying research priorities for the marine environment between academics, natural resource managers and Indigenous healthy country managers.

HABITAT QUESTIONS



Per cent of questions posed by each group under the sub categories of habitat.

FAUNA QUESTIONS



Per cent of questions posed by each group under the sub categories for fauna.

Project Summaries

Understanding the background habitats and physical structure of the Kimberley marine environment can be linked with ecosystem processes to better predict species distribution patterns and how these may change in the future.

New Knowledge and Tools

- Monitoring protocols and training materials for seagrass, coral and other benthic habitats
- Spatial database of all Kimberley reefs and their geomorphic features
- Baseline dataset and maps of benthic habitats and reef geomorphology
- Inventory and catalogue of species identified in Kimberley benthic communities

Biophysical Characterisation

The Kimberley is broadly recognised as an important coral reef province, containing extensive fringing reef around a highly indented rocky (ria) coastline and many islands, seagrass beds and mangroves, however these habitats and the ecological communities they contain remain largely unexplored.

Geomorphology is often used as a surrogate for benthic biological communities, and understanding the history of reef growth and formation can inform present day distribution of biodiversity.

The projects in this section provide a characterisation of the biophysical world of the Kimberley marine environments, including an inventory of benthic biodiversity and habitat mapping that identifies hot spot areas and environmental parameters linked with high biodiversity. This information will be useful for regional marine planning as well as biodiversity conservation management.

Key management questions

- How have the Kimberley reefs developed over the last several thousand years in response to changing environmental conditions?
- How do Kimberley reefs vary regionally (including from coastal to offshore) in response to coastal substrate controls, terrestrial inputs, types of foundations, sea levels, extreme macrotidal conditions and high turbidity?
- What is the distribution, extent, species composition, condition and conservation significance of the major benthic marine habitats (e.g. coral reefs, filter-feeders, etc)?
- Where are the marine biodiversity 'hotspots' and what environmental factors are 'driving' these distribution patterns?
- How do geomorphology, sediment composition and turbidity influence habitat and biodiversity distribution?
- Where are major benthic primary producer habitats located and what is the relative significance of different benthic primary producers?
- How representative is the biodiversity in the sanctuary zones of the proposed MPAs?

Reef Growth and Maintenance

Coral reefs persist in the Kimberley despite the extreme environmental conditions in coastal waters caused by persistent turbidity from large tidal movements and the prolonged exposure of extensive intertidal areas to daytime heat, cyclones, elevated water temperatures and large inputs of terrestrially-derived sediments.

Overview

The Kimberley coastal region is structurally complex and characterised by a highly indented rocky (ria) coast and a large number of islands mostly located within five to 15 kilometres of the mainland.

This distinctive regional geomorphology has determined both contemporary landforms and the coastal marine ecosystems that now occur in the Kimberley. The underlying geomorphology strongly influences the occurrence and distribution of coral reefs from the shelf edge, to the inner shelf and in coastal regions.

While the offshore reefs have grown vertically as successive Quarternary sea level cycles (40,000 to 100,000) drowned the shelf, the inshore reefs have developed a range of geomorphologies based on the form and structure of the underlying antecedent substrate, local current and tidal regime, and background water quality (i.e. turbidity).

However, the exact controls on reef geomorphology and how this varies spatially is still poorly understood and not well documented regionally. What we do know is that over the last 9000 years, coral reefs have experienced continual growth developing into large and complex reef structures.

This project developed a regional understanding of Kimberley coral reef geomorphology, including relationships with substrate type, morphological patterns, distribution and relative exposure to terrestrial and other impacts. This has included exploring how the extreme tides and turbidity have influenced reef structure and growth and the implications this may have for future management.

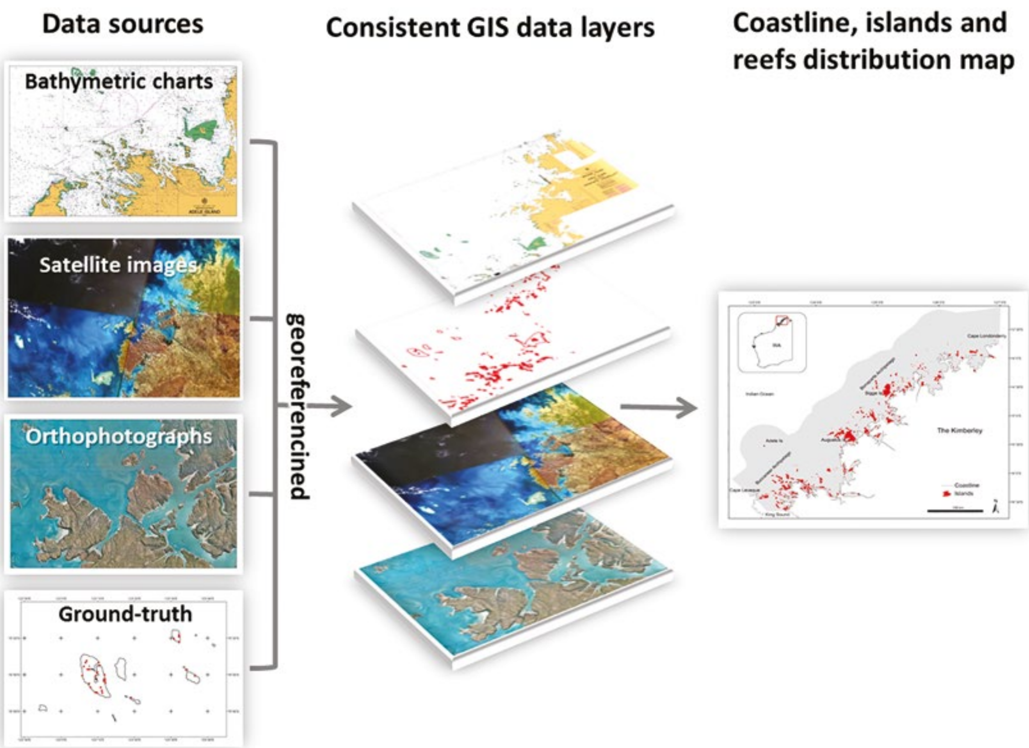
Approach

A Kimberley coral reef geodatabase has been developed using remotely sensed images to generate geomorphic, habitat and substrate maps of reef platforms.

The locations of islands, reefs and other related geomorphic features of the coast were extracted from satellite imagery, aerial photography, geological maps and bathymetric charts along the Kimberley coast. A detailed assessment was made of the substrates and habitats of 30 reefs as a subset of the broader Kimberley bioregion.

A sub-bottom profiling (SBP) field study of nine reefs in the western Kimberley was undertaken to determine the internal architecture (e.g. reef thickness) of selected Kimberley reefs as part of an assessment of reef growth during the Holocene (the current period of geological time that started some 11,500 years ago when the glaciers began to retreat) and in relation to antecedent foundations to assess reef growth. More than 294 km of SBP records were collected from a representative suite of reefs to determine reef growth history.

Cores were taken from selected reefs to examine the Holocene record in relation to sea levels and growth history responses, timing of events during the Holocene, reef building communities, resilience and climate change responses.



Data sources compiled and assessed to create ReefKIM, the georeference database on Kimberley islands and reefs.

Key Findings

A reef area of 1950 km^2, comprising 2413 islands and 853 nearshore reefs, was mapped from Cape Londonderry to Cape Leveque. This represents the largest reef system in WA and the second largest reef system in Australia, being about a third the size of the Great Barrier Reef (GBR).

Analyses showed that most Kimberley reefs occur along the inner shelf margin and less than 15 km from the coast, whereas GBR reefs are typically located along the shelf edge. This means that Kimberley reefs have a potentially greater susceptibility to terrestrial influences caused by land use.

Southern Kimberley reefs were found to differ markedly from other systems and required a new geomorphic classification scheme.

Fringing, planar, patch and shoal reef types were broadly identified across the Kimberley and about 80 per cent of the total were fringing reefs that mostly occurred in archipelagos.

Multibeam surveys identified 'high intertidal' reefs as a new morphotype which are uniquely characterised by having a reef flat with a surface elevation above the mid-tide level (i.e. mean sea level) instead of the more typical level equivalent to mean low water spring tide. The highest reef surveyed in the Kimberley (Tallon Reef) was 0.25m above mean sea level, meaning that some reefs may be exposed for longer times than they remain submerged.

Kimberley reefs were generally 10-15 metres thick with reef growth initiation occurring very soon after the inner continental shelf was flooded following the last glacial period about 10,000 years ago.

A detailed geochronology has been identified for the Holocene reef building phase from a reef sequence studied at Cockatoo Island. When compared to the Holocene sea level curve, it was shown that reefs accreted, or grew by accumulation, as sea level rose.

Shallow coring of reef building organisms found that inshore reefs (e.g. Cockatoo island) were muddy in character while offshore reefs (e.g. Adele Reef) were sandier.

Radiocarbon dating showed that inshore reef growth commenced as the inner shelf flooded and these reefs most likely initially comprised branching, plate, and massive corals. This structure has been subsequently replaced on many reefs (particularly exemplified by Montgomery and Turtle Reefs) by coralline red algae (rhodoliths), small robust corals and coral rubble as reef tops have become increasingly intertidal in nature.

Percussion coring at Adele Reef.

Management Implications

Managers now have access to the ReefKIM GIS database of habitats that includes georeferenced data and the location of every significant reef in the Kimberley along with detailed substrate and geomorphology maps for 30 reefs across the region.

This resource provides baseline data for monitoring reefs and to identify reef habitats of relatively high conservation significance.

Future Focus

This study has found that the reefs in the southern Kimberley, which are exposed to tidal extremes, are unique and support a very high diversity of corals, raising the question of whether this results from the extreme macro tidal system or the unique nature of the Kimberley bioregion as a whole.

Investigating the northern Kimberley reefs, which experience intermediate environmental conditions between the extreme macro tides of the southern Kimberley and the more moderate tides of the Great Barrier Reef on the east coast, would help to answer this question.

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Kimberley Seabed Biodiversity

The Kimberley seafloor habitats are diverse, dominated by sponges and other filter feeders (many newly identified) with patchy distribution due to varying geomorphic features and environmental variables.

Overview

The Kimberley marine environment represents a diverse and physically complex region that supports a number of different habitats and seabed (benthic) communities rich in biota.

Previous surveys and observations have noted extensive coral habitat in nearshore waters but species diversity is yet to be characterised and the communities of deeper waters remain unknown.

This project has improved our understanding of subtidal benthic habitats in the Kimberley and their distribution through detailed mapping at the local scale and quantitative predictive spatial models at the broader scale to identify the key environmental drivers.

Approach

Current physical, geomorphic and biological survey datasets from the Kimberley region were used to select survey locations and plan sampling design.

Four ship-based surveys of subtidal seabed were completed, two in the south (Camden Sound) and one each in the central (Bonaparte Archipelago) and northern (Eclipse Archipelago) parts of the Kimberley to provide a representative benthic biodiversity assessment of the Kimberley coast.

Sampling aimed to provide broad-scale information for future management of specific locations and to provide some predictive capability to identify additional areas that may support unusual or notable habitats.

The sampling designs used available information such as depth, slope, aspect and rugosity (surface roughness) to develop indices of geomorphic complexity. Sampling sites were then selected in a randomised, stratified design throughout each study area.

Sampling included towed video transects for habitat characterisation, epibenthic sled sampling to collect biota, CTD (Conductivity, Temperature and Depth) casts for water column profiling and seabed grab sampling for sediment characterisation. At night the vessel surveyed a pre-planned grid pattern with multibeam sonar to map depth and seabed morphology.

Four additional smaller-scale expeditions focused on nearshore and intertidal areas in collaboration with Wunambal Gaambera and Dambimangari sea rangers to assess shallow fringing reef and rocky shoreline habitats using single-beam surveys and drop cameras inshore of the subtidal expeditions.

Collected organisms were lodged with the Western Australian Museum (WAM) to enable a more comprehensive formally-recognised record of species distributions.

Key Findings

The study markedly increased knowledge of marine biodiversity of the Kimberley including through extensions to known distribution for a number of species and identification of new species across most taxonomic groups.

Overall, almost 2200 species or nominal species were identified from the three sampling areas with sponges, echinoderms, molluscs and crustaceans accounting for 83 per cent of all species identified.

Areas of particularly high biodiversity were found to be primarily associated with shallow geomorphic features with hard ground and seafloor complexity.

About 85 per cent of the seabed at depths below 15 metres in all three areas comprised sand and/or mixed sand-mud benthos with sparse epibenthic life.

The broad-scale distribution of substrates and associated biota was similar in the southern, central and northern survey regions.

Seabed channels were present in all regions, reflecting river valleys inundated by the Holocene transgression. These features provided diversity in seabed morphology, with rapid changes in depth, slope and aspect over relatively short distances and were typically associated with an abundant and diverse sessile (fixed) biota.

The areas of highest abundance and diversity represented 10.4 per cent of the surveyed area and tended to be closer to shorelines or paleo-channel edges.

While comparable examples were found in all three regions they were far more prevalent in the southern survey region (15.9 per cent of transects) compared to the northern and central regions (4.2 and 5.3 per cent of transects, respectively) and were mostly located around the island archipelago at the northern end of Lalang-garram/Camden Sound Marine Park, including North Lalang-garram Marine Park, or adjacent to the coast.

Most surveys were in depths of 15-60 metres where light was limited. Consequently, benthic primary producers like algae, seagrass and scleractinian corals were rare and the sessile seabed biodiversity was characterised by filter-feeding and detritivorous species.

Sponges dominated in biomass and abundance in all regions, though bryozoans, crustaceans, echinoderms and soft corals were also abundant.

Based on epibenthic sled samples, biomass was greatest for sponges, with sponges and various echinoderms also contributing the greatest number of individuals collected from all regions.

Estimates of abundance by percentage of seabed covered based on still images found that bryozoans were the most abundant taxonomic group, with sponges and soft corals being the next most common, although much less abundant.

This difference in relative abundance estimation is likely a result of the influence of growth form on sampling metric. Many of the larger sponges grow vertically and are effectively sampled by an epibenthic sled, whereas bryozoa may be very small, fragile and often spread laterally meaning they cover more surface area yet may be under-represented in analyses of sled samples.

Benthic primary producer habitats such as coral and algae were typically restricted to shallow subtidal and intertidal habitats in all survey regions.

Coral reef habitats with dense live coral cover, some with species diversity equivalent to well recognised offshore coral reef ecosystems, have been observed across the region and have been best documented around outer coastal islands. The Bonaparte Archipelago had the highest documented species diversity, however locations of high coral diversity also occurred to the north and south as well as very near the mainland.

The results of this and other recent complimentary studies confirm the Kimberley coastal region as a significant coral province, comprising large coral reef platforms, small patches of reef and coral-dominated habitat on rocky near-shore substrates.

Both abundance and diversity increase seaward from the reef crest where corals are less exposed, and within intertidal ponds and rock pools at all elevations.

Coral dominated habitat on the inshore fringing reef and rocky shelf areas did not extend beyond depths of 10-15 metres due to the absence of hard substrate at the base of the reef drop offs and perhaps less favourable environmental parameters, including the marked attenuation of surface sunlight.

Multibeam sonar provided greatly improved bathymetry for each of the three survey regions and was used in combination with benthic habitat information to develop spatial predictive models of mixed benthic assemblages, showing their probable distribution.

Number of species detected per taxa group at the three survey sites. In addition to the taxa where species numbers were determined, significant collections were made of ascidians (444 specimens), bryozoans (336), other cnidarians (232) and worms (197), all now housed in the WAM collections.

Taxa	Southern	Central	Northern
All taxa	769	578	670
Crustaceans	160	135	129
Echinoderms	116	128	138
Molluscs	115	68	75
Corals	59	51	63
Sponges	265	154	218
Fish	33	28	34

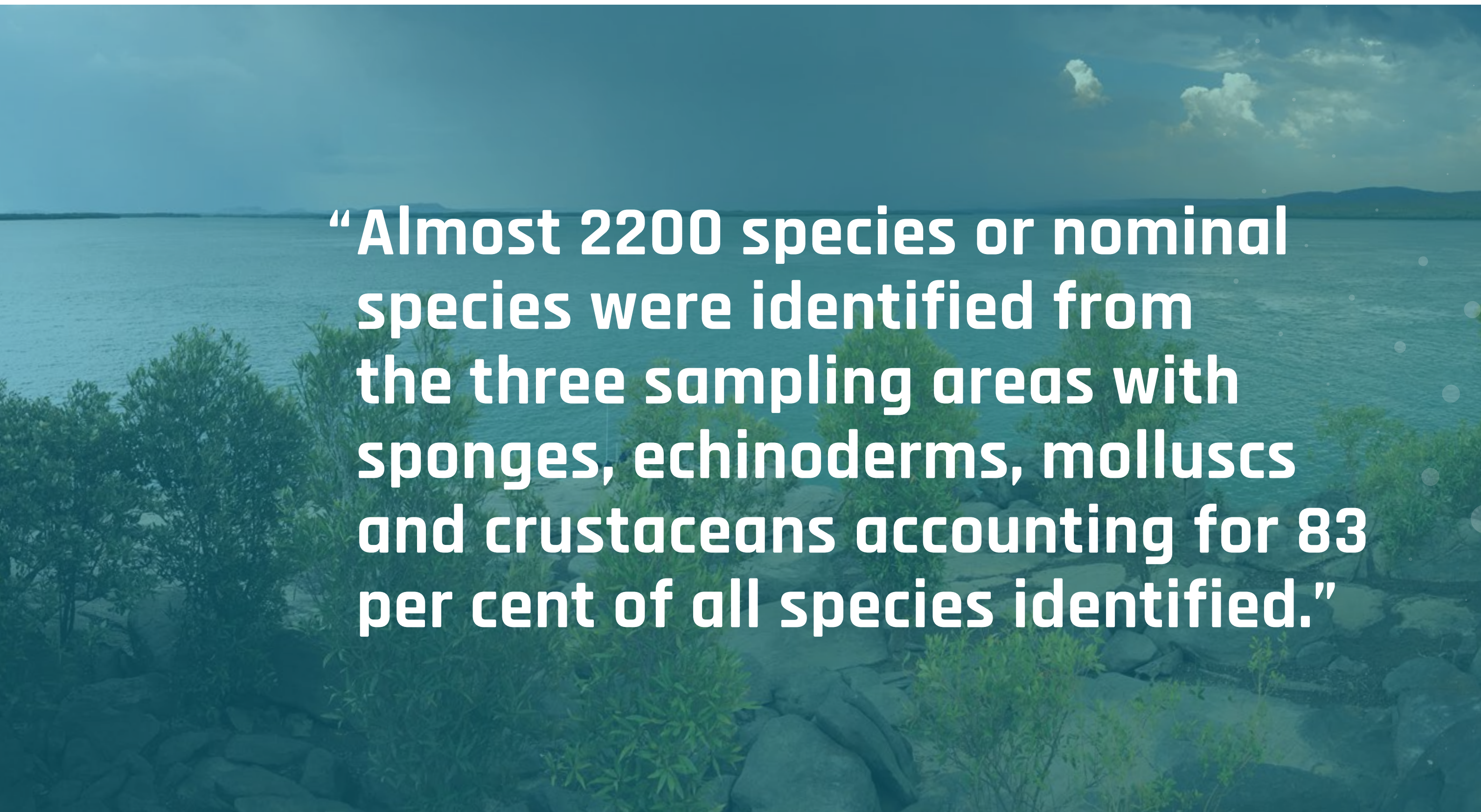
The models also provide a means to estimate the percentage area covered by each class of habitat, for example, the location and extent of dense filter feeder habitat.

In general, the benthic habitat models performed well although areas of high model accuracy were more prevalent in the southern than central and northern sites.

Nine habitat/species assemblages were identified using field data and environmental variables in an overarching spatial characterisation of the broader region.

There was a deeper offshore assemblage that ran along the entire shelf range of the three sub-regions surveyed and a series of inshore and intermediate assemblages which, broadly speaking comprised a northern set and a southern set.

In general, the offshore habitats were mostly unconsolidated sediment and were characterised by moderate diversity and low biomass while the intermediate and some inshore assemblages had a higher proportion of hard substrate, with associated high biomass and a highly diverse invertebrate fauna.



“Almost 2200 species or nominal species were identified from the three sampling areas with sponges, echinoderms, molluscs and crustaceans accounting for 83 per cent of all species identified.”

Implications for Management

- Detailed benthic habitat maps of some parts of the Kimberley are now available to managers to inform marine management decisions and future reserve planning.
- This study confirms that multiple marine park areas with sanctuary zones are needed within the Greater Kimberley Marine Park to ensure adequate and representative protection for seabed biodiversity across the region.
- Most of the more diverse and abundant filter feeding habitat was observed adjacent to shorelines, near channel margins in between islands or along drowned river channels that extend across the shelf. Therefore, areas that include inshore-offshore gradients, such as archipelagos, with a variety of environmental settings, including sheltered and exposed shorelines, should include a representative sample of coral and other benthic primary producer habitats and species.
- Broader species and assemblage distribution modelling have provided the best available estimate of benthic habitats outside the mapped areas. A northern and southern set of intermediate shelf and inshore assemblages represented the most marked biogeographic differentiation. At more local scales, sedimentary, geomorphological and oceanographic characteristics provide reasonably effective predictors of associated biodiversity. While this information can be used like the mapping information, managers should be aware of the limitations associated with this modelling with attention to the level of confidence in the predictive mapped areas.
- Where detailed bathymetric and substrate data is available, modelling information can be used for making informed spatial allocation decisions for conservation, such as determining the placement of management zones to ensure an adequate percentage of high biodiversity habitat types are protected. Regional models that are data poor in some areas perform less well in this regard. Maps of classification accuracy enable decision processes to take confidence level into account.
- The fine-scale modelling approach used in this project has worked well where sufficient data has been collected and there is a decent ecological gradient (i.e. by depth, slope, aspect or rugosity). While this approach could be extended to areas with similar geomorphology, there are limitations for its use in soft sediment environments

Future Directions

Despite the project delivering increased knowledge about marine biodiversity in the Kimberley, there is much diversity that remains to be described for most taxonomic groups.

Future research should focus on the fauna groups that were either not sampled during this study (infauna and fish) or collected, but remain unidentified because of a lack of available expertise (e.g. mobile and habitat forming species such as worms, bryozoa, hydroids and ascidians).

The taxonomy and ecology of bryozoans in the Kimberley in particular is an important knowledge gap, given they can be a major component of the benthos.

Additionally, detailed bathymetry of the broader Kimberley region is incomplete and numerous nearshore areas remain unsurveyed, a gap that, if filled, would benefit future habitat assessment and modelling.

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Exposed reef at low tide

Remote sensing tools to enhance habitat mapping across the Kimberley

The presence of key benthic primary producers such as corals, algae and seagrass in intertidal and shallow subtidal waters have been characterised through several KMRP projects, suggesting that remote sensing tools may be useful in identifying these habitats.

For example, the observation that major coral habitats are likely to be exposed at tidal heights between 0.6-1.0 metres, suggests that such areas would be detected by remote sensing reasonably often during tidal cycles.

Despite the issues associated with high turbidity across the region (identified in KMRP Remote Sensing project), tidal predictions for the ria coast indicate that low tides of one metre (lowest astronomical tide (LAT)), or less between 6am and 6pm occur on at least 50 days per year.

This is likely to allow future satellite imagery, which is rapidly increasing in temporal coverage and spatial resolution, to show major areas of fringing reef habitat with moderate to high coral cover which occur at elevations between 0.3-1.0 metres LAT. Some of the same methods used to produce fine scale spatial models of the deeper water filter feeder habitats, in combination with the increasingly accessible rapid return satellite data, are likely to produce useful outcomes for mapping and monitoring of the shallow benthic primary producer habitats.

In combination with mapping of the intertidal reef zone [Productivity] and reef morphology [Geomorphology] there is the potential to produce habitat maps for reef and shallow water areas across the Kimberley.

Given the scale of the Kimberley and expense of ship-based surveys, a remote sensing approach has great promise for detection of the most extensive coral habitats, which may take priority for conservation measures in the future.

Benthic Habitat at Flatback Turtle Foraging Sites

A collaborative project was developed between the Benthic Biodiversity study and the NorthWest Shelf Flatback Turtle Conservation Program to explore benthic biodiversity in areas considered to be turtle foraging grounds.

While there have been extensive tagging programs tracking the movement of flatback turtles there is still very little information on what they eat.

This collaboration sought to use tracking data to identify foraging hotspot areas in the Kimberley region and to conduct a field campaign to characterise the benthic communities in these areas as potential turtle forage items.

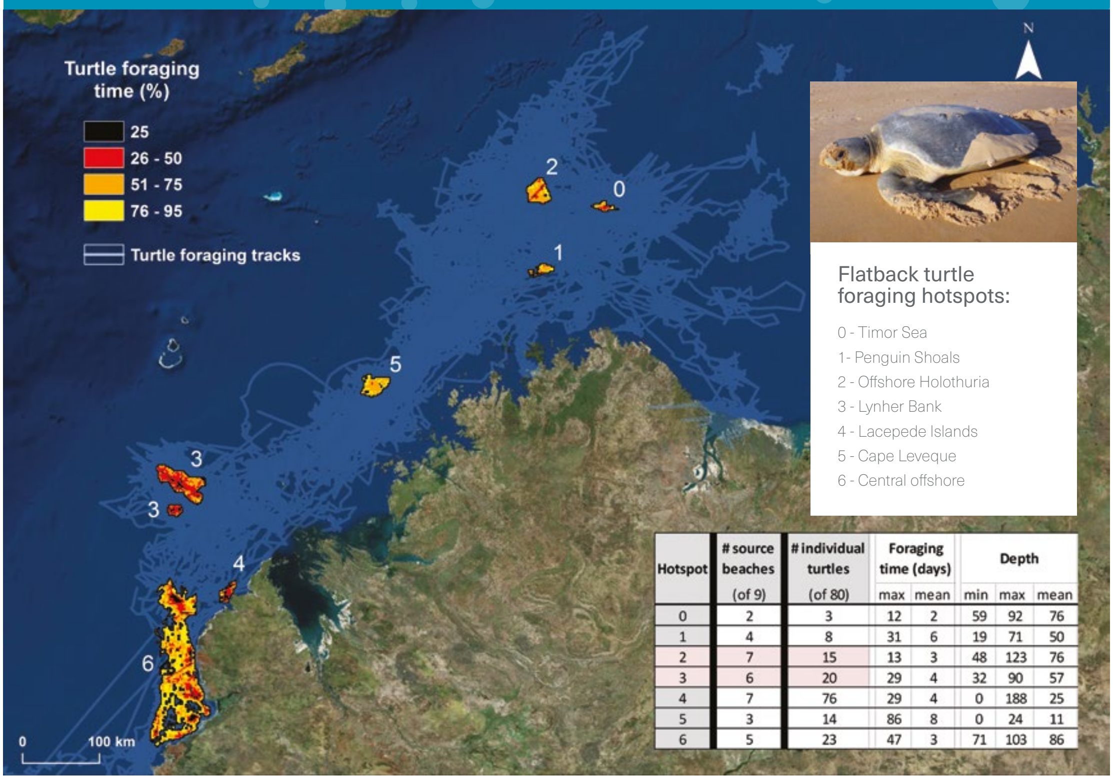
Seven foraging sites were identified in the Kimberley region and two offshore sites were surveyed.

Benthic fauna was typical of that found across the Indo-West Pacific region, dominated by non-scleractinian sessile organisms associated with soft sediment environments (e.g. sponges) characterised by moderate to high water movement and low wave action.

The most common assemblage found in the turtle foraging hotspot had a relatively even mix of sponges, soft corals, bryozoans and other invertebrates and, while similar to those found in other coastal areas, was proportionally more widespread across the turtle survey area.

The most abundant biotic group was bryozoa followed by crinoids, which was a point of distinction from the coastal regions.

Voucher specimens of various taxa have been maintained for future genetic and isotope work to confirm marine turtle diet.



Hotspot	# source beaches (of 9)	# individual turtles (of 80)	Foraging time (days) max	Foraging time (days) mean	Depth min	Depth max	Depth mean
0	2	3	12	2	59	92	76
1	4	8	31	6	19	71	50
2	7	15	13	3	48	123	76
3	6	20	29	4	32	90	57
4	7	76	29	4	0	188	25
5	3	14	86	8	0	24	11
6	5	23	47	3	71	103	86

The seven flatback turtle foraging hotspots identified across NW Australia, with the hotspots selected for survey highlighted in pink.

Benthic Primary Productivity: Production and Herbivory of Seagrasses, Macroalgae and Microalgae

Benthic primary producers form the basis of the trophic structure that supports the highly diverse Kimberley marine fauna through their productivity and ecosystem services.

Overview

Seagrasses provide numerous ecological functions and services in coastal areas, including fisheries production (e.g. nursery habitat provision), sediment stabilisation resulting in coastal protection and carbon sequestration. Seagrasses also provide habitat to a wide array of fishes and invertebrates and support populations of specially protected species like dugong and marine turtles.

Macroalgae is abundant in inshore waters of the Kimberley and some, such as the genus *Sargassum*, commonly form shelter and/or foraging habitat for juvenile fishes and other fauna. Microalgae are also known to be present in sediments.

While seagrasses, macroalgae and microalgae are key benthic primary producers of the Kimberley, little is currently known of their distribution, biomass and productivity in this region, particularly given the extreme physical conditions of the Kimberley marine and intertidal environment and the possible effects of grazing pressure by the herbivores that inhabit nearshore waters.

This research has led to a better understanding of the role of benthic primary producers on macrotidal fringing reef and terraced lagoon environments which are common throughout the Kimberley.

Spatial and temporal patterns in the abundance and growth of marine benthic primary producers (seagrass, macroalgae, and benthic microalgae) have been characterised and the rates and net effects of herbivory have been assessed.

The project was undertaken in collaboration with the Bardi Jawi Rangers to develop good working relationships and to enhance the understanding of primary productivity by incorporating Indigenous knowledge and experience.

Approach

The study focused on the Sunday Island group and coastline of the Bardi Jawi Indigenous Protected Area (IPA) in the Buccaneer Archipelago, WA. Surveys were conducted between November 2013 and November 2015, with three surveys occurring just prior to the wet season (October-November) and two surveys just after the wet season (March - April).

At each location measurements were taken of shoot and flower density: above- and below-ground biomass, and productivity of seagrass (all surveys); biomass and productivity of macroalgae (all surveys); rates of herbivory (three surveys); and biomass and metabolism of microalgae.

Concentrations of nutrients in porewater, biomass of chlorophyll-*a* in the sediment, and sediment porosity were also collected.

Monthly surveys were conducted by the Bardi Jawi Rangers from April 2014 to April 2015 to characterise monthly variability in the density, biomass and productivity of the two dominant seagrass species - *Thalassia hemprichii* and *Enhalus acoroides*. Relative rates of consumption of the seagrasses *T. hemprichii* and *E. acoroides* were measured through simple tethering experiments.

Key Findings

Thalassia hemprichii and Enhalus acoroides were the most abundant seagrasses recorded in the raised lagoons of the Sunday Island group islands, with no seasonal or temporal pattern evident in their abundance or growth.

Flowers of both species were only observed in November 2013, and it is possible that flowers are predominantly present during the wet season (November to March). Leaf extension rates (growth) were high for both species relative to typical seagrass growth rates, with some measurements exceeding several centimetres per leaf per day. Other seagrasses recorded in lower abundances included *Thalassodendron ciliatum, Halodule uninervis, Halophila ovalis* and *Cymodocea serrulata.*

Macroalgae occupied the seaward margins of lagoons and isolated rocky surfaces among the seagrass meadows. *Sargassum* was the most abundant genus, for which five species were recorded, the most abundant of which was *Sargassum polycystum*. This species also yielded the highest growth rates, which, at their peak, were in the same order as growth rates for seagrass, and among the highest rates recorded for *Sargassum*. Biomass tended to be highest during April, while the fastest growth rates were recorded during November 2013, when average extension rates exceeded one centimetre per day. These two observations imply a seasonal pattern of growth of *Sargassum*, with highest growth rates during the wet season.

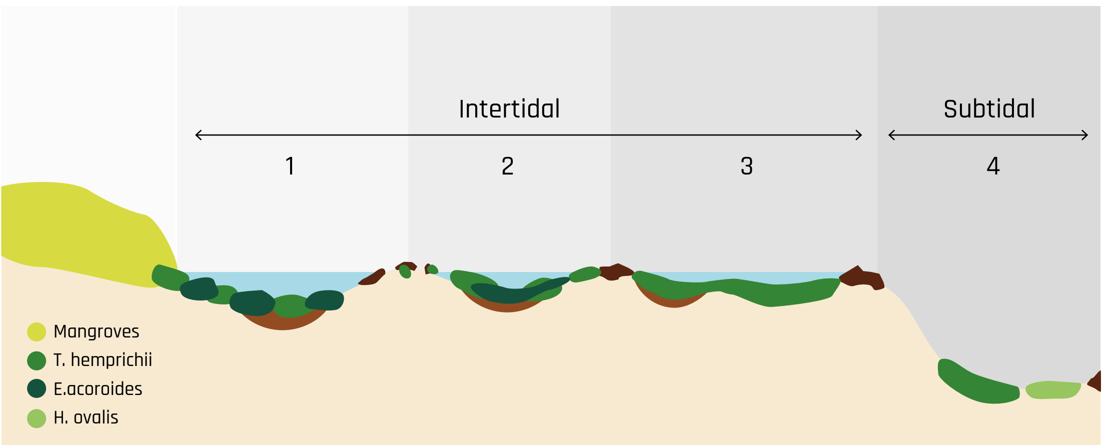
Benthic microalgae (BMA) were dominated by diatoms and their abundance and productivity did not vary according to any obvious seasonal pattern — indeed, substantial short-term variations (days) in productivity were observed, suggesting that BMA respond to local conditions which in turn are influenced by the tide and day-to-day variations in light. BMA were net producers at some sites, but were also net respirers at other sites.

A productive (fast growing) bacterial community was recorded from benthic and pelagic habitats, indicating a potentially important role by microbial cycling of dissolved nutrients in these systems. The research found variable but generally high bacterial carbon production rates that were within or above the range previously reported from tropical coastal ecosystems as well as high bacterial carbon utilisation rates, particularly of carbohydrates, amino acids and polymers. There is potentially high connectivity between benthic and pelagic habitats via the flow of Dissolved Organic Carbon (DOC) from benthic to pelagic communities.

Consumption of *T. hemprichii* was generally higher than of *E. acoroides* and at times was among the highest recorded in the world. At some sites, consumption of *T. hemprichii* appeared to be greater than production. These differences in consumption rates contrast with the relatively similar rates of productivity of the two seagrasses, implying that they might play different ecological roles. Spatial and temporal variation was high for both species, and no obvious seasonal patterns were evident.

Management Implications

- Places that support high biomass and diversity of marine plants are likely to be spatially restricted. However, because of their importance to the broader ecosystem through the ecological functions and services they provide, these places might warrant higher protection. A systematic approach to identify sites with high biomass and diversity combining multiple sources of information (e.g. existing environmental data, predictive model outputs, and herbivore density) is recommended to inform spatial planning and monitoring programs.
- The high ecological and social importance of marine plants like seagrasses and macroalgae in the Kimberley region means that they should be recognised as high-value conservation assets. Areas of high seagrasses and/or macroalgae production should be identified and these communities monitored accordingly.
- The development of standardised methods to monitor seagrasses is likely to aid regional understanding of these important marine plants. Suitable monitoring methods for large-leaved seagrass forms (e.g. *Thalassia* and *Enhalus*) have been provided, however these methods require some modification for small-leaved and ephemeral species. Some adaptation is also needed to make them suitable for application by Indigenous ranger groups for Healthy Country monitoring that is consistent with monitoring in marine protected areas.
- Strong seasonal patterns in biomass or shoot density were not detected for either of the main species of seagrasses (i.e. *Thalassia* and *Enhalus*), but patterns were irregular through time, suggesting that monitoring will need to understand and take into account patterns of considerable natural variation.
- It is likely that the highest growth of *Sargassum* in the Kimberley occurs during the wet season, though this prediction should be verified. While monitoring during the wet season would be recommended to capture maximum productivity, it is more important that monitoring be seasonally consistent to account for this variance.
- Making sense of measurements of seagrasses and macroalgae is difficult without corresponding environmental data. A network of coastal temperature sensors installed at monitoring sites throughout areas of the Kimberley where ecologically significant primary producer habitats exist would provide data for this purpose and would inform other physical and ecological processes (e.g. water temperature has broad relevance).
- Microalgae and sediment-dwelling microbes are vital components of the ecosystem, but tend to be highly variable. As a result, they do not lend themselves to regular ecological monitoring. Nevertheless, occasional measurements can reveal whether the mudflats are net autotrophic.



Schematic drawing of a cross section of the intertidal and subtidal zones in the Kimberley depicting the main primary producers (mangrove and seagrass).

Future Focus

A number of knowledge gaps remain regarding the natural dynamics of in the Kimberley. Priorities for future research should include improving our understanding of spatial and temporal patterns of reproduction by seagrasses and macroalgae as well as the environmental thresholds and determinants of abundance that might affect primary producers exposed to climate change.

Research should also be extended to deeper water habitats where there has been some indication of strong seasonality in both growth and reproduction.

Finally, there is a key need to improve our understanding of the role benthic microalgae play in the broader ecosystem.

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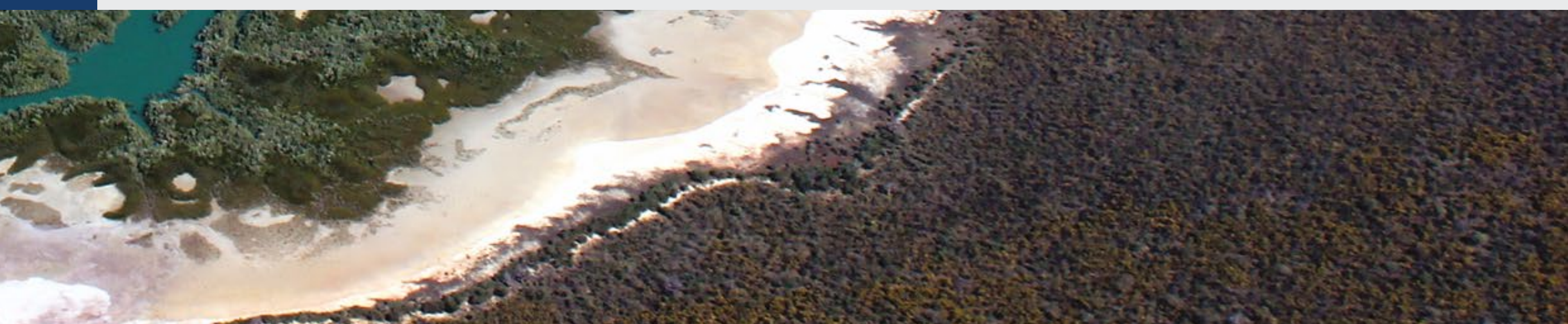
This information can be applied to studies on connectivity and fish and coral recruitment to improve our understanding of these ecological processes.

New Knowledge and Tools

- Numerical models of hydrodynamics, nutrient flow and terrestrial inputs into the coastal environment for the Kimberley
- Conceptual model of nutrient pathways in the marine system



Physical Characterisation – Flow of Energy Through the System

While a broad scale understanding of ocean dynamics in the Indian Ocean has been developing through research on the Indonesian Throughflow, circulation within the region was not well defined.

It is recognised that the Kimberley region is a tidally driven system, however there has been insufficient oceanographic and fine resolution bathymetry information to understand and predict the physical processes that support and drive the ecology and biodiversity for the Kimberley region.

Research was needed to develop our understanding of the ocean-atmosphere system along with continental shelf and near shore circulation patterns and processes. This information could then be integrated with an improved understanding of the sources of energy that flow through the system from both pelagic and terrestrial sources to better understand the processes that support coastal biodiversity.

This characterisation and baseline understanding of the physical processes and drivers of the Kimberley region will also improve our understanding of the potential responses to climate change, both in the physical processes and environmental parameters as well as their consequent influence on the ecology and ecosystem processes.

The projects in this section focussed on the physical characterisation of the Kimberley marine ecosystems to address key questions identified in the KMRP Science Plan.

Key management questions

- How are large-scale oceanic processes related to local physical and biological oceanography?
- How do large tides and fresh water input influence inshore and estuarine ecosystems?
- How significant is pelagic primary productivity to the maintenance of Kimberley ecosystems?
- What is the relative significance of terrestrially-derived nutrients in sustaining inshore marine food webs and how is this influenced by seasonal and cyclonic riverine discharge?
- Are there large spatial (e.g. inshore-offshore) and temporal (e.g. tidal, seasonal, inter-annual) variations in productivity in the Kimberley region and what physical processes 'drive' this variation?
- How might we best measure changes in physical and biological oceanography, particularly in relation to climate change?
- How will climate change impact on catchment to ocean interactions, in particular on key physical processes?
- What are good potential indicators of climate change that should be followed to understand the potential impacts to bio-physical asset condition?

Using models to understand the environment and ecosystem function in the face of change

Models are an abstraction of a real-world system and are used to reconcile theory with observation in order to improve understanding of how systems function. They can take the form of a conceptual model that describes a system, statistical models that help interpret long-term data sets, or mechanistic models that mathematically represent real-world processes.

While models can make sense of large amounts of data and are an important management tool for examining complex systems, confidence in such models relies on validation that demonstrates how well and accurately they describe the system in question.

A goal of the KMRP was to collate existing data for the Kimberley and combine this knowledge with results of the current projects to formulate an improved understanding of how the broader Kimberley ecosystem functions at local, (e.g. the hydrodynamics around a reef system) or broader scales (e.g. water exchange across a bay and into the pelagic system). Similarly, the systems in question can include terrestrial (e.g. the flow of nutrients from the land into the marine environment) or marine (e.g. marine food webs and nutrient exchange) as well as social elements (e.g. management strategies).

The KMRP projects have developed conceptual models across a variety of topics to build understanding of different aspects of the system and have worked towards validating these models to make them available to help understand the system, its function and how management may influence potential future scenarios.

The collection of projects characterising the physical processes and flow of energy through the marine environment have shared data and model platforms to capture the flow of energy throughout the system from the ocean to the coast and including rivers, estuaries and terrestrial as well as pelagic inputs.

Physical Oceanographic Dynamics in the Kimberley

The Kimberley region is a macrotidal environment with spring tidal movements of up to 12 metres which drive strong horizontal currents over rough substrates in shallow water and around the complex coastal and island structures of the region.

Overview

Effectively managing a marine ecosystem requires detailed knowledge of the physical oceanographic dynamics including tides, currents and circulation, mixing, temperature, salinity and density fields and the influence of bathymetry. These factors may also combine to create complex patterns of flushing and water exchange between the open ocean and bays and reef systems.

The Kimberley region is a macrotidal environment that creates very strong horizontal currents in shallow coastal waters. In moving over the hydraulically rough seabed, these tidal flows can generate very strong turbulent mixing that can be further influenced by prevailing winds and episodic events like tropical cyclones in the austral summer months. These flows interact with the complex coastline of headlands and bays, offshore island and reef systems, to define the physical oceanography of the Kimberley. Characterising the physical environment on a localised and regional scale provides essential knowledge to understand the biological processes in the region.

This project has quantified the physical oceanographic dynamics of the coastal Kimberley region by undertaking field studies and developing a field-validated three-dimensional hydrodynamic model extending from the coast to the shelf waters.

These integrated approaches enable a detailed understanding of the dominant tidally-driven dynamics in the region including the transport pathways, exchange rates and flushing processes, and provide insight into the role of the catchment versus the open ocean in coastal ecosystem dynamics.

In addition to the regional perspective, this project quantifies the flow fields over intertidal reef platforms and provides physical insight into how the very productive reef ecosystems living within the intertidal zone of reefs in the Kimberley, and high above the offshore low tide elevation, can remain submerged (and hence survive) over a full tidal cycle.

Approach

The Collier Bay/Camden Sound region was chosen as representative of the western Kimberley area that experiences the most extreme tidal range in the Kimberley.

The field program involved two components, firstly the deployment and maintenance of three oceanographic moorings in Collier Bay/Camden Sound over an annual cycle at the inner, mid and outer shelf regions. The second component was two ten-day process-oriented research cruises, one in the dry season and one in the wet season, conducted to provide high-resolution spatial and temporal observations of key physical processes in the contrasting seasons.

A Regional Ocean Modelling Systems (ROMS) three-dimensional hydrodynamic model for the Camden Sound/Collier Bay region was developed and validated using the field observations, in particular using the moorings placed at the three shelf regions.

Kimberley region oceanographic dynamics.

Key Findings

Tidal movement is the dominant oceanographic influence on coastal Kimberley waters with wind-forcing and baroclinic forcing, due to density differences between fresh water input from the coast and offshore ocean waters.

The strong tidal forcing and associated turbulence generated by tidally-forced flows moving over rough seabeds ensures the water column is vertically mixed over the entire annual cycle in water depths up to approximately 50 metres.

Macrotidal forcing, with tidal amplitudes up to 12 metres, and the complex topography/bathymetry formed by islands and reefs, dominantly influence horizontal circulation with depth-averaged instantaneous currents at some locations attaining three metres per second.

Despite the presence of large instantaneous currents, tidal currents averaged over a full tidal period are better predictors of net circulation.

Due to flow restrictions caused by reef and island channels, highly energetic jets can be locally generated at each tidal cycle, which reverse direction every tidal cycle and pump water masses and suspended matter both in and out of the coastal region.

The asymmetry of this tidal pumping is the underlying mechanism that drives the complex net or residual circulations. The spatial pattern of this residual circulation strongly reflects the underlying topography/bathymetry.

Residual depth-averaged velocities can reach as high as one metre per second, particularly over shallow reefs and in narrow channels, but bay-scale residual currents are typically of the order of one centimetre per second.

While the residual circulation is highly spatially variable, the numerical model shows that in Camden Sound/Collier Bay the residual currents form a slow anti-clockwise residual circulation with oceanic water entering from the west and exiting towards the northeast.

This tidally-dominated complex residual circulation drives flushing and the mechanisms and exchange times vary across Camden Sound/Collier Bay.

The dry season takes up most of the annual cycle, given the relatively short wet season, and the mechanism of flushing is the entry of open ocean water entering and diluting the coastal waters.

The flushing times vary strongly across the bay from less than 20 days on the western side, 60-80 days in the central region and up to 120-140 days in the eastern side and the small coastal estuaries. Hence, while the bay has an overall average flushing time of 60-80 days, there is a near seven-fold variation in flushing times at particular locations.

During the wet season some regions receive fresh water input from the catchment, reducing local flushing times by up to 50 per cent, but this is strongly dependent on the location and the duration and intensity of the inflows from the catchment which are a consequence of periodic rainfall events.

Management implications

- This new knowledge of oceanographic processes in the west Kimberley region provides a better understanding of some ecological processes, such as dispersion, connectivity and nutrient/energy flows, that are important to the long-term management of key ecological values in the Kimberley marine reserves.
- This knowledge can be used to assess the potential impact of oil and pollutants that may be released into the system at surface or over depth.
- The model can also be used as a tool for long-term forecasting of response to climate change scenarios, such as sensitivity to changes in offshore ocean properties and/or rainfall in the Kimberley catchment. This may inform Environmental Impact Assessment processes for future development.

Future Focus

The project has focused on the Camden Sound/Collier Bay region, which has the highest tidal amplitude of the Kimberley. It would be informative to extend the model to include the entire Kimberley coastline.

Increasing the overall scale of the model, while retaining the fine resolutions needed to understand processes, would require high-quality bathymetric information, (i.e. channel and reef characteristics are needed in shallow waters less than 50 metres depth) to describe this extended domain, and long-term simultaneous moorings in multiple locations along the coast.

The long-term moorings would also provide records of aperiodic intense tropical cyclones and thus provide a greater understanding of the short-term variability of the oceanographic processes of the region during the wet season.

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Biogeochemical Processes in Kimberley Coastal Waters: Pathways to Production

The biodiversity of the Kimberley coast is fuelled by oceanic and terrestrially derived nutrients which vary spatially and temporally across the region. The coastal waters have a uniquely adapted pelagic microbial community that has adjusted to the highly variable environment.

Overview

Understanding the processes that determine biological productivity is important to ensure effective management of coastal waters, especially when considering future changes in climate and land use.

The biological productivity of the Kimberley coast is most likely driven by oceanic and terrestrially derived nutrients, but little is known about how these nutrient sources vary or interact in these often-turbid inshore waters.

Understanding how nutrients vary spatially and temporally and how they are used and recycled across the region is essential for management of the marine resources in the region.

Specifically, it is important to link physical processes and riverine inputs of carbon and nutrients to food web structure and function to improve understanding of pathways and material flows that connect habitats, populations and bioregions in the Kimberley.

Identification of the sources of nutrients and how they translate to productivity for consumers, can generate an improved understanding of how such processes may be modified by a changing climate or changing land use patterns.

This project defined variation in nutrients, light and microbial communities of the Kimberley coast, delivered an understanding of the limiting factors on productivity and trophic pathways and developed numerical models that integrate this knowledge into process understanding.

Approach

The research results were achieved through field cruises, experiments and modelling activities.

Two research voyages were undertaken in Collier Bay in October 2013 and March 2014 to gather information on dry and wet season environmental conditions. Data from a previous voyage in 2010 that measured conditions across the continental shelf were also analysed.

Data collection during the cruises included profiles of physical attributes, nutrient concentrations, light, chlorophyll-*a* and samples of the pelagic planktonic community. Samples were processed in the laboratory to assess cellular response to light intensity.

Secondary productivity was computed using novel enzyme-based methods and used to quantify rates of grazing, respiration and biomass accumulation of the zooplankton community. Three zooplankton size classes were compared to highlight the trophic transfer of carbon and nitrogen through the food web, and this was further supported through stable isotope assessment.

To complement the data collection, a shelf-scale hydrodynamic-biogeochemical model was developed to investigate the influence of oceanic and terrestrial nutrients.

Model simulations highlighted the importance of tidally-driven upwelling and vertical mixing to regional productivity across the Kimberley shelf.

The combined biological dataset and information from the regional model was used to develop an improved framework for a high-resolution hydrodynamic-biogeochemical model able to simulate drivers of productivity in Collier Bay, as an example of the broader Kimberley region and allowing linkages between physical and biological processes in the region to be investigated.

Key Findings

This study identified key rates of primary and secondary production for the region, allowing the Kimberley ecosystem and its dynamics to be put in context alongside other Australian and international coastal systems.

While there are some unique differences between other coastal systems, the average levels of nutrients and productivity are comparable to those recorded across northern waters of Australia, including the Great Barrier Reef.

In particular, the findings show there is a uniquely adapted pelagic microbial community in coastal embayments that can exist in the highly variable Kimberley environment associated with strong spatial gradients in light and seasonal variation in nutrient delivery.

Microbial phytoplankton productivity is highest near the coast where light conditions are typically very poor rather than in clearer oceanic water further offshore.

Experiments that measured how phytoplankton responds to varying light intensity revealed that the phytoplankton living in turbid nearshore waters can withstand unusually high light intensities. It's thought that this growth strategy allows them to grow rapidly during frequent excursions to the brightly lit surface as a result of strong tidal stirring.

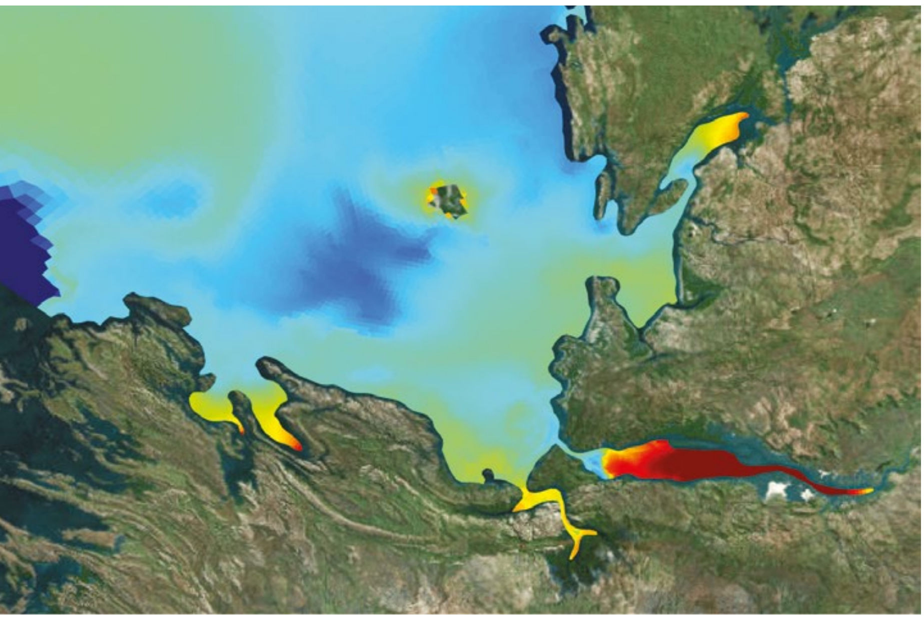
Results from the numerical modelling suggest that switches from light to nitrogen limitation controls primary productivity and this differs in the wet and dry seasons, and between different phytoplankton groups.

Scenario modelling predicts that while 20 per cent of nitrogen input from ocean boundaries can be attributed to ocean upwelling, this translates to only a five per cent increase in primary productivity in the nearshore zone, with implications for the sensitivity of the marine parks to changes in terrestrial nutrient supply.

The biomass and growth rate of zooplankton, which mostly feed on phytoplankton, was found to be two to four times higher than on the east coast of tropical Australia despite broadly similar temperatures and nutrient regimes. This suggests that zooplankton in the Kimberley region are efficient consumers and provide a strong link between phytoplankton and higher trophic levels such as fish.

Tides play an important role in nutrient supply. At the shelf-edge, evidence suggests that tides generate strong vertical circulation that brings deep-water nutrients to the surface and stimulates biological productivity. Further inshore, tidally-driven vertical mixing distributes nutrients evenly in the water column and can stimulate phytoplankton growth near the surface.

Strong spatial gradients in coastal plankton productivity have been identified with distance from river inlets. The gradients are associated with a transition from light to nutrient limited growth, and vary strongly with river flow.



Model predictions of primary productivity from the AED2 model (with red colours indicating higher levels of primary productivity).

Management Implications

This study provides the first detailed baseline information on nutrient dynamics and plankton productivity in Kimberley coastal waters and has established the main processes that determine plankton productivity across the region. It has also shown that the microbial plankton community is highly specialised, making it both unique and potentially vulnerable to change.

This information could be used in planning and management of marine protected areas in the Kimberley. The light data, for example, may be used to assist planning decisions for areas that are set for protection since, in areas where the amount of light reaching the benthos is less than one per cent of the surface light, there is limited potential for benthic vegetation and more diverse communities.

Furthermore, the detailed understanding of ecosystem processes developed here have provided critical input into a coupled hydrodynamic-biogeochemical model, which can also be used going forward to assess scenarios that can inform adaptive management processes designed to minimise negative impacts from climate change, tourism, recreational and commercial fisheries, pearling and aquaculture.

Productivity may change in response to variations in ocean conditions brought about by climate change and changes in land use and subsequent river inputs of nutrients and sediment.

The foundational biophysical datasets on pelagic primary productivity, community metabolism, community and food web structure can provide baseline support for the development, design and delivery of a program to monitor the long-term health of this ecosystem.

Future Focus

These findings suggest that productivity in this region could be impacted by increased nutrient influx despite the high rates of tidal flushing. However, the magnitude of such change required to create problematic conditions such as algal blooms or low oxygen is unclear.

Further research on the extent to which land management practices, increasing tourism and current development proposals in the Kimberley would increase nutrient export to the coast is therefore recommended.

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Terrestrial-Ocean Linkages: The Role of Rivers and Estuaries in Sustaining Marine Productivity in the Kimberley

Rivers and estuaries are a significant source of nutrients in the Kimberley marine environment and waterways are critical biogeochemical hotspots that link terrestrial ecosystems to the coastal ocean. Estuarine processes determine the net export of sediment and nutrients to coastal regions.

Overview

River mouths and estuaries can be highly productive habitats that support biodiversity and important species for commercial, recreational, and traditional fishing.

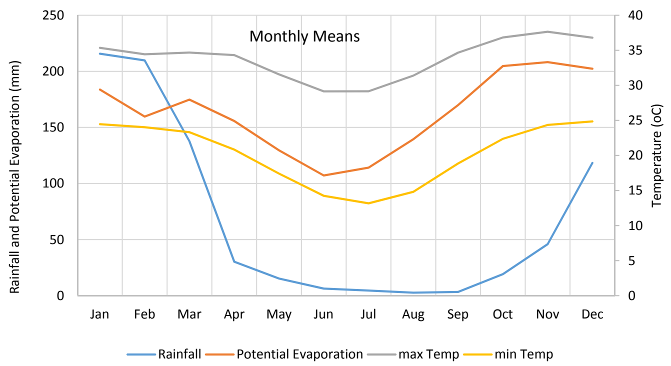
Productivity in the inshore environment is sensitive to terrestrial runoff that generates turbidity, deposits sediments, and subsidises marine carbon and nutrient pools.

Significant freshwater (30,000 GL/y) and associated carbon (C) and nutrients are delivered to Kimberley coastal marine environments in Western Australia during the relatively short period of the summer monsoon season. This means inshore and estuarine environments are strongly influenced by river flows, exhibiting strong seasonality and high inter-annual variability.

While the western Kimberley is among the most pristine marine environments in Australia, abundant water and energy resources will likely be developed in the near future that may influence river, estuarine and inshore environments.

Characterising the interaction between largely undeveloped catchments and the coastal environment and determining the role large coastal inlets play in transforming material transported from those catchments during large flows before it reaches the coast is essential to understand the terrestrial inputs into the marine environment of the Kimberley.

This then allows an understanding of how future development scenarios and changes in climate might impact these processes.



Mean monthly rainfall, temperature and potential evaporation across the Kimberley during the years 1961 to 2014. The data are averages across the entire Kimberley.

Approach

Catchment-based modelling tools have been developed that estimate freshwater discharge and the delivery of carbon and nutrients to inshore coastal environments at Walcott Inlet, which flows into Collier Bay.

Wet and dry season observations of stratification, currents and biogeochemistry were gathered to evaluate the performance of the modelling tools.

As limited water quality data exists for streams and rivers flowing into Walcott Inlet, modelled flows and loads to the inlet were generated for the estuarine modelling.

Simulations of stream flows under projections of future climate were also completed based on global climate models (GCMs) and were run under several future emission scenarios.

Circulation of the estuary/ bay system was explored using ROMS simulations.

Salt (a tracer) was used to trace the cross-shore exchange of water within the system, identifying the important patterns of exchange flows with the open ocean.

A high resolution coupled hydrodynamic-biogeochemical model was also established to focus on interactions in the coastal margin and estuarine portion.

Importantly, this model was configured to simulate turbidity (including particle resuspension), inorganic and organic carbon and nutrients. It was validated and then used to assess how far terrestrial nutrients might extend from the river into Walcott Inlet and possibly Collier Bay.

Key Findings

This project found that Kimberley catchment responses were dominated by the seasonality of rainfall and the inter-annual climate variability. It also found that there could be large differences in material export due to different catchment types across the region.

Walcott Inlet appears to be a carbon-poor environment, where labile carbon from algae is rapidly re-mineralised by bacteria.

There is evidence that large amounts of more recalcitrant terrestrial material may be transported into the inlet during high flow events, but there is little evidence that this becomes incorporated into sediments, suggesting it is most likely transported directly through the inlet.

Limited water quality data for streams and rivers flowing into Walcott Inlet hampered the capacity to relate flow to the input of material.

Primary productivity in the nearshore environment around Walcott Inlet is light limited due to high turbidity but this changes to nitrogen limitation once outside the inlet with the distance from the inlet to where this transition occurs dependent on flow out of and ultimately into Walcott Inlet.

Future climate scenarios suggest no major changes in mean rainfall or flows between the three possible future climates and the historical sequence.

The projections for all future climates, even the driest one, are for an increase in mean annual rainfall and flow.

However, the projections are also for a greater inter-annual variability, so that while the average flows may increase, there will be a greater difference between wet and dry years and low flow years will be more severe.

Furthermore, the modelling of different climate scenarios demonstrates that near-shore primary productivity is sensitive to changes in catchment hydrology.

ROMS simulations of circulation of the estuary/bay system demonstrates that the complex bathymetry of the coastal region had a large impact on the interaction between tides and freshwater inflow.

Results from the physical-biogeochemical interactions model indicated that flows greater than 300m^3/s dominated nutrient loads within Walcott Inlet itself and significantly contributed to the inner reaches of Collier Bay.

Management Implications

The detailed understanding of the nature of the bay and estuarine hydrodynamics provides an important foundation for the more complex assessment of carbon and nutrient fate and transport that will further our understanding of the importance of terrestrially-derived nutrients versus oceanic nutrients in sustaining inshore marine food webs.

If catchment derived nutrients are a significant contribution to nearshore coastal environments, then any changes in catchment use or flow restrictions could impact on delivery of this material.

Therefore, management of catchments and/or rivers should consider the system as a whole, with an understanding of the origins of the material being delivered into the environment.

These findings can be used to inform future development scenarios and how changes in climate might impact coastal processes.

Future Focus

While this project has provided the first real insight into the terrestrial material entering the Kimberley coastal environment, key questions around the role this material might play in the food web, to better understand ecosystem level impacts, are yet to be answered.

Also, development of extended spatial datasets on water quality of streams flowing into the estuaries, including dissolved organic nitrogen, would significantly improve the model outputs.

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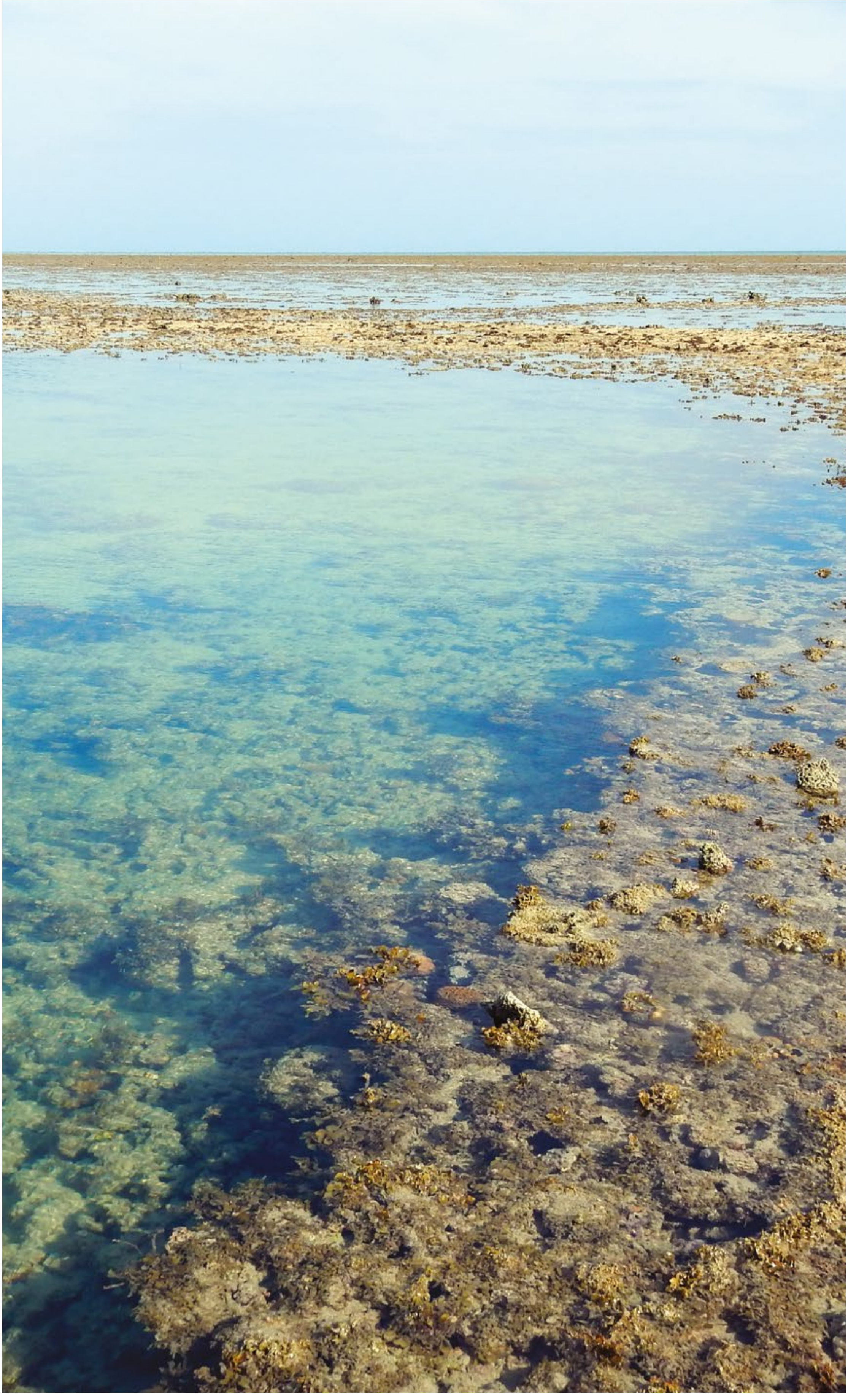


Rollolith habitat on the southern Adele Reef consisting of both coralline algae (rodoliths) and corals (coraliths). [Geomorphology]

Combining the information on populations and patterns of distribution with the new knowledge on ecological processes and habitats across the program has resulted in a better understanding of how these species may respond to future changes.

New Knowledge and Tools

- Updated abundance estimates for snubfin dolphins, dugong, crocodiles and shorebirds at key sites or across the Kimberley.
- Maps of spatial and temporal use patterns and high-density areas for humpback whales, snubfin and humpback dolphins, dugong, crocodiles and nesting turtles across the Kimberley.
- Protocols and survey design for turtles, whales, dolphins, dugong, crocodiles and shorebirds as part of cost-effective monitoring programs.
- Participation and training provided to Indigenous and marine rangers in survey techniques for turtles, dolphins, crocodiles and dugong.

Biological Characterisation: Understanding Populations of Key Megafauna Species

Large marine fauna are an iconic group of species that is valued by a wide range of stakeholders for their biodiversity, contribution to marine tourism and education, cultural significance and as a traditional food source.

Megafauna species in the Kimberley include; humpback whales, coastal dolphins, dugong, marine turtles, crocodiles and shorebirds. A number of these are either listed as threatened, are specially protected under state or federal legislation, or are subject to international agreements relating to conservation.

These species are recognised as key ecological values in marine protected area and healthy country management plans, however they often have wide ranging populations that commonly extend beyond administrative borders such as protected areas and state jurisdictions.

To achieve visible, tangible and significant conservation benefits for the rich and unique megafauna of the Kimberley there needs to be an understanding of how each species uses the region. This information can then be used to determine whether patterns of use change over time in response to natural or anthropogenic pressures in addition to directing management mechanisms to protecting life history traits at risk of disturbance.

Knowledge of relative abundance, distribution, movement patterns (travelling, resting, etc.) and critical habitat, along with the environmental context of these patterns is fundamental to develop appropriate management strategies at both single species and ecosystem scales.

The KMRP research has provided answers to a range of management questions that apply across these species by providing a better understanding of species abundance, distribution and important areas within the Kimberley, as well as appropriate spatial scales for management.

Developing appropriate and cost-effective monitoring techniques and indicators for these species and the pressures upon them has also been a priority.

Key management questions addressed by KMRP megafauna projects

1. What are the distribution, abundance and movement patterns of megafauna populations?
2. What, when and where are their critical habitats?
3. How will they likely respond to climate change?
4. On what scales are these species connected both within and outside the Kimberley (e.g. appropriate spatial management units)?
5. What are the major pressures on megafauna in this region, and how can they be measured using key indicators over the long term (e.g. marine debris)?
6. What role can marine fauna play in identifying areas of high productivity (e.g. tracking key species to hotspots)?
7. What cost-effective methods can be developed to monitor species/population condition?

Marine Turtles: Understanding and Managing Nesting Turtles Along the Kimberley Coast

Marine turtles show unique patterns of biological, genetic and developmental change across the Kimberley region. New scientific information about turtle nesting has been linked to traditional knowledge, resulting in a more informed set of management insights and priorities.

Overview

Marine turtles are ecologically and culturally important. This iconic species is not only an Indigenous cultural symbol and resource, it captures the broader community interest in nature and conservation.

Marine turtles are increasingly impacted by anthropogenic pressures including changes in climate, marine debris, coastal development and disturbance to nesting sites.

The KMRP has developed an important understanding of critical habitat for these species across the Kimberley, including when and how they are used and developed methods to monitor population health over time.

The Kimberley coast and inshore marine waters supports foraging habitat and nesting beaches for five species of marine turtles: Loggerhead turtle (*Caretta caretta*); Flatback turtle (*Natator depressus*); Green turtle (*Chelonia mydas*); Olive ridley turtle (*Lepidochelys olivacea*); and Hawksbill turtle (*Eretmochelys imbricata*).

Existing regional information on the distribution and relative abundance of nesting was collated, which highlighted gaps in knowledge about the importance and extent of nesting across the Kimberley, as well as connectivity between nesting sites.

The most pervasive pressure facing turtles in the Kimberley is climate change, as increased temperatures can skew sex ratios to predominately female, increase embryo mortality and potentially shift the distribution of nesting.

These major knowledge gaps have been addressed through the objectives of this project which were:

i. to map the spatial and temporal distribution of turtle nesting across the Kimberley;

ii. to define nesting stocks of green and flatback turtles; and

iii. to develop understanding of the thermal biology of turtle nesting in the Kimberley and the potential implications of climate change.

A fourth overarching objective that guided the program was to ensure Indigenous involvement through engagement, planning, participation, training and knowledge sharing.

Traditional Owners (TO's) and sea rangers will play a key role in long-term monitoring and management.

Approach

This project brought together teams of scientists with Traditional Owner groups and marine park managers to develop and implement a strategy to meet the three objectives. Kimberley-wide aerial surveys of turtle tracks were conducted in January (summer) and August (winter) 2014 to capture both summer and winter turtle nesting sites. The aerial surveys were complemented by ground surveys for verification and to increase temporal coverage.

More than 44,000 geo-referenced aerial images were taken covering 91 per cent of the Kimberley islands and mainland beaches, including all known rookeries. The images were assessed for visual evidence of turtle tracks or body pits.

On-ground surveys were conducted in 37 accessible locations to verify species by visual inspection of track characteristics.

This single summer and winter season snapshot inventory quantified Kimberley turtle nesting at scales of 1-10s-100s-1000s of tracks.

Genetic samples of 388 flatback and 125 green turtles were systematically collected from a selection of rookeries across the west, north and east Kimberley, including offshore sites for green turtles, to clarify genetic population boundaries and appropriate management units. A genotype-by-sequencing approach was employed to characterise genetic diversity within and between these sampling sites.

A sample of eggs from summer and winter flatback and summer green turtle rookeries was collected and incubated in a laboratory across a range of temperatures (28-32°C) to delineate the temperature dependent sex determination (TSD) parameters that influence the sex of the hatchlings.

Development rates were also calculated for each rookery allowing for estimations of upper thermal limits through non-lethal incubation methods.

These parameters were coupled with environmental data to model sex-ratios and mortality at rookery beaches, and were validated with empirical observations using temperature loggers within natural nests.

Eleven Indigenous groups were involved through informal and formal approaches from informal talks with people on Country through to joint field work, presentation of maps while talking with rangers over a cup of tea about important turtle habitats recognised by deep collective knowledge, as well as formal presentations to council elders and Aboriginal Corporations.

Key findings

Turtle nesting tracks were noted on almost all silica sand beaches across the Kimberley, with fewer tracks recorded along coastal areas bordered by rocky cliffs or mangroves.

The most important rookeries ranked by track counts and density are Cape Domett, where flatback turtles nest during winter, the Lacepede Islands, where green turtles nest during the summer, and Wallal Downs-Eighty Mile Beach where flatbacks nest during the summer.

Aerial surveys were suitable to identify green and flatback rookeries but did not provide enough power to detect nesting by olive ridley or hawksbill turtles.

No leatherback or loggerhead turtle nesting tracks were observed, although both species are known to occur in the region.

Six regions were found to be genetically different from one another for flatback turtles based on rookeries sampled from the Pilbara, Eighty Mile Beach, Eco Beach, King Sound, northwest Kimberley and northeast Kimberley.

Most green turtle samples were weakly genetically distinct from each other, indicating that interchange of adult females between rookeries is infrequent.

In contrast to earlier work, green turtles nesting at the southwestern extremity of their Australian range (Barrow Island and North West Cape) were significantly genetically distinct from those at the Lacepede Islands and could be considered a distinct stock from those further north.

Restricted movement followed an “isolation by distance” pattern, where sites furthest apart exchanged the fewest migrants.

Management Implications

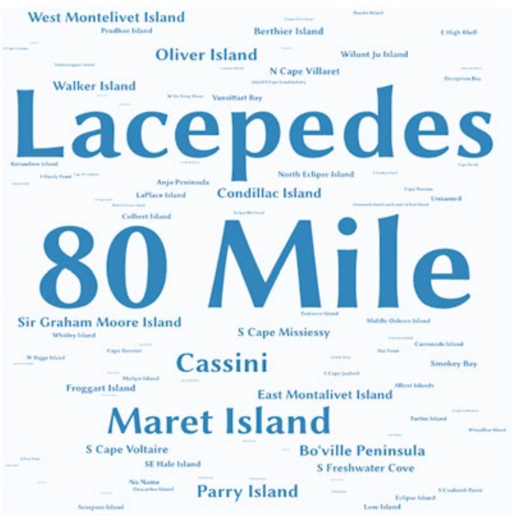
Turtle nesting locations of high management value recommended for regular monitoring include:

- summer nesting green turtles at the Lacepede Islands;
- summer nesting flatback turtles at Eighty Mile Beach; and
- winter nesting flatback turtles at Cape Domett.

While the latter two rookeries have been monitored annually since 2006, turtle nesting at the Lacepede islands has not been surveyed since 2002.

Given the high nesting density at the Lacepede Islands, important population information would be gained from an intensive (2-3 week) tagging survey or track count program.

- A geo-referenced map of all green and flatback turtle rookery beaches across the Kimberley including priority ranking has been prepared and provided to managers. This information is complementary to that held by Traditional Owners about important turtle areas within their local and Indigenous protected areas.
- Six management units, or stocks, of flatback turtles are represented in Western Australia based on a combination of previous and current analyses, adding two units (King Sound and northwest Kimberley) to the four already recognised (Pilbara, Eighty Mile Beach, EcoBeach and northeast Kimberley). Genetic exchange is limited between these stocks and each should be managed as a unit.
- Previously identified management units for green turtles have been supported by contemporary analyses and confirm that there is genetic exchange among green turtle rookeries along the Western Australian coast, but little exchange among offshore atolls, or between offshore and coastal rookeries, highlighting that these should be managed as separate units. The contemporary analyses found that there is enough separation between the Pilbara and Kimberley rookeries to manage them as separate units.
- Eleven Traditional Owner groups were engaged in field research across the three-year program and consulted on their traditional knowledge of marine turtles. A central aim of all field trips was knowledge exchange with rangers and TOs and delivery of hands-on training to build capacity for ongoing monitoring. The rangers shared cultural background about the coast and islands and relevant information from their previous experiences on Country.
- There are multiple methods of monitoring nesting beaches to determine trends in the population with pros and cons for each. At a minimum, an index nesting population requires nightly or daily track monitoring for a minimum of two weeks at midseason by either on-ground staff, drone surveys or camera trapping, although the actual methods used may depend upon nesting density and the remoteness of the location. The (DBCA) has developed a Standard Operating Procedures manual for nesting turtles which has been shared with Indigenous rangers across the Kimberley.



The Word Cloud font sizes reflect a numerical input for turtle track counts at island or mainland beaches of the Kimberley region. A large font size shows higher track counts; small font indicates lower track counts. Left image shows the high summer abundances of marine turtle at the Lacepede Islands and Eighty Mile with relatively few other secondary sites in smaller font size. Right image shows the high winter abundance of turtles at Cape Domett and a widespread nesting across many secondary sites.

How will nesting turtles in the Kimberley respond to increasing temperatures caused by global climate change?

An increase in ambient temperatures has the potential to adversely affect all life history stages of marine turtles, with the embryonic stage being the most vulnerable due to narrow physiological thresholds and their inability to avoid excess heat during incubation.

Incubation temperatures are important drivers of population demography. Marine turtles have a temperature-dependent mechanism of sex determination, where females are produced at warmer temperatures and males are produced at cooler temperatures.

As a consequence, increasing temperatures have been predicted to lead to rookery feminization and increased embryonic mortality. This is already being observed at many marine turtle rookeries within and outside of Australia.

Marine turtles in the Kimberley have the potential to respond through both spatial and temporal shifts in nesting.

The KMRP marine turtle project examined the thermal profile for green and flatback turtles. This included determining incubation conditions for sex determination and sex ratios in the laboratory and recording regional weather data using thermal data loggers at a number of key nesting sites along the Kimberley coast.

There was a marked variation in the temperatures of nesting beaches in the Kimberley, highlighting the need for populations to be managed at the individual rookery level.

These data were used to develop predictive numerical models to forecast future incubation conditions under changing climate conditions and the potential effects on sex ratios and mortality.

Current summer nesting flatback and green populations may shift nesting to earlier or later in the season to avoid lethal and sex-ratio skewing temperatures.

Winter nesting populations have a limited capacity to shift nesting season, and climate predictions suggest highly female-skewed sex-ratios and substantial mortality for these populations.

Management should seek to support ecological resilience at a regional scale by protecting a broad nesting distribution across all habitat types, latitudinal ranges and including mainland and island rookeries.

The future management focus should be on regular beach temperature monitoring and periodic measurements of hatchling sex ratios and hatching success of nests to further validate the predictive models developed in this project. The models can then be used to evaluate the impact of management actions and to identify the rookeries that are most likely to be key recruitment sites under warmer future climates.

Localised management for mitigating female-biased sex-ratios and high mortality at particular nesting beaches could include artificial shading of natural nests (via shade cloth or vegetation plantings), or relocation of egg clutches to cooler sites or beaches. Under extreme warming scenarios, these key sites could be much further south than the current nesting distribution.

Future Work

The timing of the aerial surveys did not provide information on nesting of hawksbill or olive ridley turtles, even though both are reported in the Kimberley. Future surveys should be spatially and temporally targeted to fill this knowledge gap.

Potential population threats that need better quantification for appropriate management include dingo predation of turtle eggs at mainland nesting beaches and the impacts on turtles from marine debris and Indigenous harvest.

In addition, the proportion of Kimberley stocks impacted by outside threats, such as illegal international harvest, should be quantified through genetics and surveys.

Finally, research is still needed to better understand connectivity between rookeries as well as between rookeries and foraging areas. Rookeries most at risk from anthropogenic and climate change pressures also need to be identified.

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The highest priority rookeries are based upon the summer (red) and winter (blue) highest density and highest abundance of track counts with the Kimberley marine turtle track distribution, plotted on a log-log scale. When plotted over the Kimberley ranger/Traditional Owner boundaries (black lines), it combines a local operational scale with the regional scale.

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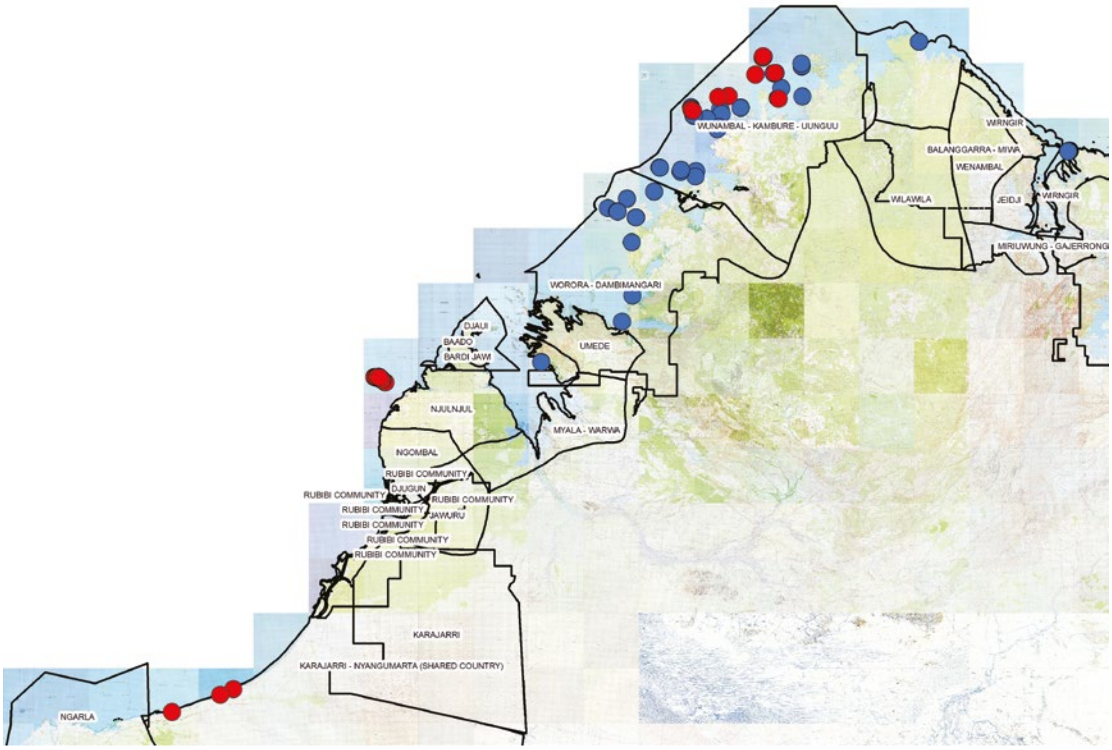

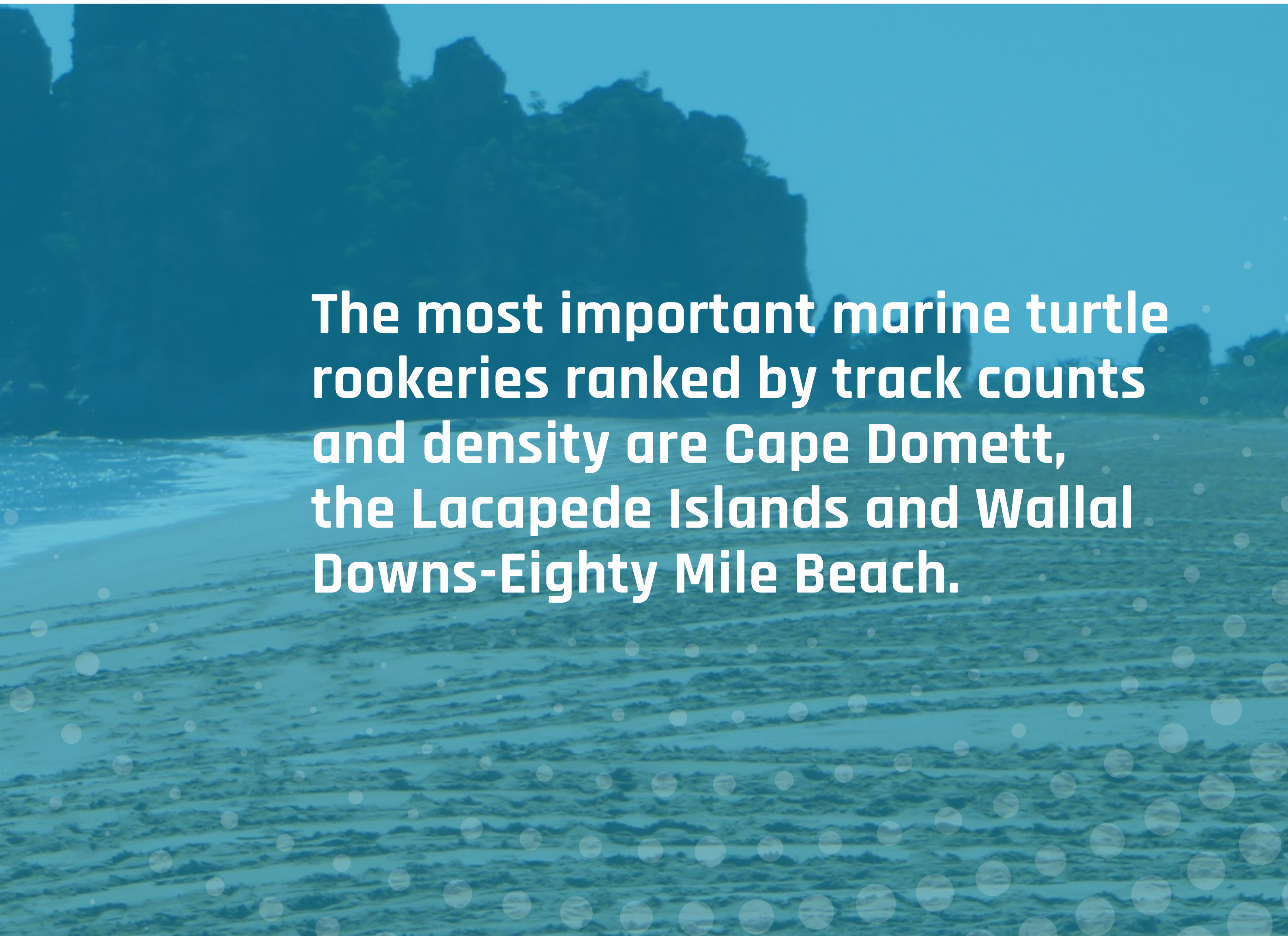

The most important marine turtle rookeries ranked by track counts and density are Cape Domett, the Lacapede Islands and Wallal Downs-Eighty Mile Beach.

Saltwater Crocodiles *(Crocodylus Porosus)* in the Northwest Kimberley

An estimate of the current abundance and size structure of saltwater crocodiles in the northwest Kimberley demonstrates their gradual recovery.

Overview

Saltwater crocodiles have been protected in Australia since 1969 after three previous decades of unregulated hunting drove numbers down to less than 8000 across the Kimberley and Northern Territory (NT).

While annual surveys since 1975 in the NT have documented a spectacular recovery of the population, there has not been a similar sustained effort to monitor crocodiles across their distribution in WA. Also, limited genetic information is available on crocodiles to determine connectivity between regions and assist to identify appropriate management units.

While saltwater crocodile population surveys were conducted annually in the Ord River of the east Kimberley between 1992 and 2012 as part of monitoring associated with egg harvesting in the region, no surveys have been undertaken in the west Kimberley (ie west of Cape Londonderry) since that led by Professor Harry Messel and colleagues in 1986, some 30 years ago. The Messel surveys concluded that the total adult crocodile population of the West Kimberley at that time was approximately 2,500.

It is critical for the management of crocodiles across the North West to determine the current status of this population, including demographics and range, and to develop a monitoring plan to document the recovery or otherwise of this population relative to saltwater crocodiles in the NT.

Approach

Night-time spotlight surveys were undertaken in late July and early August 2015 at the Prince Regent and Roe-Hunter rivers in the West Kimberley following the exact survey design established by Messel in 1986.

This consistency of methods enabled a direct comparison of data collected during the 1986 survey. These rivers were selected for the survey as they had been identified by Messel as the two major breeding rivers for crocodiles along the west Kimberley coast and have linear lengths greater than or equal to comparable NT rivers. In addition to direct counts, an estimation was made of the size of each animal to understand the population demographics. Tissue samples were also collected from 70 crocodiles (~35 in each river system) to contribute to a study of crocodile genetic structure across their range in Australia.

Key Findings

A total of 626 non-hatchling and 82 hatchling crocodiles were counted in the Prince Regent River system in 2015, compared to 242 non-hatchlings and 5 hatchlings counted in 1986.

In the Roe-Hunter River system, 545 non-hatchling and 131 hatchling crocodiles were observed, compared to 263 non-hatchlings and 10 hatchlings counted in 1986.

These counts indicate that the abundance of non-hatchling crocodiles in both river systems has increased by more than 200 per cent over the past 30 years.

A higher proportion of large crocodiles, greater than 1.8 metres in length, was also observed during 2015, suggesting that this crocodile population is maturing following the depletion of larger animals.

Similar changes in size-structure have been observed in recovering saltwater crocodile populations in the NT. However, both the density and biomass of crocodiles in the West Kimberley rivers were lower than comparable NT habitats.

The large discrepancy detected between relative biomass per river system is most likely due to the number of very large crocodiles, greater than three metres in length, in the NT whereas few animals of this size were observed in the Kimberley in 2015. This result suggests that west Kimberley populations may still be recovering towards a population structure similar to that observed in the NT.

While only three time points are available to represent population trends (1978, 1986 and 2015), crocodile abundance continues to increase in a linear pattern across both systems, suggesting that West Kimberley crocodile populations are still recovering compared to those in the NT.

West Kimberley and NT river systems differ in ways that may influence crocodile populations. NT rivers, for example, more commonly contain billabongs and savannah floodplains, which are critical nesting habitats for crocodiles, whereas the west Kimberley coast is defined by cliffs, boulder shores and high-sided ravines and may have much less suitable breeding habitat.

While Kimberley rivers might eventually hold similar densities of crocodiles to the NT, it is equally possible that the major geomorphological differences may limit population size and structure to a lower level than occurs in the NT. Nevertheless, with more-than 200 hatchlings observed across both Kimberley river systems in 2015, indications are they are successfully breeding and recruiting in these rivers.

Tissue samples collected in the Prince Regent and Roe Hunter rivers have provided evidence that these crocodiles are genetically distinct to those in the NT.

Management implications

- Saltwater crocodiles in two major West Kimberley river systems have recovered significantly since the 1980s.
- Comparisons with NT populations suggest that the crocodile population surveyed in this project will continue to recover with densities and standing biomass increasing towards a stable population structure in the future. Possible limitations on the availability of optimal nesting habitat may constrain population growth and the rate of recovery in the Kimberley compared to the NT.
- Monitoring protocols and survey design have been developed to assist ongoing management by DBCA and joint managers.
- The project developed an application for collecting and storing data while in the field that can then be uploaded to a centralised database and accessed via a web interface.
- Limited evidence indicates that crocodiles in the West Kimberley are genetically distinct from those in the NT. However, more sampling between these locations is required to better understand the population structure. The project has developed standard methods (including a biopsy pole) to collect genetic samples.

Future focus

Research on saltwater crocodiles should seek to improve knowledge of population connectivity across the Kimberley, reproduction in this region, and the factors influencing their movement southwards from the major river systems of the West Kimberley.

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Dambimangari Traditional Owner Gary Umbagai holds a hatchling crocodile caught so that a tissue sample could be taken as part of a genetics study on *C. porosus* population structure across Australia.

Integrating Indigenous Knowledge and Survey Techniques to Develop a Baseline for Dugong *(Dugong Dugon)* Management in the Kimberley

Establishing a regional baseline of distribution and abundance of dugong in the Kimberley through the integration of traditional and scientific knowledge provides an effective management tool for future conservation management of the species.

Overview

Dugongs are an important species in marine ecosystems and are of high cultural value to Indigenous coastal communities.

The coastal waters of northwest Australia, encompassing the Kimberley, Pilbara and Gascoyne regions southwards to Shark Bay, support one of the largest remaining dugong populations in the world.

Until recently there has been limited information available on dugong distribution, abundance and traditional ecological knowledge (TEK) in the Kimberley, representing significant knowledge gaps for management.

There have been few anthropogenic pressures on dugongs in the Kimberley, with the exception of cultural hunting, making the area an important global stronghold for the species, however more may arise with increasing development of the area and the emerging influences of climate change.

As such, knowledge of seasonal movement patterns and habitat use by dugongs in the Kimberley, including their long-distance dispersal patterns, are essential for the long-term management and conservation of this iconic species.

Approach

Distribution and relative abundance:
The first systematic baseline study of dugong distribution and abundance across the Kimberley comprised several standardised fixed-wing low-level aerial surveys of coastal waters out to the 20 metre depth contour.

Surveys were conducted between the NT border and Cape Leveque in September-October 2015 and from Broome to Port Hedland in May 2017. Data for the west coast of Dampier Peninsula were derived from a previous aerial survey in 2009. Continuous observer data were used to map abundance "hotspots" using kernel density extrapolation and smoothing methods.

Movement and Diving Behaviour:
Satellite tags were deployed to gain an understanding of movement and habitat use in a targeted area of the West Kimberley.Deployment of satellite tags enabled dugong movement and diving behaviour to be recorded from small local habitats up to scales encompassing the size of IPAs and marine parks.

Bayesian Approach:
A Bayesian approach to the probabilities of the likely occurrence of dugongs in the north Kimberley was completed using:

i. aerial survey data;
ii. a preliminary seagrass map derived from satellite imagery; and
iii. the intersection of cultural hunting areas.

This approach allowed for the integration of western science and TEK to best inform dugong management in the Kimberley.

Key Findings

Distribution and relative abundance:
The estimated number of dugongs in the Kimberley region is about 12,600, with an average density of one dugong for every four km² over 67,163 km² of coastal waters.

The abundance of dugongs in the survey area east of Cape Leveque to the NT border is approximately five-times that for the area from Cape Leveque to Port Hedland (10,513 $\pm$ 497 cf. 2,087 $\pm$ 197), most likely reflecting the absence of deep bays and shelter from storms along the Eighty Mile Beach coastline.

The highest densities of dugongs were found in areas with extensive seagrass habitat associated with sheltered areas of shallow (<20 m bathymetry) relatively clear water and were predominantly located within Wunambal Gaambera sea country encompassing the North Kimberley Marine Park.

Roebuck Bay was identified as an abundance hotspot for dugongs, with no significant change in density detected across an eight-year period. This suggests that current cultural harvests in the area have been sustainable over this timeframe.

A strong positive relationship was found between dugong abundance in the north Kimberley and the extent of likely seagrass mapped using Landsat imagery (R^2 = 94 per cent, n=7, P=0.002), suggesting that cultural harvests throughout are remarkably uniform or currently minor throughout that area.

Calf sightings were spread uniformly throughout the north Kimberley in areas that encompass coastline with many bays and islands. In contrast, few calves were observed between Roebuck Bay and Port Hedland, and those observed were close to Port Hedland.

No calves were observed in Eighty Mile Beach Marine Park.

Movement and Diving Behaviour:
The movement study (n = 5 tags) showed that dugongs in the Kimberley can move large distances over short periods of time, supporting previous knowledge of dugong movements.

An adult female travelled 325 km over 14 days (averaging 23.2 km per day) and was 75 km from her capture point when the tag apparently detached. Similarly, a young adult male travelled 1,160 km over 78 days (averaging 14.9 km per day) and was 85 km from his capture point when the tag likely detached.

Analysis of diving data (per cent time under water and number of dives) showed that dugongs have distinct diving modes for travelling and foraging.

Whilst results are limited by the small sample size and limited duration of data, they nevertheless strongly suggest that dugong management in the Kimberley is both a local and regional-scale issue that transcends existing jurisdictional boundaries (e.g. sea country & marine reserve boundaries), supporting all previous studies on dugong movements.

Management Implications

The following tools have been developed and provided to managers to assist in ongoing dugong conservation and management:

- GIS based dugong abundance “hotspot” maps and Bayesian likelihood maps that indicate critical habitat and areas of relatively high abundance (e.g. North Kimberley Marine Park, Roebuck Bay); and
- Region-scale baseline abundance estimate, survey data and monitoring protocols.

The above provide the necessary baseline information for both marine reserve and healthy country planning, assisting with questions related to: location of critical habitats in the Kimberley, determining appropriate spatial management units for dugongs; and identifying areas of overlap with the likely major pressures on dugongs in the region.

The methods, used to estimate population size, provide sufficient statistical power to track significant changes in abundance derived over the same area and sampling intensity, while

smaller areas would require greater sampling effort to detect change.

Bayesian likelihood maps of important dugong areas present an exciting opportunity for the integration of TEK with scientific techniques for the management of ecological and cultural values.

Cultural harvesting is recognised by Indigenous ranger groups as a local pressure on dugong populations in the Kimberley, particularly in areas subjected to other multiple cumulative impacts such as habitat degradation and climate change.

Although Roebuck Bay was identified as a regional abundance hotspot for dugongs, repeat surveys completed in 2009 and 2017 indicated that there has been no significant change in density suggesting existing cultural harvest practices have been sustainable in this area.

Future Focus

Whilst important for regional-scale planning purposes, broad-scale baseline surveys rarely provide the fine-scale temporal and spatial resolutions necessary to manage transient or resident dugongs at important locations (i.e. Roebuck Bay) that are subject to multiple anthropogenic pressures.

Future effort should look toward alternative cost-effective survey methods that can provide early warning for possible management adjustments in cultural take combined with proactive management of seagrass habitat by community, government and industry stakeholders.

This could include improving understanding of genetic connectivity between regional population concentrations through a program of opportunistic tissue sampling by Traditional Owners engaging in field surveys and cultural harvest.

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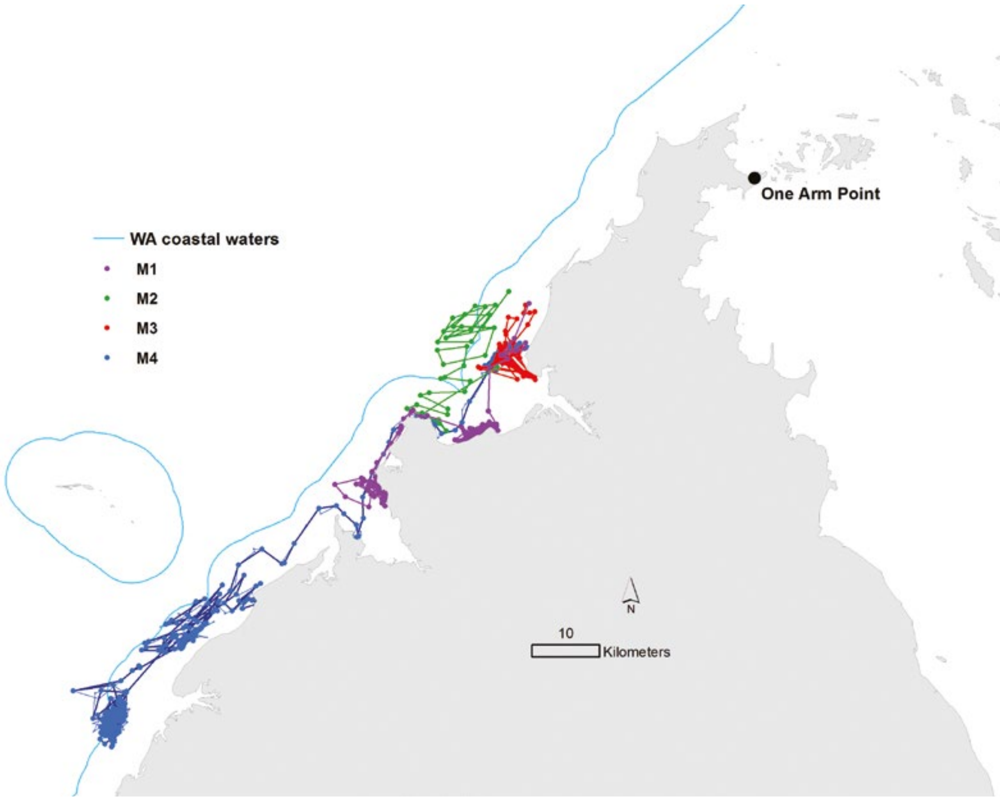


Trajectories of tagged dugongs over variable tracking intervals between August 2016 and February 2017. Young adult males (M1-M4) tagged north of Pender Bay on Dampier Peninsula (Bardi Jawi sea country) (after Bayliss and Hutton 2017).

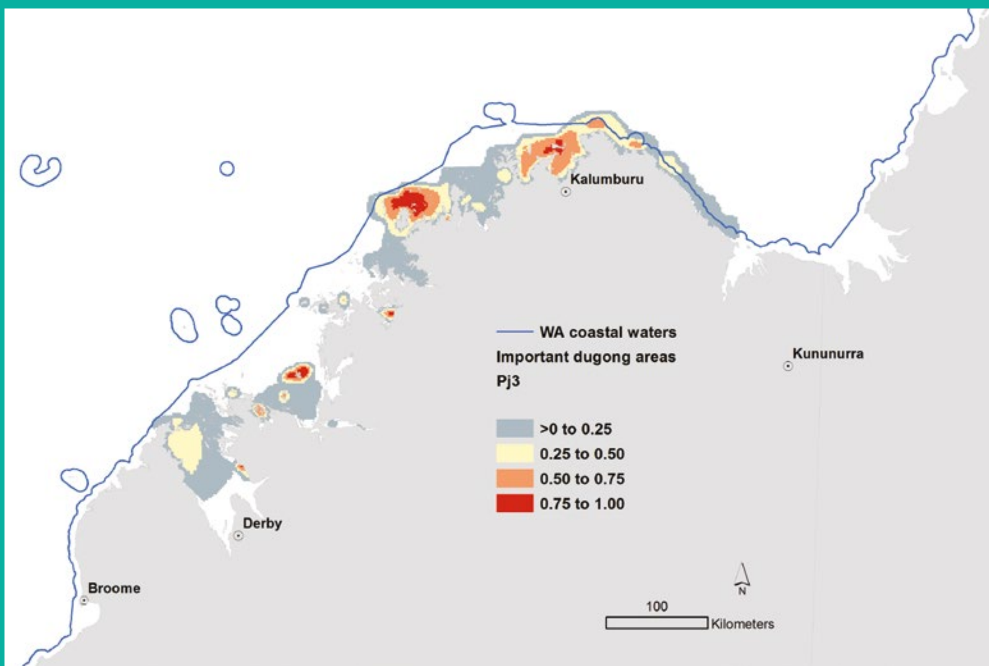
A strong positive relationship was found between dugong abundance in the north Kimberley and the extent of likely seagrass.

Integrating Indigenous and scientific knowledge of dugongs.

Indigenous people have cultural, linguistic and environmental knowledge about the marine-coastal domain in the Kimberley, which is intimately tied to traditional ownership and management protocols. Ongoing development and passing on of this knowledge are important objectives for all Indigenous groups.

Indigenous communities are themselves research and knowledge generators. The integration of Indigenous or traditional ecological knowledge (TEK) of dugongs with scientific survey data is important for the development of culturally appropriate and, hence, more effective monitoring and decision support tools for dugong management.

The Bayesian approach to mapping probabilities of dugong occurrence integrating all available spatial knowledge sources, particularly TEK, may be one of the most useful approaches to identifying important dugong areas given the inherent limitations associated with "one-off" scientific surveys.



Map of Bayesian probabilities of dugong occurrence across the 5km survey grid, combining Indigenous ecological knowledge (location of hunting sites) with the preliminary map of seagrass extent in 2014 only using the "likely" classification and the 2015 aerial survey data (after Bayliss et al. 2016).

Modelling the Movement and Spatial Distribution of Humpback Whales in the Nearshore Waters of the Kimberley

Spatial models integrating 13 years of aerial and shipboard surveys of humpback whales with environmental covariates have been used to estimate abundance, create distribution maps and understand drivers of distribution and abundance in the Kimberley.

Overview

A population of at least 33,000 humpback whales (*Megaptera novaeangliae*) annually migrate from summer feeding grounds in Antarctica northwards along the WA coast during winter to breed and calve in coastal waters of the Kimberley.

Many boat-based and aerial surveys have been conducted in the region along with complementary studies using satellite tagging to determine abundance, distribution and movement patterns of this population since the mid-1990s when the importance of this area was first noted. However, much of the data remain unpublished and has not been reviewed to provide a broad understanding of how humpback whales use the Kimberley, particularly as a breeding area.

This project compiled existing survey and tracking data on humpback whales in the Kimberley to identify patterns in the distribution, abundance, movements and habitat use (particularly relating to calving) across the region, and to identify the environmental factors that are associated with these patterns.

Additionally, the project has provided guidance for future monitoring and management by assessing a range of methods for detecting and counting whales (e.g. aerial and boat-based surveys, high resolution satellite imagery and a land-based platform).

With the increasing anthropogenic pressure associated with recreational and commercial interests this information is essential for ongoing sustainable management.

Approach

Survey data of humpback whales were collected and compiled across three decades in the Kimberley region, including from systematic and non-systematic surveys.

These data were combined with environmental covariates obtained by remote sensing to develop spatial models using both density surface modelling and species distribution modelling.

Very high resolution satellite imagery from WorldView satellites was obtained (archived WorldView-2 (46 cm res)) and tasked (WorldView-3 (0.31 cm res)) to determine whether humpback whales could be detected and counted in the images using visual and automated methods.

The strengths and weaknesses of this monitoring technique were then compared to those of other monitoring methods such as land, vessel and aircraft surveys to assist management agencies to determine the most effective and efficient method for management-related humpback whale monitoring in the Kimberley region.

Key Findings

The highest density occurred in mid-August, when an estimated 9,558 humpback whales were present between Gourdon Bay and the Maret Islands.

Abundance and habitat suitability were highest in Pender Bay throughout the migration season with Camden Sound also important but predominantly only in August.

Other important areas included the Buccaneer Archipelago/Tasmanian Shoal area and Gourdon Bay at the southern extent of the surveyed area.

A seasonal shift in abundance was detected with Camden Sound, Gourdon Bay and the Tasmanian Shoal area more important early in the season (August) with Pender Bay as the main core area later in the season (September/October).

The consistent importance of Pender Bay might be heightened by its proximity to the migratory path, such that most whales pass close by as they enter and leave the Kimberley region.

This contrasts with Camden Sound, which is at the northern extent of the breeding grounds, making it a destination rather than a transiting area.

However, the habitat suitability models confirm previous findings that all whales may not travel to more northerly sites, like Camden Sound, and that calving and breeding may also occur at Pender Bay and possibly other areas further south.

Distance to coast was by far the most important predictor of humpback whale habitat suitability, with habitat suitability highest within 20-40 km of the shore.

These inshore areas may offer more protected conditions, such as from the strong tidal currents in the Kimberley, and might be especially important for an animal living on fixed energy (as they do not feed other than possibly opportunistically during migration), particularly for groups containing females and calves.

Groups with calves were usually found closer to shore and over smaller areas than areas used by all whale groups combined.

Similarly, the top predictors of abundance were water depth and day of year, with the model predicting that numbers increase up to mid-august and to peak in water depth of around 35 metres.

The trial of satellite imagery demonstrated that the higher resolution imagery obtained from WorldView-3 was needed to successfully identify and count humpback whales.

While a semi-automated detection algorithm significantly reduced the time taken to count whales in the images compared to visual searching (~30 mins compared to 1 day), this method would currently only be economically viable for small areas with relatively high whale densities, such as Pender Bay or Camden Sound.

Where resources limit broader coverage of the region (either via satellite imagery or aerial surveys), tasking the WorldView-3 satellite to obtain images at Pender Bay could provide a cost-effective method for monitoring the Kimberley humpback whale population. Such methods could also be complemented by vessel-based surveys of these areas.

Aerial surveys of the whole Kimberley region are key to monitoring trends in absolute abundance of Kimberley humpback whales over time, however they have high cost and need a high level of expertise.

Although land-based surveys were considered to be the cheapest monitoring method, their capacity to provide adequate management-related information at a regional scale would be limited.

Management Implications

This project's modelling confirms the importance of Camden Sound and surrounding areas as a major calving area for humpback whales, particularly in August (the peak of parturition), however it also suggests that calving occurs southwards along the Dampier Peninsula and is not confined to the Camden Sound area.

Pender Bay had high abundance and high habitat suitability across the entire breeding season and not only as a resting/transiting area for humpback whales.

While the Camden Sound site is within a marine park, Pender Bay currently has only limited protection for waters further offshore (outside three nautical miles) by the multiple use zone, Kimberley Commonwealth Marine reserve. Thus, additional sites in the Kimberley, like Pender Bay, should also be recognised as important humpback whale breeding habitat and considered for additional protection.

- A basic monitoring protocol and design for ongoing vessel/satellite imagery surveys of humpback whale relative abundance at Pender Bay and Camden Sound is provided.
- Periodic aerial survey of the region is recommended to monitor long-term trends in abundance of the Kimberley population and should be considered where budget allows, but given that cost and expertise required is high, it should be undertaken every five-10 years at a minimum.
- A basic monitoring protocol and design for land-based data collection using volunteers at Pender Bay is also provided and can be a cost-effective means of assessing the timing of the humpback whale migration season and the demographics of whales using Pender Bay.
- While there are limitations on spatial extent and suitability for abundance estimates of these data, there is the added bonus of including community education and participation objectives in conservation initiatives.

Future Focus

The last systematic survey of humpback whales across the entire Kimberley region was undertaken in 2007 and, while it is widely recognised that the population has been increasing each year as it recovers from whaling, there is no current estimate of the absolute population size nor of how population growth may have affected spatial use in these important breeding habitats in the Kimberley.

A region-wide aerial survey is needed to adequately monitor the recovery of this population.

Further, the relative importance of additional core areas as humpback whale calving/nursing grounds (Pender Bay, Tasmanian Shoals, Eighty Mile Beach) is not fully understood. Surveys that identify neonates and post-neonates would confirm if these areas are used for calving.

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Abundance, Population Genetic Structure and Passive Acoustic Monitoring of Australian Snubfin and Humpback Dolphins Across the Kimberley

Limited understanding of the abundance, distribution and genetic connectivity of Australian snubfin and humpback dolphins has precluded assessment of their conservation status and consequent management in relation to natural and anthropogenic pressures in the Kimberley.

Overview

The Australian snubfin dolphin *(Orcaella heinsohni)* and Australian humpback dolphin *(Sousa sahulensis)* are poorly-understood tropical species with distributions restricted to shallow coastal and estuarine waters of northern Australia and southern New Guinea.

Current information suggests that both species occur in small populations of 50-200 animals that have limited genetic connectivity and rely on near-shore habitats. These characteristics, combined with their slow growth, late maturation, and low reproductive rates, render them vulnerable to anthropogenic pressures.

A lack of data on the distribution, abundance, trends and threats to these species has precluded comprehensive assessment of their conservation status under national and Western Australian criteria.

Estimates of snubfin and humpback dolphin population size and structure in the Kimberley are currently limited to accessible areas such as Roebuck and Cygnet Bay.

There is a pressing need for an improved understanding of these species' occurrence and population dynamics across the region to assess and manage impacts from human activities such as vessel traffic, commercial fishing and coastal habitat modification.

This project has built on several existing studies that aim to improve knowledge of snubfin and humpback dolphins in WA waters by developing new methods to monitor their condition over time.

A combination of techniques has been used to address relative abundance at key sites, genetic connectivity and the potential for passive acoustics as a long-term monitoring tool.

Approach

Relative abundance:
Boat-based surveys and photo-identification were used to obtain information on encounter rates of snubfin and humpback dolphins to estimate local population size at Cone Bay, Prince Regent River and Cambridge Gulf for comparison with known hotspots for these species such as Roebuck Bay.

Population genetic structure:
Tissue samples were collected from free-ranging dolphins at several key sites in the Kimberley and combined with existing samples from additional sites in the Kimberley and the Pilbara to assess genetic connectivity and population structure across the Kimberley and more broadly across their range in WA.

Passive acoustic monitoring (PAM):
Methods for recording and analysing the vocalisations (underwater sounds) produced

by snubfin and humpback dolphins were tested to determine their application as a cost-effective tool for monitoring the occurrence and abundance of dolphins. This included assessing capacity for vocal detection in relation to their occurrence and developing an acoustic repertoire for identification of each species relevant to behaviour and location.

Key Findings

Relative Abundance:

Snubfin and humpback dolphins were recorded at all surveyed sites, although numbers were highly variable.

Snubfin dolphin encounter rates were lower (≤ 0.20 dolphins/km effort) than those previously reported for Roebuck and Cygnet bays. However, repeated sightings of the same individuals between years at Cone Bay and regular sightings of a small numbers of animals in Prince Regent River by tour operators and marine rangers suggest the likely presence of small local populations of snubfin dolphins.

The relative abundance of humpback dolphins was fairly low at each site surveyed (≤ 0.15 dolphins/km effort) and comparable to other reported surveys for the Kimberley.

Overall, these findings provide further evidence that snubfin and humpback dolphins are present at low densities and probably as relatively small local populations across the Kimberley.

Difficulties in approaching dolphins by boat limited the effectiveness of photo-identification techniques at some sites, most notably Cambridge Gulf in the eastern Kimberley, possibly as a consequence of the typically low vessel traffic in this area and dolphins being less familiar with boats.

Other survey techniques may be needed to monitor or further assess these species in such remote areas.

Population Structure:
Genetic analyses have confirmed that, while there is evidence of limited gene flow between snubfin dolphins at Roebuck Bay and areas of King Sound (c. 250 km distant), there is significant gene flow between populations within King Sound (e.g. Cone Bay and Cygnet Bay) over distances of ca. 60 km. There is limited evidence of a possible third genetically distinct snubfin dolphin population north/east of King Sound, however additional sampling will be needed to clarify this.

Humpback dolphin populations were found to be genetically distinct between the Kimberley and Pilbara region, however the lack of genetic samples from animals in the Kimberley prevented the identification of population structure at a finer scale.

These findings provide further evidence of limited genetic connectivity between some local populations of both species, although further research is required to understand the complexity, variability and spatial scale of such patterns.

Acoustic Monitoring:
While dolphins can be detected using PAM, vocal rate was found to be linked to behaviour which differs by species and by location. Consequently, when using PAM to assess the occurrence and density of snubfin and humpback dolphins, prior information on their behaviour, the duration of time they spend in an area, and typical group sizes would be needed.

Further, while PAM effectively detects snubfin and humpback dolphins in high-use areas, more work is needed to:

i. reliably distinguish between the two species;
ii. develop efficient automatic detection algorithms for processing large acoustic datasets; and
iii. estimate abundance from these data.

Management Implications

- This project provides managers and policy-makers with new knowledge, including baseline information, on the relative importance of several Kimberley region sites to snubfin and humpback dolphins (e.g. Cygnet Bay, Cone Bay, Prince Regent River)
- Improved understanding of the connectivity of populations indicates that snubfin populations should be managed at local scale and humpback dolphins at a regional scale until further information is available on fine-scale population structure in the Kimberley.
- While PAM has been demonstrated as a cost-effective technique to confirm dolphin presence, further work will be required for it to reliably be used to monitor abundance and distribution and to identify species. Meanwhile, vessel-based surveys should continue to be used as the primary method to monitor abundance.
- The collaborative approach to boat-based surveys, which included training and participation by Traditional Owners, Indigenous rangers and marine park rangers, has resulted in an improved understanding and capacity of relevant local land and sea managers to collect data in remote areas, and has laid the foundation for ongoing research and monitoring across the Kimberley region.

Future Focus

Given the challenges and costs associated with collecting data on relative or absolute abundance, future targeted research should prioritise the dolphin populations and areas of high conservation and management importance such as those with the greatest current or projected exposure to threatening processes and/or that are most suitable for cost-effective long-term monitoring to determine population trends (e.g. Roebuck Bay).

Further collection of genetic samples should also be selectively focused on seeking to identify broad-scale patterns of population structure with priority areas to include Yampi Sound and further into the central and northern/eastern Kimberley and adjacent Northern Territory waters.

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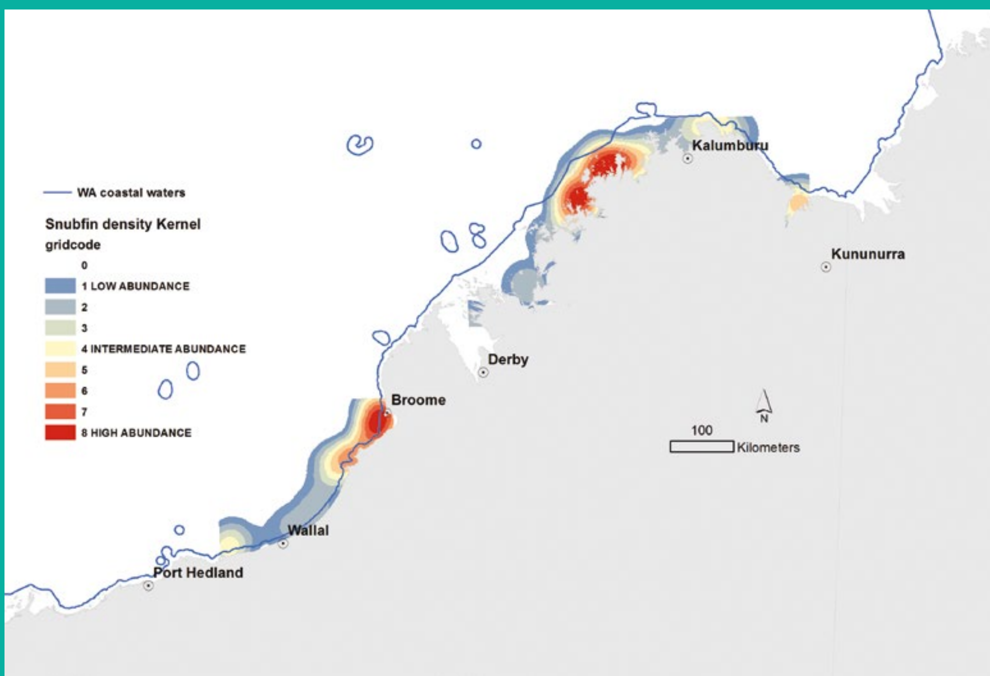
Integrating data across projects

Aerial surveys of dugongs conducted across the Kimberley region provided an opportunistic record of sighting data for dolphins as well. These data were used to derive relative abundance "hotspot" maps for snubfin dolphins.

The surveys also identify relative hotspots in other coastal areas of the Kimberley that could be considered for future survey effort in line with the recommendations.

Areas of interest should include northeast Eighty Mile Beach to Roebuck Bay, and the northwest Kimberley between Cape Voltaire and Cape Bouganville.



Snubfin abundance "hotspot" map. Dampier Peninsula surveys did not differentiate snubfin dolphins, hence there is no coverage over that area.

Evaluating the Impacts of Local and International Pressures on Migratory Shorebirds in Roebuck Bay and Eighty Mile Beach

Systematic monitoring of migratory shorebirds provides the necessary information to manage population impacts from local-scale habitat changes, in comparison to external pressures which cannot be managed locally.

Overview

The tidal flats of Eighty Mile Beach and Roebuck Bay support the largest non-breeding populations of migratory shorebirds in Australia and the East Asian - Australasian flyway. Both sites are recognised as Wetlands of International Significance under the Ramsar Convention and were recently listed as jointly managed CALM Act marine parks.

Shorebird numbers in parts of northwestern Australia have been monitored systematically since 2004.

While most of the Kimberley coast is remote and sparsely populated, human populations and economic development in the region are increasing. Monitoring shorebird numbers in the region allows for the detection of population changes driven by local-scale pressures that can be managed and/or mitigated by local conservation actions.

However, migratory shorebirds are also affected by remote pressures, such as loss of migratory stopover sites in Asia, on which they depend when migrating to their breeding grounds in Siberia and Alaska.

A key step to arresting the ongoing decline of migratory shorebird populations is to be able to distinguish changes caused by local factors (the responsibility of Australian governments, conservation agencies and land managers) and external factors (the responsibility of international agencies and governments).

This project has maintained the time-series dataset on shorebirds and has undertaken some initial analysis to determine whether declines in bird species noted in Korea, after the large-scale habitat loss due to land reclamation operations in Saemangeum between 2006 and 2008, are also reflected in abundance and survival in northwestern Australia.

In addition, the project assessed whether roost-site preferences of shorebirds at Roebuck Bay and Eighty Mile Beach have changed, and whether any changes are associated with pressures like disturbance or mangrove encroachment.

Approach

Shorebirds on the northern beaches of Roebuck Bay, Bush Point (at the southern end of Roebuck Bay) and a 60 km stretch of Eighty Mile Beach were identified to species level and their numbers counted by an experienced team of professional and volunteer shorebird experts during two summer surveys in 2013/14 using the methodology established by the long-term monitoring project.

Surveys were carried out at high tides, when the tidal flats are submerged and shorebirds are forced into relatively small roosts where it is possible for a team of experienced surveyors to count all birds of each species.

Trends in counts were examined over the entire study area, and on a roost-by-roost basis, to identify roosts where relative usage by shorebirds has changed. This information was compared with previously collected data on human disturbance of roosts to assess whether local influences are affecting shorebirds in northwestern Australia.

Integrated population models that combine data on changes in shorebird numbers (from counts), annual survival (from mark-recapture analyses) and breeding success (from winter counts, and from age-ratio data on birds captured in the northwestern Australian summer) are being developed to assess whether populations underwent changes coinciding with the land reclamation activities in Korea, and the extent to which these changes were driven by adult mortality and annual breeding success.

Key Findings

Did the Saemangeum reclamation in Korea affect Australian shorebird populations?

The loss of a major Korean staging site for great knots at Saemangeum, in the Republic of Korea during 2006, coincided with the disappearance of some 100,000 great knots from Korean staging grounds, which comprised about 20 per cent of the estimated world population.

Counts of great knots and the annual apparent survival of this species in northwestern Australia also declined by about 20 per cent at this time.

However, continued declines in adult survival since 2008 are not matched by declining population counts, which have fluctuated from year to year without showing consistent decline.

The data strongly suggests that the Korean reclamation caused rapid population decline in northwestern Australian great knots, adding to a growing body of evidence demonstrating that declines in shorebird numbers in Australia are driven largely by loss of migratory stopover habitat in Asia.

However, the relationship is imperfect, and there is a need for integrated population modelling to fully understand the interactions between annual survival, recruitment, immature dispersal and population counts.

Have shorebirds changed their patterns of high tide roost usage on the Kimberley coast?
Some of the changes of roost usage in northwestern Australia are consistent with disturbance and mangrove encroachment restricting their use of roosts.

In winter, when disturbance from humans and birds of prey is highest, some roosts in Roebuck Bay (including those with encroaching mangroves) are abandoned by shorebirds and they relocate to other roosts on the shores of Roebuck Bay with less human disturbance.

It is not clear whether this affects their survival, but it is noteworthy that counts of migratory shorebirds at northern Roebuck Bay declined during the study, in contrast to less disturbed sites at Bush Point (where numbers increased) and Eighty Mile Beach (where numbers have been reasonably stable).

In contrast, no significant changes were found in the relative numbers of birds at individual roosts during summer in the period 2004-2017. This may indicate that roost protection measures in Roebuck Bay (primarily public education) are succeeding, but it is also possible that the variability of counts at individual roosts has concealed less obvious changes.

Management Implications

- Continued monitoring of shorebird populations in northwestern Australia is essential to continue to inform management of both local and international pressures as shorebird numbers and roost usage can be highly dynamic. Shorebird counts can provide direct evidence of local pressures and the success or otherwise of management initiatives.
- In addition to counts of shorebirds, annual estimates of adult survival and recruitment of immature birds enable an understanding of the causes of population changes shown by counts and may provide early warning of significant changes.
- Roost disturbance remains an issue in Roebuck Bay and may cause shorebird population declines, and potentially threatens the shorebird spectacle that attracts many tourists to Broome. An education program has proven to be effective in reducing the disturbance and should be continued to minimise any impact on the population.

Future Focus

Future research should focus on integrated population modelling of existing count and demographic data to fully understand the interactions between annual survival, recruitment, immature dispersal and population counts.

Comparison of shorebird monitoring data with that from benthos surveys in northwestern Australia will indicate whether any of the observed changes in roost location can be associated with changes in local food supplies.

Finally, disturbance levels of shorebirds in Roebuck Bay need to be re-appraised to determine whether public education measures (e.g. signposting, public meetings) have been successful.

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Considering new information from the social characterisation of the Kimberley in the context of the future will help us understand and manage change to meet community aspirations and needs.

New Knowledge and Tools

- Benchmark spatial datasets of human activities, values and management preferences across the Kimberley coastal environment.
- Protocols for monitoring human use patterns.
- A regional framework and toolbox of protocols for monitoring in the marine environment.
- Protocol to guide the development of collaborative research between scientists and Indigenous communities.

Social Characterisation

Environmental management relies on knowing how people value and use the environment in order to understand anthropogenic pressures and to ensure management strategies are effective.

In Australia, coastal and marine environments are highly valued for the range of cultural, traditional, commercial and recreational opportunities they provide.

The current major uses of the Kimberley coastal waters include: traditional Indigenous use, marine tourism, commercial and recreational fishing, pearling, aquaculture, and oil and gas exploration.

Given the large area, small population, limited land access and remoteness of the region, anthropogenic disturbance has remained minimal across much of the Kimberley. However, understanding the spatial and temporal extent of human use, how people value the region and their aspirations for it, is essential for policy, planning and management.

Indigenous people, with their strong connection to and stewardship of saltwater country, hold substantial knowledge about the coastal environment. The integration of Indigenous knowledge and western science can improve decision making, management and monitoring of the region and marine protected areas.

The projects in this section were designed to provide a social characterisation of the Kimberley, including understanding what people value in the region and attitudes towards resource management along with how people use the marine environment. As the long-term inhabitants and custodians of the Kimberley, an understanding of Indigenous saltwater country knowledge, practices and values is integral to future joint management.

Key management questions

- What does the community value and what are their aspirations for the area?
- What are the patterns and trends of human use and what impacts and risks will these pose to the marine biodiversity?
- How can we best monitor human pressure on marine resources?
- What collaborative processes can we develop to share, use and co-produce knowledge that can be used for decision making, management and monitoring of the Kimberley saltwater country?

Values and Aspirations for Coastal Waters of the Kimberley

The remote wilderness of the coastal and marine environments of the Kimberley are highly valued for the range of cultural, traditional, commercial and recreational opportunities they provide.

Overview

Most coastal and offshore waters of the Kimberley region comprise existing or proposed Commonwealth or WA state marine reserves and are also subject to native title claims or determinations.

Conservation estate managed by WA is increasingly being jointly managed with Traditional Owners. Understanding how, where and why people value coastal and marine environments is essential for effective planning and management of this region.

Here we define social values as the importance of places, landscapes, and the resources or services they provide as defined by individual and/or group perceptions and attitudes towards a given place or landscape.

This project has provided social characterisation of the Kimberley coastal and marine environments that goes beyond a focus on people as the cause of impacts and incorporates an understanding of people's needs and values for the region.

Approach

A range of methods were used to capture and map social values across a broad range of stakeholders in the Kimberley region and further afield.

Stakeholders targeted in the research included; Traditional Owners; Aboriginal and non-*a*boriginal residents; tourists and the tourism industry; commercial and recreational fishing interests including aquaculture; federal, state and local governments; mining, oil, gas and tidal energy interests; marine transport and aviation; environmental non-government organisations and the broader WA public.

Face-to-face interviews were conducted with 232 stakeholders in 2013 using participatory mapping to document spatially explicit information on how people value coastal and marine environments and linking this information with specific geographic locations. These data were used to generate 'hot spot' maps for each value type, highlighting the places most frequently identified in the interviews.

A two-part online public participation geographic Information system (PPGIS) mapping and discrete choice experiment survey was undertaken in 2015 to capture values of the broader community.

Respondents were asked to mark areas corresponding to values and management preferences on a map of the Kimberley. They were also asked to choose their preferred option between alternative management scenarios, comprising different levels of management outcomes, across a number of hypothetical management zones within the study area.

Finally, in collaboration with the Karajarri Traditional Lands Association, the project investigated the activities undertaken and management improvements desired by visitors to the Port Smith coastal area, located within the Karajarri Indigenous Protected Area, to inform healthy country management.

Key Findings

More than 75 per cent of respondents highlighted the biodiversity and the physical landscape of the Kimberley coast and marine waters as key values for use (e.g. recreation) and non-use (e.g. biological, bequest) attributes with strong support for marine and coastal protection and conservation along the whole coastline.

Seventeen different social values were associated with the Kimberley coastal environment, including a range of direct, indirect, consumptive and non-consumptive values, though non-consumptive, direct use values dominated the interviews with biodiversity, physical landscape and Aboriginal culture the most widely held values.

Social values were highly concentrated at Roebuck Bay, the northwestern coastal fringe, Dampier Peninsula and Buccaneer Archipelago, Horizontal Falls and Montgomery Reef.

While residents and non-residents of the Kimberley held similar views of values and management preferences, residents were more likely to identify recreation and recreational fishing values and to seek additional recreational facilities and port development while non-residents were more likely to identify biological/conservation and wilderness values.

Although some regions attract high levels of attention at particular times, there is a general set of non-use values, such as bequest and spiritual values which can be significantly impacted upon by proposed development and require focused management consideration.

However, there was not always agreement on management preference by area, for example, Roebuck Bay and Dampier Peninsula were identified as hotspots for both pro-conservation and pro-development management preferences by different stakeholder groups.

Aboriginal culture and heritage values are widespread across the study area, with hotspots identified around Dampier Peninsula, Roebuck Bay and the northern Kimberley, and respondents generally positively predisposed towards recognising and increasing Aboriginal management.

Management Implications

- This research provides essential baseline information on human values and aspirations that will inform future planning and management of the Kimberley coastal and marine environments. The spatially explicit nature of the data makes it suitable to integrate with existing planning and management frameworks.
- Strong local and broader community support exists for management to maintain important biodiversity and the visitor experiences along the entire Kimberley coastline. While physical landscape values are pivotal to people's experiences of the Kimberley, both use and non-use values need to be recognised when considering changes to management or potential developments.
- Recognition of biodiversity and social values should be promoted through education programs to raise awareness, capitalising on broad community support for marine parks and their nature conservation objectives. This should include consideration of the differences in values and preferences noted for various stakeholder groups and the development of targeted education and communication initiatives to be relevant to different audiences.
- Both PPGIS and choice experiments provide spatially explicit information that can be used by planners and managers to understand the complex nature of human values associated with the Kimberley coast.

  In particular, these methods can provide rich detail on how particular places are valued and what management is preferred to protect these places into the future, as well as providing insights into people's preferences for management outcomes when trade-offs are required to manage areas of potential conflict.

  This information can guide decisions about management frameworks for conservation estate and be used to focus public support for management. It can also be used in developing education and compliance programs that will best suit the values and preferences of the local and visitor community to meet aspirations and enhance experiences.

These methods can also be used to monitor values and attitudes to determine if management strategies (including education components) have been effective.

Managers should consider repeating these combined methodologies in line with marine reserve management review processes, or with any other major change planned for the region (i.e. improved access, new development, etc.).

- Indigenous people's values for the Kimberley coast and marine environments extend well beyond cultural values and, as such, Indigenous people must be included in decision making associated with all social values of the Kimberley coast.

  Opportunities exist to build upon and develop new conservation and tourism-related products that harness stakeholder interest in Indigenous culture. Indigenous ranger groups in particular, present an ideal means of combining conservation, tourism and Indigenous culture in a manner that will help to foster greater understanding of, and support for, cultural values and Indigenous management of saltwater country.

Future Focus

Further research is needed to validate and extend these findings regarding values, particularly for the northern and eastern Kimberley coastlines.

In particular, opportunities exist to more comprehensively map the cultural and other values held for Kimberley sea country by Traditional Owners. This could also lead to the development of agreement-based research with Traditional Owner groups at a smaller scale, to explore values held for country by a range of stakeholder groups. This information can then be used to progress Indigenous management of Country (including tourism development) through Healthy Country Plans.

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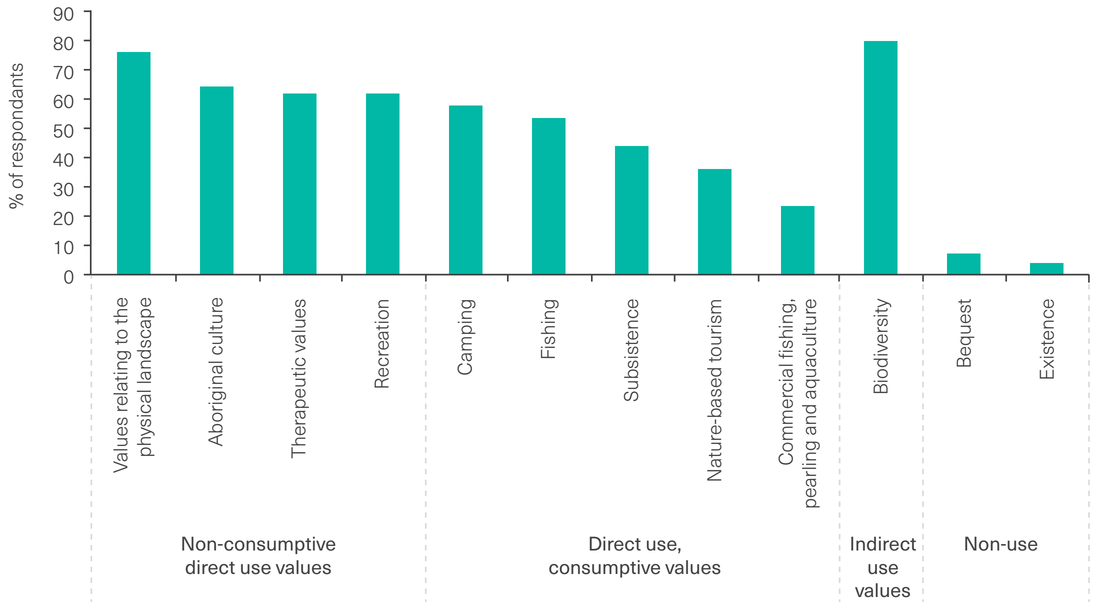

Responses across the different value categories, subsistence included food collection.

Human Use Patterns and Impacts for Coastal Waters of the Kimberley

The remote coastal and marine environments of the Kimberley are utilised for a range of cultural, traditional, commercial and recreational opportunities.

Overview

The remote Kimberley coast has been used by Indigenous peoples for thousands of years for subsistence and cultural activities and more recently for commercial opportunities like pearling, commercial fishing and aquaculture, resource extraction, tourism and broader recreational activities.

In 2011, the WA Government committed to the creation of a network of marine reserves in the Kimberley to sustainably conserve and manage the unique marine and coastal values of the region.

Understanding the cumulative impacts of different human uses on the marine and coastal environment of the Kimberley is essential to effectively manage these unique natural values.

This requires knowledge of the spatial and temporal extent of traditional, recreational and commercial human use and, while the extent of commercial activities across the Kimberley (e.g. commercial fishing effort and catch, resource development, pearling and aquaculture) is moderately well known, there was little quantitative information on recreational activity at the time of this study.

This project has provided a benchmark of human use patterns at various scales in the Kimberley marine and coastal environment and assessed the potential for impacts on marine and coastal habitats from these activities.

Approach

Investigations of human use patterns in coastal and marine environments of the Kimberley were undertaken using a variety of tools and at various spatial scales prior to the implementation of the marine park system.

Monthly aerial surveys were flown to benchmark the use of the southern (Port Hedland to Crab Creek, Roebuck Bay) and western (Crab Creek, Roebuck Bay to Point Torment, King Sound) sections of the west Kimberley throughout the year.

Only exploratory surveys of the central (Camden Sound) and eastern (Augustus Island to Wyndham) portions of the eastern Kimberley were used to provide an understanding of relative human use across these vast and remote stretches of coast during the peak tourist season.

The cumulative visitation by expedition cruise vessels across the entire Kimberley region was estimated using a desktop study of the number and passenger capacity of expedition cruise vessels along with their activity itineraries and sites to be visited.

On a local scale, recreational fishing pressure was evaluated using remote camera surveillance to quantify the number of boat launches relative to a number of temporal (e.g. week versus weekend, holidays, season) and environmental (e.g. wind speed and direction) factors.

Finally, a review of the potential impacts from recreational and tourism activities was also completed to provide a better understanding of the key impacts on which natural resource managers should focus to ensure the sustainability of the unique Kimberley environment.

Key Findings

Visitor use of the western Kimberley is strongly seasonal and spatially focused with most human presence and activity concentrated around a relatively few sites with coastal road access, a population centre or available tourist accommodation (e.g. caravan parks or camp sites).

Southwest from Roebuck Bay, the seasonal contrast and visitor focus on nodal areas was more defined and dominated by shore-based fishing while walking and relaxing on the beaches dominated the Dampier Peninsula, particularly along the western side. Activities were similarly nodal and often radiated from access points via 4WD vehicles, although there were many more vessels and vehicles in general along the Dampier Peninsula, particularly around Broome.

Boat activity was concentrated around established ramps and also near other sites where boats could be launched from the beach, while shore-based fishing, particularly in the southern Kimberley, extended along the coast from access points where people use 4WD vehicles.

Recreational use was far more limited from Derby to Wyndham due to the lack of roads and the exploratory surveys indicated low numbers of people. Activity was mainly associated with popular tourist destinations, camping areas or commercial operations. Vessel numbers were also low, with nodes of activity around commercial operations such as pearl farming, mining and mariculture.

Tourist visitation to the central and northern Kimberley was mainly conducted by recreational or expedition cruises with overall visitation low compared to other tourist destinations in Australia and globally. Most of the vessels being used have a limited passenger capacity (fewer than 20 passengers).

The site-specific evaluation of the use of Entrance Point boat ramp found that, while boats were launched all year round, ramp activity was related to temporal and environmental factors, with periods of greatest vessel activity in the mornings, on non-school holiday weekends during the dry season when wind was light.

Management Implications

- This study benchmarks human activity across the Kimberley with a seasonal understanding of use across the western Kimberley from Port Hedland to Derby together with a dry season snapshot of the extent of visitation in the more remote central and eastern Kimberley against which to plan management measures.
- The repeated surveys of the western Kimberley between Port Hedland and Derby benchmarks the level of use prior to the implementation of Eighty Mile Beach and Roebuck Bay marine parks and significant changes to coastal infrastructure, such as upgrading the road from Broome to Cape Leveque. Subsequent surveys could assess changes in use in relation to these factors.
- The development of a repeatable aerial survey technique for measuring human use in the Kimberley enables long-term monitoring to be established that allows for periodic evaluation of changes in tourism and recreational activity across the Kimberley. A number of other complimentary desktop and smaller scale techniques have also been established to provide benchmarks against which to monitor change.

Future Focus

While the study clearly identified sites where human pressures are relatively higher, a more detailed, fine scale assessment of human use patterns and impacts at nodes of high activity would assist management of these sites.

Expanding the research to include understanding the impact of nodal pressure on the ecology and biology of the surrounding environment would further support management decision making at these and other high use sites.

Additional monitoring techniques and potential indicators should be explored for their utility in the Kimberley, e.g. vehicle counters to monitor the number of vehicles entering key access points and camp grounds along Eighty Mile Beach to measure temporal use of beaches.

Finally, the exploratory surveys undertaken across the eastern Kimberley should be expanded to provide more quantitative data on nodal use of the area to inform management.

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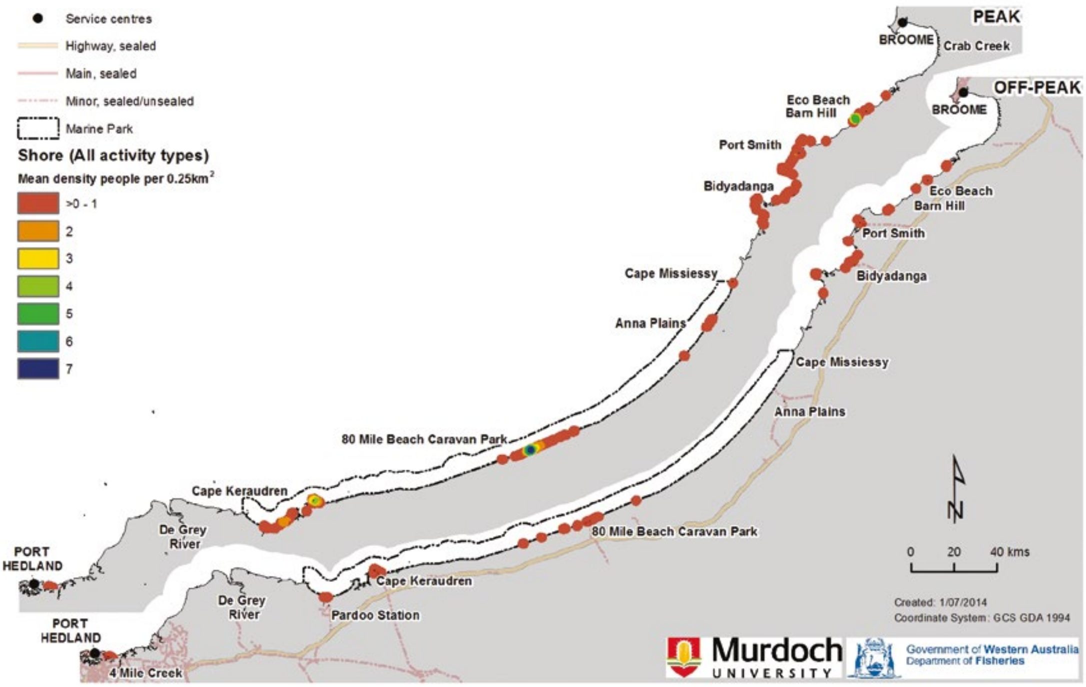

Mean density of people recorded during aerial surveys along the shore between Crab Creek (Broome) and Four Mile Creek (Port Hedland) during the peak (dry) and off-peak (wet) seasons (n= 6 survey flights each season).

Kimberley Indigenous Saltwater Science Project (KISSP)

KISSP has provided a legacy of stronger relationships between land and sea researchers and Traditional Owners of the Kimberley to continue to work together for healthy country.

Overview

The Kimberley has a wealth of natural features, with large areas of remote and largely unaltered terrestrial and marine ecosystems. While this unique environment continues to be of scientific interest and focus for researchers, the care and management of Kimberley land and seascapes by Traditional Owners reflects a deep and rich cultural association that has formed over thousands of years.

The Kimberley Science and Conservation Strategy (WA 2011) identified that integrating both Indigenous peoples' knowledge and western scientific knowledge is a key element for ensuring the best outcomes for the management and conservation of the Kimberley coastal and marine environment into the future:

"Immense traditional ecological knowledge has been handed down from generation to generation and this can be used in conjunction with modern science to inform land management practices and decisions."
WA 2011, p.20

This project was founded on the understanding that:

"Indigenous knowledge holders are scientists in their own right,"
Karajarri Traditional Owner

and that traditional knowledge and western science can both provide critical roles in supporting the management of land and sea country in contemporary Australia.

The Kimberley Indigenous Saltwater Science Project (KISSP) was developed to improve the ways in which research and monitoring of the natural and cultural resources of the Kimberley are planned, assessed and undertaken to include both Indigenous and western science partners.

Seven Indigenous saltwater groups came together to achieve the following objectives that will address some of the current challenges facing both Kimberley researchers and saltwater country managers:

- Integrate traditional ecological knowledge (TEK) and management practices into Kimberley marine conservation and management.
- Develop standard and agreed protocols and a research agreement template to facilitate land and sea research in the Kimberley and an implementation strategy to build awareness in the science community of the need for Traditional Owner engagement.
- Develop a framework and protocols for standardising data collection, storage and analysis methodologies that can be used to monitor saltwater country across the Kimberley, including a training package that enables rangers to undertake scientifically rigorous monitoring.

Approach

A workshop in October 2014 engaged all Kimberley saltwater country groups which led to the establishment of the KISSP working group with representatives from seven saltwater country communities (Balanggarra, Wunambal-Gaambera, Dambimangari, Bardi-Jawi, Nyul Nyul, Yawuru and Karajarri). The exchange of information to and from the participating communities, where the decision for management actions and project development take place, was facilitated by these representatives.

Through a series of planning meetings and conversations among Traditional Owners, the initial research aim proposed by WAMSI was tailored to meet local priorities and aspirations, culminating in the final research objectives.

Research collaborators were selected by the working group to undertake the research elements to meet these objectives through 'on-Country' workshops or meetings with each of the seven communities represented in KISSP to capture their input and priorities.

Each community decided how the research happened (i.e. workshop or interviews) and ensured that the 'right people' were involved in the workshops, which mostly included Traditional Owners, rangers and Prescribed Body Corporate (PBC) staff.

Several other research activities were completed to support the engagement of the broader Indigenous communities, including a review of previous monitoring and evaluation initiatives in the Kimberley and a questionnaire to obtain information on current monitoring and online surveys of researchers who had experience working in the Kimberley region.

Key Findings

More than 100 Indigenous community members, rangers and Indigenous Protected Area staff from the seven Kimberley saltwater communities have contributed their time and knowledge to this project along with 25 research scientists from several institutions with research experience in the Kimberley.

The value of 'right way' research is a key theme of this project and refers to the expectation of a respectful relationship between visiting scientists and Traditional Owners, where each share knowledge and experience with the expectation of mutual benefit.

There are synergies in many of the challenges experienced both by researchers working in the Kimberley and by Indigenous people who enable work on Country throughout the development and delivery of research projects.

This project confirmed the value of communication and collaboration between researchers and Indigenous people in contributing to successful research outcomes for both parties.

A clear focus on respectful negotiation, appreciation for the value and knowledge each brings to the table and alignment of priorities are key to this success.

Although these groups may use different approaches in response to local environments, cultural practices, resources, logistical constraints, local knowledge and experience, there is a strong interest in working together to build a regional picture of ecosystem health and maintain healthy country.

Management Implications

Insights gathered through the KISSP have been synthesised to guide and support the ongoing development of collaborative research, management and monitoring in Kimberley saltwater country through a set of key documents and associated tools:

- Mobilising Indigenous Knowledges for Collaborative Management of Kimberley Saltwater Country – Guiding Principles (Understanding how to bring knowledge streams together);
- Guidelines for Collaborative Knowledge Work in Kimberley Saltwater Country;
- Collaborative Science on Kimberley Saltwater Country, A Guide for Researchers; and
- A Regional Framework and Toolbox for Saltwater Monitoring in the Kimberley (a regional framework for Traditional Owners monitoring Kimberley saltwater country)
  - Saltwater Monitoring Fundamentals– Building a Knowledge Base Together

These documents and tools employ current theory and best practice approaches to collaborative research, management and monitoring to provide practical 'tools' for knowledge production and management.

The outputs and outcomes will be of interest to Traditional Owners and other local Indigenous people, researchers and those with an interest in looking after Kimberley saltwater country.

The Kimberley Traditional Owners that form the KISSP working group have given the project its strength and have provided a useful forum for bringing people together in collective consideration of healthy country management and to share knowledge.

Working group members have actively participated in all forums and have become knowledge brokers, not only between remote Indigenous communities and western scientists but also between saltwater groups across the Kimberley region.

Based upon sharing knowledge in good faith and building upon established Indigenous governance structures, an effective network of Indigenous groups, saltwater managers, agency stakeholders and scientists has developed.

New knowledge about Kimberley saltwater country will continue to be produced and flow through the region and beyond. These knowledge currents have the potential to follow multiple pathways depending on relationships that emerge and the questions they seek to answer. We hope to shape the contours of these currents so they are collaborative, leverage the knowledge of both Indigenous peoples and scientists, and produce an enriched picture of Kimberley saltwater country.

Future Focus

The KISSP working group will seek to continue supporting saltwater science and management in the Kimberley and will continue to promote and progress the KISSP outputs. Areas of future work will include:

Development of 'knowledge prospectuses' by PBCs and/or rangers that highlight the knowledge gaps local Indigenous people have for Country and the type of scientific support they would like to receive to support decision making and management of Country. This would give some guidance to the research community on how best to align with healthy country priorities and needs when initiating engagement;

- Consolidation of Indigenous knowledge including through the development of communication products, especially for local schools, that assist in intergenerational knowledge transmission and the engagement process; and
- Implementation of the research protocols developed through KISSP by investing in raising awareness and capacity building.

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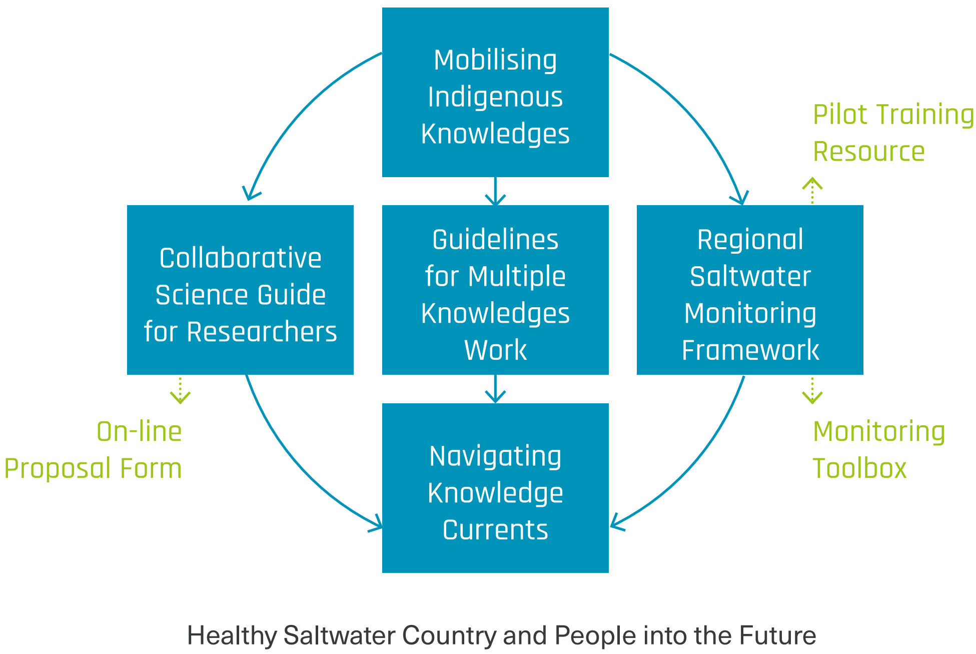
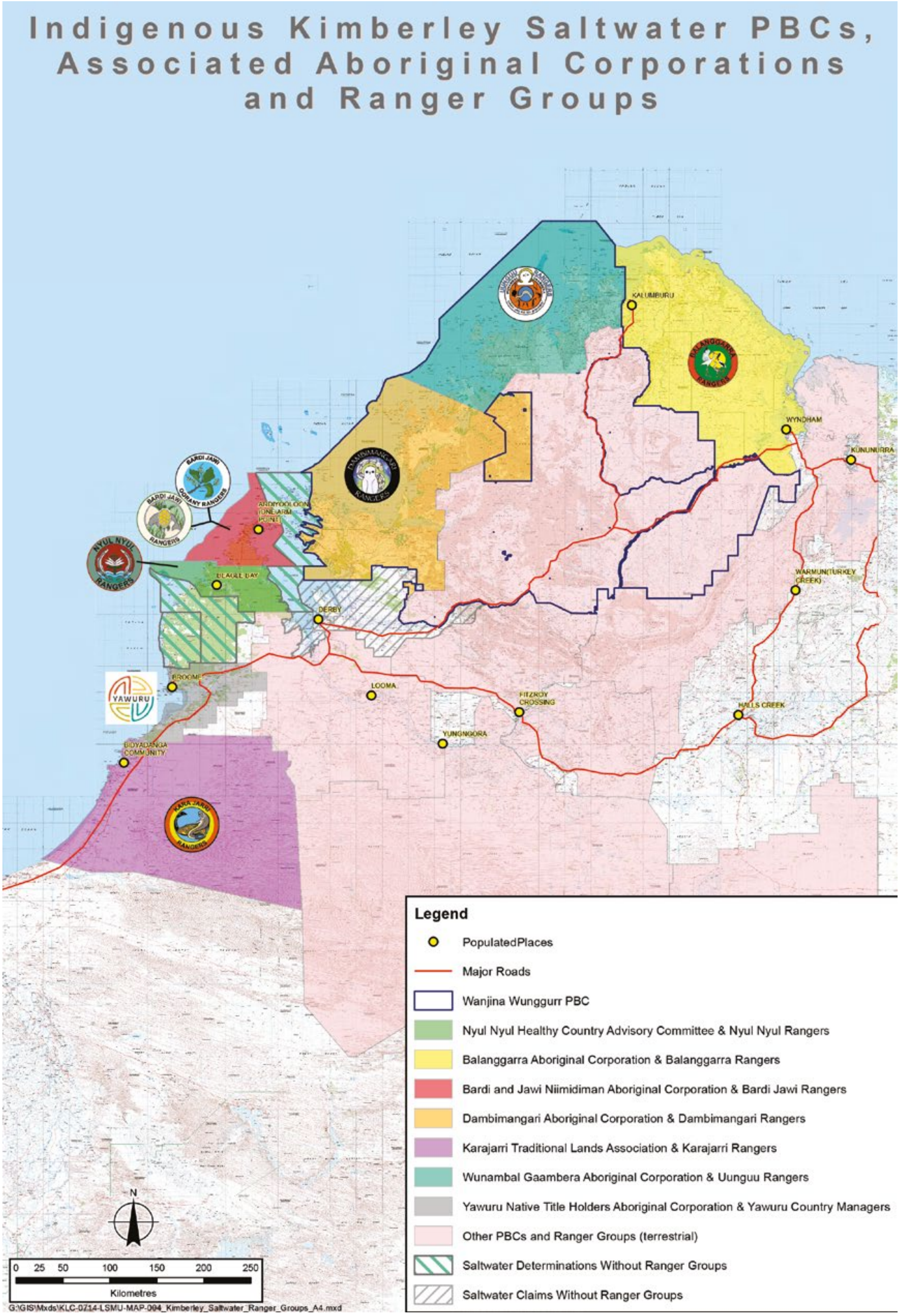
www.wamsi.org.au/indigenous-knowledge

Products (blue) and tools (green) produced by KISSP.





Map showing the Aboriginal corporations and Indigenous ranger groups partnering in the Kimberley Indigenous Saltwater Science Project - KISSP (courtesy of the Kimberley Land Council, 2016).

Objective	Management Implication
Mobilising Indigenous Knowledges for Collaborative Management of Kimberley Saltwater Country	
Integrate Indigenous Knowledge (IK) and management practices into Kimberley marine conservation and management through articulating the importance of multiple evidence-based approach and how this applies to integration of IK and western science.	Offers examples of contemporary IK for Kimberley saltwater country to build awareness and partnerships and clarify key differences to western scientific knowledge (WSK). Provides a framework and process for mobilising IK and the parallel integration and/or co-production of new knowledge to support collaborative management. Outlines impact pathways for IK and WSK to support decision making, inform management and design policy.
Guidelines for Collaborative Knowledge Work in Kimberley Saltwater Country	
Integrate IK and management practices into Kimberley marine conservation and management through providing practical steps that can be followed to develop appropriate collaborations for 'right way' science.	Provides clear principles and a stepwise process to ensure Indigenous people and scientists are able to work collaboratively and for shared benefits. Triggered whenever research, monitoring or management involves IK and WSK working together, the process is tailored to meet the needs of Traditional Owners, Indigenous rangers, scientists and others involved in collaborative management of Kimberley saltwater country. Removes uncertainty and increases confidence of all involved in collaborative research.
Collaborative Science on Kimberley Saltwater Country, A Guide for Researchers	
Develop standard and agreed community protocols and a research agreement template to underpin land and sea research in the Kimberley and an implementation strategy to build awareness in the science community of the need for this engagement.	Provides western science researchers and their Indigenous research partners with a practical sequence of culturally appropriate steps to progress Kimberley saltwater research projects from start to finish. Facilitates collaborative research that meets the needs of all research partners. Incorporates the learnings of researchers with experience working with Indigenous people in the Kimberley region. Provides access to a wealth of experience held by an established network of Indigenous land and sea managers across Kimberley saltwater country.
Collaborative Science Research Proposal Form	
Develop standard and agreed community protocols and a research agreement template to underpin land and sea research in the Kimberley through provision of an online research proposal template that can be submitted to relevant Aboriginal Corporations.	Identifies the information required by the local Indigenous community when considering research proposals. Provides a flexible interface for simple and complex proposals that can be revisited over time by the researcher and used for other purposes, e.g. human ethics applications. Supports development of a research or fee for service agreement.

KISSP products (blue) and tools (green), the purpose for each and how they might be applied to continue to build positive collaborations for healthy country management.

Objective	Management Implication
A Regional Framework for Saltwater Monitoring in the Kimberley	
Develop a framework and protocols for standardising data collection, storage and analysis methodologies that can be used to monitor saltwater country across the Kimberley.	Provides a regional monitoring framework designed to address the diverse features and challenges encountered in Kimberley saltwater country, that recognises local aspirations, obligations and threats allowing integration of local issues into a regional context. Facilitates the inclusion of both WSK and IK monitoring to support decision making (i.e. aligns with the multiple evidence-based approach). Provides a practical set of steps to address regional monitoring of saltwater country. Highlights the gaps /opportunities /limitations in current monitoring, the tools developed to assist in implementation of the framework and future requirements for local monitoring and the role out of the framework.
A Toolbox for Saltwater Monitoring in the Kimberley	
Develop a framework and protocols for standardising data collection, storage and analysis methodologies that can be used to monitor saltwater country across the Kimberley by presenting a range of products and tools that will support the implementation of the Regional Framework.	Provides a "Toolbox" of monitoring methods for saltwater country that summarises the techniques and tools available and how to access information on these techniques (including data recording, analysis tools etc.). Supports groups to undertake adaptive management at both the regional and local scale, ensuring questions clearly defined, results analysed, and monitoring and management actions evaluated. Highlights the gaps /opportunities /limitations in current monitoring tools providing a clear process for identifying what tools groups are currently using and where researchers can assist in developing new tools to assist rangers with long term monitoring.
Pilot Training Package: Saltwater Monitoring Fundamentals (A) – Building a Knowledge Base Together	
	Provides a training package for Indigenous rangers on fundamental concepts around marine monitoring practices. Demonstrates how both Indigenous monitoring and western scientific monitoring practices can contribute to an overall monitoring program. Supports Indigenous ranger participation in monitoring practices and design.

Findings from these projects have been integrated with results from the physical characterisation of the Kimberley in the KMRP projects on understanding change.

New Knowledge and Tools

- New techniques and protocols for assessing fish and coral recruitment and herbivory
- Baseline data on recruitment, herbivory and productivity
- Identification of new species and delineation between stocks and populations

Characterising and Understanding Ecosystem Processes

Marine ecosystems function as a result of a number of physical and ecological processes which operate across a wide range of time and space scales.

The physical processes have been considered under the chapter on physical characterisation of the Kimberley. Here we consider some of the sustaining processes responsible for maintaining the biodiversity and productivity of the Kimberley marine ecosystems.

Building on the extensive existing knowledge of tropical ecosystem functioning in northern Australia, the KMRP ecosystem process studies have been designed to enhance the fundamental ecosystem understanding needed to better address a range of current and future pressures on the region.

Some of the key ecological processes structuring marine ecosystems include: productivity, recruitment, herbivory and connectivity. Understanding the nature of these processes underpins effective management by providing a baseline from which to forecast and monitor ecosystem integrity.

Despite their importance, we currently have limited knowledge of how these processes influence and characterise the Kimberley region and the influence of the unique macrotidal environment. A better understanding of the nature of these processes is critical for the sustainable management of the Kimberley region and begins with establishing quantitative baselines at varying spatial and temporal scales.

Key management questions

- What processes are 'driving' benthic primary productivity and where are the major primary producer habitats?
- How do key physical (e.g. oceanography, temperature, estuarine discharge, etc) and biological (e.g. nutrients, herbivory, etc) processes influence primary productivity?
- What are appropriate and cost-effective methods for long-term monitoring of benthic primary producer habitats (e.g. seagrass, algae) and associated processes (e.g. herbivory)?
- How do macro-tidal systems influence ecological connectivity of key taxa at both fine-scale (within a reef) and broad-scale (coast to offshore reef)?
- Are proposed management areas sufficient for ecological connectivity to support populations of key taxa?
- What role does the Kimberley play in the maintenance of systems outside of the region?
- Are there hotspots for spawning and recruitment for reef fish and are these hotspots in ecologically resilient or sensitive areas?
- What are current baseline levels of fish and coral recruitment and herbivory at representative reference sites?

Benthic Community Production and Response to Environmental Forcing

Benthic primary producers survive and often thrive in the Kimberley despite the extreme conditions.

Overview

Benthic primary producers, such as coral, seagrass and macroalgae, play important roles in a variety of coastal processes. They provide habitat for marine organisms, stabilise sediments, attenuate water motion, and support coastal food webs. Through photosynthesis, primary producers use sunlight as the energy source to convert dissolved carbon into new biomass.

Tropical reef systems often display high rates of primary production, however, these rates are closely coupled to local physical (e.g. water motion, light, temperature) and biogeochemical (e.g. nutrient) factors.

Our present understanding of environmental controls on reef productivity is based primarily on studies from reefs of the Caribbean, Hawaii, southern Great Barrier Reef and other Indo-Pacific regions. Water motion on these reefs is controlled primarily by wave energy, so they can be considered 'wave-dominated'.

Reefs where tides primarily control water motion (such as those in the Kimberley region, where tidal range can reach 12 metres) can be considered 'tide-dominated' and comprise approximately 30 per cent of tropical reefs worldwide.

Tide-dominated reefs can experience much greater ranges in environmental conditions than wave-dominated reefs, yet have been largely unstudied.

This study has quantified the environmental variability across a macrotidal reef system in the Kimberley and assessed how benthic primary producers generally respond to extremes in water motion, light, and temperature.

More specifically, the project investigated:

i. how tides interacted with reef morphology to drive extreme daily variability in environmental conditions; and
ii. how this environmental variability influenced the productivity and nutrient uptake of different benthic communities on the reef platform.

Approach

Three field experiments were conducted on an intertidal platform reef at Tallon Island in the Sunday Island group of the west Kimberley.

During each experiment, an array of instruments was deployed measuring hydrodynamics, water temperature, light levels at the reef surface, and water column dissolved oxygen.

Based on changes in water column oxygen, the researchers were able to estimate community-scale (at 100s metres) rates of primary production in seagrass-dominated and macroalgal-dominated (including small corals and crustose coralline algae) communities on the reef.

Rates of primary production were then related to environmental data to assess whether communities were stressed during extreme environmental conditions.

In addition, concentrations of dissolved and particulate nutrients and chlorophyll-*a* (a food source for reef communities) were measured on the reef. This information was used to derive uptake rates of nutrients and chlorophyll-*a* by reef communities to assess how tides controlled uptake.

Key Findings

Macrotidal reefs in the Kimberley are subject to some of the most extreme conditions recorded for reef habitats worldwide. Extreme daily variability in temperature and dissolved oxygen occurs on the reef platform and is driven by semi-diurnal tides and solar (light) cycles.

The shape and roughness of the reef platform causes water to 'pond' on the reef for up to 10 hours during each ebb tide (twice daily). When these extended low tide periods occur near noon, ponding water heats rapidly with the temperature rising by 10°C over several hours and reaching up to 38°C.

The high light availability also drives high rates of benthic primary production, which releases oxygen into the water column and results in extremes in oxygen saturation (~270 per cent).

When low tide periods occur near midnight, respiration (the consumption of oxygen and carbon to create energy) by the reef community causes oxygen levels to plummet, reaching hypoxic levels (concentrations <63 µmol L^{-1}).

While hypoxia is known to harm or kill organisms in other ecosystems, such conditions are not typically recorded on reefs.

Despite these extreme conditions, this project found that rates of gross primary production of the dominant communities (macroalgae and seagrass) were close to the mean of reef communities globally, demonstrating that tide-dominated reefs can maintain moderate rates of production despite daily extremes in temperature. Environmental conditions and community productivity varied on a day-to-day basis over a cycle lasting ~15 days due to the timing of noon relative to low tide.

Water quality (nutrient and chlorophyll-*a* levels) on the reef also displayed strong variability linked to tidal cycles, with particulate nutrients and phytoplankton (food sources for reef organisms) flooding the reef at high tide and being consumed during low tide.

Towards the end of low tide, grazing by reef organisms depleted these nutrients, identifying the tidal cycle as a key process that replenishes reef food sources.

Waters surrounding Tallon Reef were oligotrophic (low concentrations of nutrients and chlorophyll-*a*) during this study, which is typical of tropical waters that do not receive substantial anthropogenic nutrient loads from terrestrial runoff.

Seasonal increases in nutrient and chlorophyll concentrations were detected from the end of the dry season (October) to the end of the wet season (April).

The estimated uptake of dissolved nutrients by reef primary producers (such as seagrass and macroalgae) was also strongly linked with tidal cycles.

Fast water flow during flood and ebb tides caused nutrient uptake rates to rise dramatically (~an order of magnitude) compared to slow water flow during high or low tides (slack water).

These findings demonstrate the important role that tides play in controlling the productivity and biogeochemistry of Kimberley reefs.

While the macrotidal regime of the Kimberley is extreme compared to most tropical reefs, many of the findings are relevant to reefs that experience mesotidal regimes (tidal range two – four metres), including the Great Barrier Reef.

Management Implications

This study documents some of the unique aspects of Kimberley reefs that experience conditions among the most extreme measured worldwide.

This study was conducted on a single reef, with a focus on developing general (transferable) process knowledge of how physical conditions within macrotidal reefs interact with communities of primary producers.

Measurements of the physical conditions (e.g. hydrodynamics, reef slope, reef morphology, and platform height above sea level) suggest these outcomes can be extended more broadly to other Kimberley reefs, particularly when considered in conjunction with findings from the reef geomorphology project, which classified major Kimberley reefs based on their morphology and height relative to sea level.

These characteristics determine the length of low tide on a reef flat, and thus the extremes in environmental conditions (flow speeds, temperature, light, dissolved oxygen and pH) that will develop there.

Environmental extremes and productivity measured on other high intertidal reefs, such as Montgomery Reef and Irvine-Bathurst, would likely be very similar to those measured at Tallon reef.

In contrast, relatively low intertidal reefs, such as Cockatoo Reef, and those formed below sea level would experience shorter periods of low tide exposure and thus less extreme environmental conditions.

Similarly, sloping reef platforms would experience a subtler version of the 'ponding' effect than near-horizontal platforms.

Managers may use this information to identify reefs vulnerable to climate change and to help inform future monitoring of Kimberley reefs, such as documenting high temperature events, or planning process-based scientific field studies.

For example, on high intertidal reefs (where platform level is above mean sea level), the timing of noon relative to low tide is the primary driver of reef conditions and varies over a 15 day cycle. This would be an important consideration for research on any reef process affected by temperature, light, dissolved oxygen or carbonate chemistry as studies less than ~15 days may greatly over or underestimate the process of interest.

Alternatively, for low intertidal reefs (where the platform is below mean sea level), the spring-neap cycle would be an additional driver of environmental variability and a high-frequency record of water depth at the study site would be needed to interpret results and position them within tidal and light cycles.

The KMRP results provide a foundation for developing predictive models of conditions on Kimberley reefs under future climate change scenarios.

As temperature variability can be predicted on these reef platforms, this can be combined with predictions of ocean warming and sea level rise to estimate future conditions on reef platforms. Prioritisation of management actions or protection status can then be applied considering climate change predictions and other anthropogenic pressures.

Finally, while the study found that overall rates of productivity in this Kimberley reef system were comparable to other coral reef habitats worldwide, the environmental conditions under which primary producers survive and grow are extreme. This has implications for the resilience of these producers in the face of climate change across the Kimberley environment.

While these organisms appear well adapted to the local environmental conditions of the Kimberley, many are still likely operating at the edge of their capacity, as evidenced by coral bleaching in the inshore Kimberley associated with the 2016 El Niño.

Management should consider strategies that will ensure any additional anthropogenic pressures that could add stress to the system are minimised and also be aware of environmental conditions that may change over time.

Future Focus

The project has provided an assessment of how environmental variability influences the productivity of a benthic reef community that could be extended to other reef systems across the Kimberley where the environmental conditions and benthic primary producers are known, or can be reasonably predicted.

Primary producers on Tallon's reef platform were highly tolerant to short-term extremes in temperature and light. At present, it is unclear if this tolerance will convey resilience to any future ocean warming, and further research into the susceptibility of low intertidal reefs and the potential resilience of tide-dominated reefs is warranted.

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Key Ecological Processes in Kimberley Benthic Communities Recruitment and Herbivory

Researchers collaborated with Bardi Jawi land and sea rangers to develop a detailed understanding of how fish, coral recruitment and herbivory act as key processes that sustain the health of the Kimberley marine ecosystem.

Overview

Recruitment and herbivory are key ecological processes that support coastal marine ecosystems.

Recruitment is essential for sustaining populations of fish and invertebrates, such as corals, whilst herbivory transfers energy from primary consumers to higher trophic levels and inhibits overgrowth of coral reefs by fleshy macroalgae.

This project has resulted in a better understanding of these processes in the Kimberley by quantifying when, where and how coral and fish replenishment takes place and what herbivores are responsible for most grazing on seagrass and algae in coastal marine areas.

Recruitment studies focused on hard corals, which provide complex habitat for many species but are threatened by climate change, and teleost fishes, many of which are of ecological, cultural and/or commercial value.

Herbivory studies focused on fish and turtles, which are prominent seagrass and algae consumers and are culturally significant to Indigenous people throughout the Kimberley.

This project has provided baseline knowledge of recruitment and herbivory across these plant and animal groups as well as to develop appropriate techniques that could be used to facilitate future research and monitoring to assist and inform management of marine ecosystems in the Kimberley.

Approach

This research was undertaken in collaboration with the Bardi Jawi Rangers in the Cygnet Bay and Sunday Island group area at the mouth of King Sound.

There were 24 field trips during 2015-16, with 13 trips focused on coral, eight on fish and four on herbivory.

Seven fish recruitment sampling techniques were trialed in five different habitats (intertidal pools, seagrass, mangrove, algal meadows and coral reefs). Unbaited stereo-RUV (remote underwater video) was found to be the most suitable technique and was used to assess seasonal trends across all five habitats during wet (March-April) and dry (October) seasons.

Coral recruitment was sampled each month at five locations for a 13-month period using coral settlement plates attached to frames that were specifically designed to withstand the strong tidal currents of the study area and were able to be deployed and retrieved from the surface rather than by SCUBA divers.

RUV footage was used to identify and quantify the key herbivores foraging in seagrass and macroalgal habitats.

Feeding rates of green turtles and rabbitfish on seagrass were assessed through tethering experiments combined with stomach content and stable isotope analyses to identify components of their respective diets.

Satellite tags were also deployed on 10 green turtles to assess their movement patterns and home range relative to available seagrass habitat.

Key Findings

Fish Recruitment:

Tidal current strength and habitat type was identified as critically important variables structuring fish recruitment patterns. Sampling was best undertaken using unbaited stereo RUVs during neap tides or 1.5 hours either side of spring high and low tides to minimse the effects of macrotidal currents.

Adults and juveniles of 125 fish species were identified across the five habitats. Among the juveniles, 88 per cent comprised the top 12 species including several of high value to the Bardi Jawi community because of their dietary and/or cultural significance (e.g. mangrove jack, golden-lined rabbitfish, spanish flag).

The highest diversity of juvenile fishes occurred on coral reefs (35 species), followed by mangroves, seagrass and algal habitats (18-20 species) and intertidal pools (13 species). Only six per cent of the total species were observed in all five habitats.

Distinct partitioning of nursery grounds was detected with mangroves and seagrass areas found to be critical nursery habitats for a number of important species.

The other three habitats shared a more common species pool, indicating that any future sampling should concentrate on mangrove, seagrass and, given their increased diversity, coral reef habitats to provide comprehensive coverage of fish recruitment.

Seasonally, fish recruitment was strongest in the wet season (March-April) for most species. Interestingly, some of the species considered important to the local Indigenous community were found to have year-round recruitment providing scientific support for documented traditional Bardi Jawi fishing knowledge and management practices.

Coral recruitment:

Our study was disrupted by a high water temperature event that culminated in coral bleaching in March-April 2016, affecting 30-60 per cent of the community. This coincided with the predicted mass-spawning period and led to reduced rates of recruitment for all corals, particularly for spawning corals.

Recruitment of *Acropora spp*. peaked in March-April 2016 and to a lesser extent in September-October, at the same time as mass and multi-specific spawning events were documented on oceanic reefs of the Kimberley and Pilbara to the south.

Recruits from pocilloporids (comprising both brooders and broadcast spawners) and genus *Isopora* were more abundant in the summer months.

The research also uncovered evidence of multi-month reproductive output and subsequent recruitment by poritid corals.

The number and composition of coral recruits differed considerably among the study locations, reinforcing the spatial heterogeneity evident in most studies of biological communities in the Kimberley.

Fine-scale spatial heterogeneity also varied, with evidence of recruitment in brooding corals over distances of less than a few hundred metres while broadcast spawning corals recruited over tens of kilometres, which concurs with genetic evidence from the KMRP connectivity project.

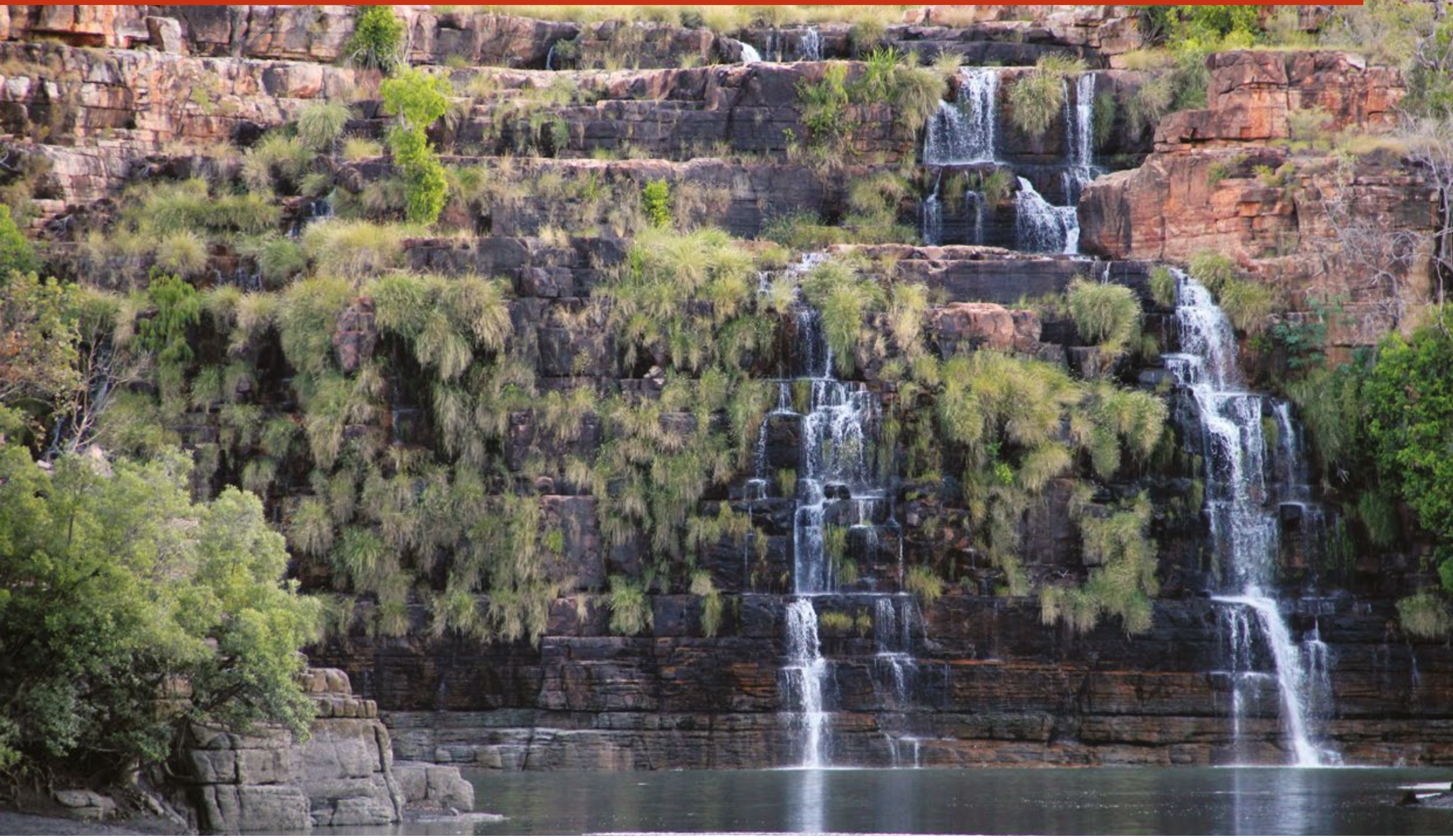
Herbivory:

Higher rates of seagrass consumption were documented compared with almost anywhere else in the world, more than ten times that of growth at some locations. This was particularly pronounced for the seagrass *Thalassia hemprichii* (turtlegrass), one of the most abundant seagrasses in the terraced lagoons of the Kimberley.

The apparent contradiction of high seagrass abundance and high consumption is probably reconciled by a combination of fast growth rates and patchy grazing; as rates of consumption of Thalassia varied by two orders of magnitude.

In contrast, consumption of the seagrass *Enhalus acoroides* was on average lower than growth, making it likely that much of its production is probably not consumed by herbivores.

Several herbivore species were abundant in the seagrass meadows, among which the golden-lined rabbitfish, *Siganus lineatus*, was ubiquitous and most consistently abundant. This species is a highly valued seasonal food source for the Bardi Jawi people, who call them barrbal. Stable isotope and gut-content analyses confirmed that rabbitfish primarily consume seagrass, especially Thalassia.



Stable isotope and gut-content analyses of green turtles, *Chelonia myas*, present in the area showed that they consumed a range of plant foods, but brown algae and *Thalassia* were particularly prominent in their diet and satellite tags confirmed that turtles frequently spend time in places with abundant seagrass. There was some, albeit equivocal, evidence that individuals exhibit different preferences for brown algae or seagrass.

Implications for management

Fish Recruitment

- Conservation policy and planning should recognise the conservation significance and ecologically important roles of nursery habitat for juvenile fishes when considering zoning for protected areas.
- This study provides a blueprint for future fish recruitment monitoring and includes established best-practice sampling techniques and locations of appropriate monitoring sites for quantifying fish recruitment across a range of representative habitats to form the basis for future long-term monitoring in the western Kimberley.
- More importantly, while recruitment is a key ecological process that sustains fish populations, rates of recruitment vary spatially and temporally and comprehensive fish recruitment monitoring could be expensive and ineffective. Monitoring of adult fish numbers may be an easier way to assess the health of the Kimberley's fish fauna and should take priority over recruitment surveys.
- Finally, this project provides quantitative evidence that traditional management practices have been effective in maintaining these ecological processes. Indigenous and local knowledge was integral in this project in understanding recruitment and in developing sampling strategy and sites. Integration of Indigenous and western science practices should continue to be implemented.

Coral recruitment:

Corals are important habitat-forming organisms in the inshore Kimberley and they rely on the dispersion and settlement of larvae to maintain populations and recover from disturbance. Understanding coral reproduction and recruitment promotes a greater understanding of which populations are potentially vulnerable to disturbance and should be taken into consideration in spatial planning and management.

This project has provided a protocol for quantifying coral recruitment suitable for the extreme environment of the Kimberley. This protocol was developed and implemented with assistance of the Bardi Jawi rangers and should be continued for cost effective monitoring.

Herbivory:

This research reinforces the importance of marine plants, especially seagrasses, to the diet of Kimberley marine fauna including species important as a seasonal cultural food resource.

Given the important ecological role that seagrass consumers play, monitoring these taxa should be given consideration for protected areas containing seagrass beds or macroalgae.

Several techniques are described by this study that are useful to understanding the relationship between seagrass habitat and herbivores, e.g. tethering experiments to assess the resilience of the seagrass and its grazers and tagging to assess movement patterns and identify important primary producer habitats.

Some work is still needed to develop methods for monitoring that can be adopted and applied uniformly by Indigenous ranger groups for Healthy Country Plan monitoring that are consistent with methods used in marine protected areas.

Future Focus

Additional surveys using the same technique would be needed to properly characterise fish recruitment across the broader Kimberley and should also take into account inter-year variability.

Further targeted research to better understand the ecological strategies used by fishes in the macrotidal environment of the Kimberley is needed.

Similarly, the mode of reproduction for some common Kimberley corals (e.g. broadcast spawning or brooding) remains unknown and warrants further investigation.

The importance of herbivory in habitats other than seagrass meadows such as reef and deep water meadows, and for other key herbivores such as surgeonfish and dugongs, remains an important gap in our overall understanding of the Kimberley.

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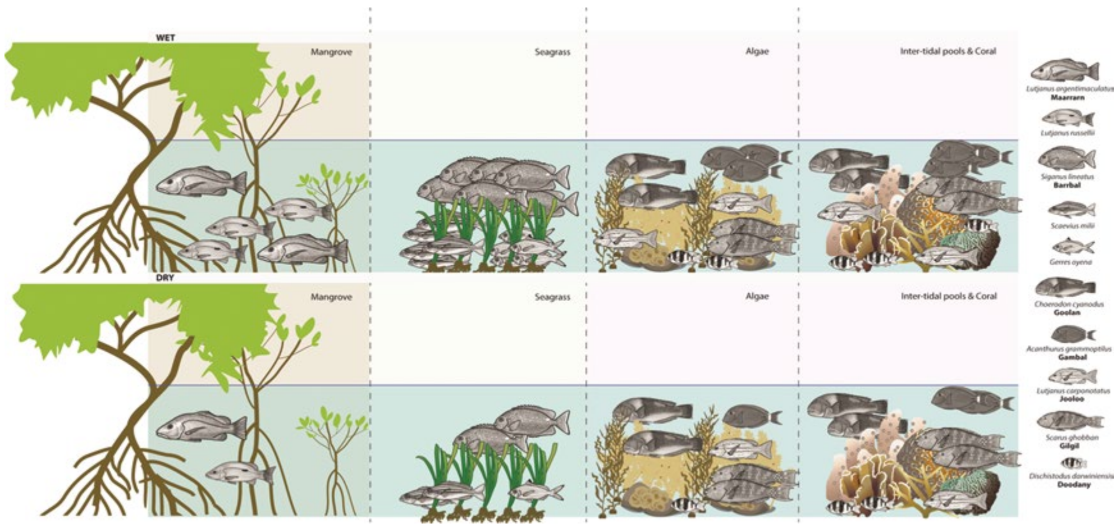


Graphical representation of juvenile fish distribution across five habitats during the wet (top panel) and dry (bottom panel) seasons in the southern Kimberley. Relative numbers and diversity types of fishes in each of the eight separate panels is representative of the key findings in this report.

Ecological Connectivity of Kimberley Marine Communities

The unique tidal regime and harsh environmental conditions of the inshore Kimberley provide a new frontier for understanding ecological connectivity and the environmental influences on the dispersal of marine larvae.

Overview

How far marine organisms move in their lifetimes depends on the interplay between their biology (capacity to swim or float) and the physical environment such as ocean currents and the distribution of habitat.

"Connectivity" describes how the movements of organisms can link the fates of distant populations. It determines the distribution and abundance of marine organisms and is especially important in enabling recovery after disturbance. Environmental managers can use an understanding of connectivity within marine systems to aid the design of management strategies, such as marine protected areas and the identification of fishery stocks.

The coast represents a fascinating, yet particularly challenging arena to investigate connectivity because of its uniquely powerful tidal regime, complex coastline and harsh environmental conditions. Added to this, Kimberley marine species exhibit an enormous range of capacities for movement, suggesting that connectivity in this region is likely to be highly complex and vary between species and across the region.

Approach

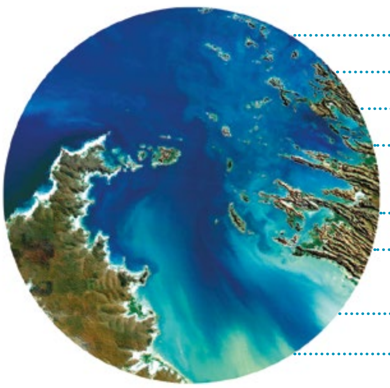
This research investigated connectivity in Kimberley marine species that have a range of capacities for movement.

Seven organisms (two hard corals, two seagrasses, a mollusc and two fishes) were chosen as models for exploring connectivity at both fine and broad scales based on their importance as habitat forming species, harvested species or trophic role.

Focal taxa were selected according to a range of life history traits that may be influenced by different hydrodynamic processes (i.e. larval brooders, broadcast spawners and demersal spawners).

A hierarchical sampling design was employed, whereby an intensive fine scale study at Dampier Peninsula and Buccaneer Archipelago, was nested within a regional study of the broader Kimberley, Pilbara and Gascoyne regions of WA and the NT.

Samples were genotyped using either single nucleotide polymorphism DNA markers (SNPs; corals, mollusc, fishes) or microsatellite DNA markers (seagrass). Wherever possible, taxa were sampled at the same geographic location.



1. Fine scale: the extent of connectivity differs among species
2. Fine scale: population boundaries are shaped between some taxa
3. Final scale: some sites act as links between otherwise isolated regions
4. Fine scale: King Sound and Sunday Strait are barriers to dispersal in some species
5. Broad scale: the inshore and offshore Kimberley are poorly connected
6. Broad scale: connectivity between the Kimberley and neighbouring bioregions differs among species
7. Broad scale: genetic diversity is distributed differently in each species
8. Broad scale: cryptic genetic diversity was detected in the broadcast spawning coral

Key Findings

Fine scale:

The extent of connectivity differs among species:

Despite experiencing a common set of environmental conditions, the extent of connectivity differed among the focal organisms.

Expectations of realised connectivity based on simple life history characteristics were found to be unreliable, suggesting patterns should be assessed on a species-by-species basis.

Habitat forming organisms (coral and seagrass) typically exhibited the most localised population structure, with evidence for limitations to routine dispersal evident on scales of tens of kilometres or less.

In the remaining organisms (fishes and trochus), population structure was weaker or not detectable, with limits to dispersal evident on scales of eighty to several hundred kilometres.

Population boundaries are shared between some taxa:

Major population boundaries were identified in several, but not all taxa, notably the habitat-forming corals and seagrasses, and the pelagic spawning fish.

Broadly, the divisions were between the Dampier Peninsula and Buccaneer Archipelago sites, with specific positions and breadths of boundaries differing for individual taxa.

This is likely due to the extreme environmental conditions, including tidal range, current speed, turbidity and freshwater input at the mouth of King Sound.

Some sites act as links between otherwise isolated regions:

Although restricted connectivity was detected in the region of Sunday Strait and the Dampier Peninsula for corals, seagrasses and fish, exchange of genes across this barrier over multiple generations occurs through the important stepping-stones at intermediate sites within this range.

Broad scale:

The inshore and offshore Kimberley are poorly connected:

The inshore Kimberley reef populations are highly divergent from the offshore ‘oceanic’ reef populations, including Rowley Shoals, Scott Reef, and Ashmore Reef, strongly indicating that these regions are ecologically and evolutionary independent for the species of corals and trochus that were sampled.

Connectivity between the Kimberley and neighbouring bioregions differs among species:

The seagrass *T. hemprichii* and the damselfish *P. milleri* exhibited a sharp discontinuity between the Kimberley and Pilbara while populations of stripey snapper *L. carponotatus* exhibited only weak genetic distinctiveness between the regions.

Genetic diversity is distributed differently in each species:

Within the Dampier Peninsula – Buccaneer Archipelago region, corals and seagrass exhibited large variation between sites in genetic diversity, whereas fishes and trochus exhibited similar amounts of diversity at each site.

For example, genetic diversity within seagrass *T. hemprichii* populations was significantly lower in the Kimberley than in the Pilbara whereas genetic diversity for the damselfish *P. milleri* was highest in the Kimberley and declined progressively with latitude towards the Gascoyne bioregion and the stripey snapper, *L. carponotatus*, demonstrated consistent levels of genetic diversity across the entire northwest coast.

These contrasting results likely reflect:

i. differences in population size;
ii. differences in connectivity between regions; and
iii. differences in colonisation history of the different regions.

Cryptic genetic diversity exists in the broadcast spawning coral:
Four genetically distinct, but morphologically cryptic, genetic lineages were detected in the coral *A. aspera* collection, strongly suggesting that these lineages are reproductively isolated, and thus likely represent unique evolutionary significant units and/or unrecognised species.

Management Implications:
The resilience of marine ecosystems to anthropogenic threats (e.g. overfishing, tourism, industrial development and oil spills) will critically depend on how ecological processes such as connectivity, which promote population persistence and regeneration, will be affected.

A better understanding of connectivity will enable the application of management strategies that protect healthy sources of recruits and maintain the exchange of adaptive genes which will nurture resilience in marine ecosystems.

Results of this study suggest that for all species examined (with the exception of trochus) movement and gene flow in the southern Kimberley is limited to scales of less than ~ 20km.

There are important hotspots of genetic diversity along with transition zones which act as conduits of gene flow and dispersal between otherwise isolated reefs.

The macro-tidal conditions experienced in the Dampier Peninsula – Buccaneer Archipelago are largely a barrier to the immigration of larvae from outside the Kimberley bioregion and in the case of the coral, *A. aspera*, may have led to a high level of cryptic speciation.

Importantly, the Kimberley bioregion, and some areas within it, is largely a demographically independent system that will require targeted management to safeguard its unique marine resources.

These findings should be recognised and considered in the planning and management of marine/Indigenous protected areas and fishery stock management.

Future Focus:
The scales of connectivity identified relate to the macro-tidal west Kimberley where sampling was intense. It is unclear whether these patterns would differ in the central and northern Kimberley where tidal currents are less extreme, possibly with less capacity to transport organisms. Additional comprehensive sampling and analysis throughout the Kimberley would be required to evaluate this hypothesis.

The high level of cryptic species-level diversity revealed in the coral *A. aspera* indicates that current estimates of species diversity in hard corals may be substantial underestimates and further taxonomic work is required for this and potentially other species.

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"Despite experiencing a common set of environmental conditions, the extent of connectivity differs among the focal organisms."

The Modelling the Future of the Kimberley Region project represents a synthesis of the whole KMRP program, using the new knowledge of the Kimberley marine environment and its many ecological, physical and social components to explore future scenarios in both regional development and climate change, as well as the impact and relative success of various management strategies.

New Knowledge and Tools

- Contemporary and historical coral calcification rates
- Baseline data on coral health before and after bleaching event
- Numerical model simulating coastal circulation
- Conceptual and numerical models of the links between land, coastal and marine systems in the Kimberley

Measuring Changes to the System

Together the KMRP results have characterised the Kimberley marine environment, providing an understanding of the biodiversity, its distribution and the physical and ecological processes that support it along with information on some of the key pressures. Having that foundational information establishes an important capacity to detect change and consider when management is needed to mitigate impacts.

While the Kimberley is a remote area with low population and minimal anthropogenic impacts to date, it's on the threshold of change as regional development, the resource industry and tourism expands.

The impact of climate change however, is considered to be one of the biggest future influences on the Kimberley marine environment that will likely affect marine processes and ecosystems.

The projects highlighted in this section have each provided a means of detecting, predicting and understanding change to the environment.

Key management questions

- How have environmental conditions, including water quality, changed in the inshore Kimberley region over the past 50-100 years?
- How will coral reefs of the Kimberley respond to increasing water temperature, ocean acidification and frequency of cyclones with ongoing climate change?
- What methods can be used to measure the condition of marine assets and pressures upon them in long term monitoring programs?
- What are the main climate change threats to marine biodiversity in the Kimberley and what indicators can be used to understand these impacts?
- How will existing marine habitats and biodiversity respond to change?

Remote Sensing for Environmental Monitoring and Management in the Kimberley

Remote sensing technologies offer a cost-effective method to monitor change in the marine environment which can be used to inform management of the coastal region.

Overview

Remote sensing is the acquisition of data at a distance from the area of interest using aircraft, satellites, ships etc. Remote sensing data has increasingly been used to monitor the natural environment as it can offer a cost-effective method to gather historical and baseline data at synoptic (large) scales, as well as near-real-time observations at increasingly fine spatial resolutions. Its application in the Kimberley is particularly beneficial as remote sensing can complement and at times reduce the need for large-scale fieldwork which can be both hazardous and prohibitively expensive across this vast and remote region.

This technology can contribute to improving asset inventories and monitoring changes in the marine and coastal environments.

Archives of remotely sensed data extend back more than 25 years providing a potentially valuable record of changing environmental conditions.

Furthermore, through providing observations that can be used to validate or challenge models, they can increase the reliability of the deterministic models (hydrodynamics, biogeochemical) and probabilistic models required to develop adaptive management related approaches to manage these unique environments.

The turbidity of inshore Kimberley waters is considered one of the most important influences on marine communities of the region as it affects light transmission through the water column to the seabed substrate, with potential impacts on the rates of production for photosynthesising organisms.

The visible spectrum and near-infrared (NIR) sensors on earth observing satellites can provide estimates of total suspended solids (TSS) concentration and diffuse attenuation of light (Kd).

This information, coupled with bathymetry data, is used to estimate light levels in the water column and at the seabed substrate. This is important for assessing the impact of turbidity on primary production and monitoring changes in the system through spatial and temporal variability in the turbidity.

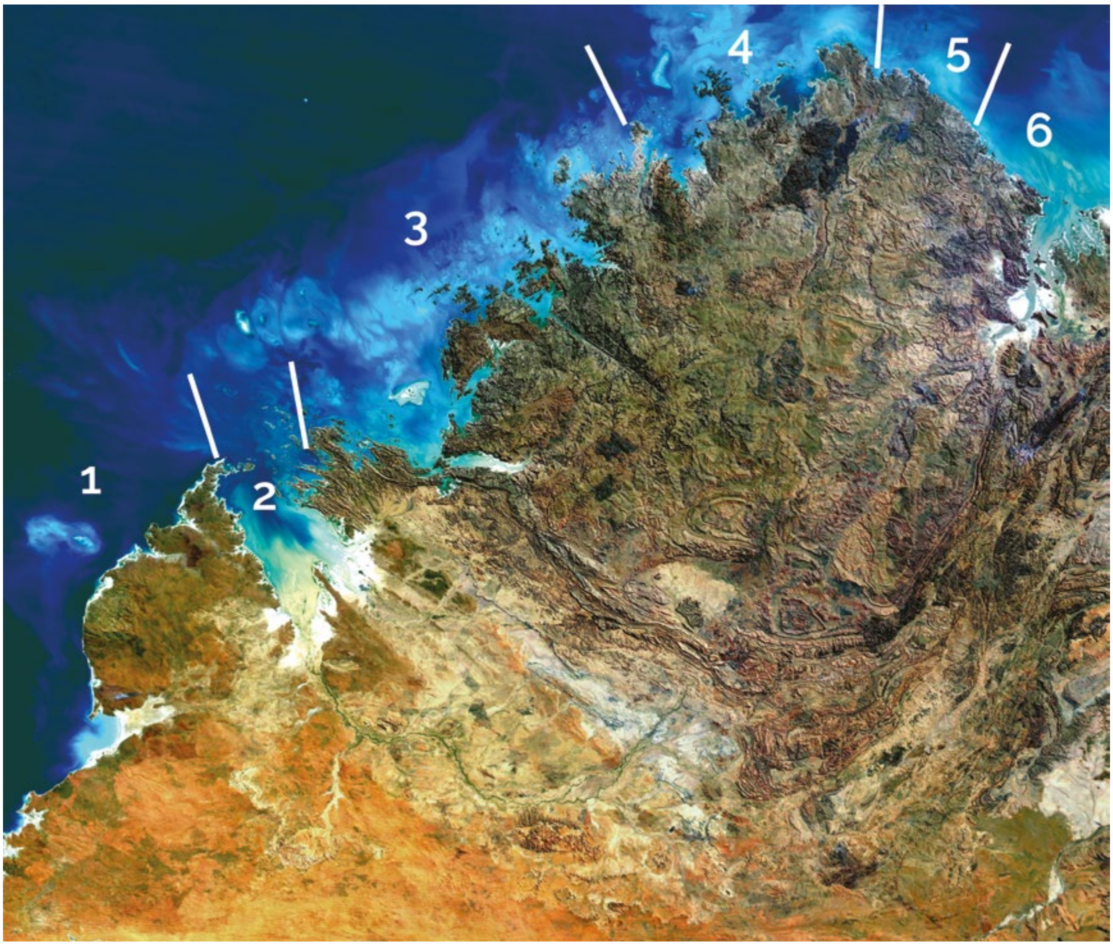
Before such technologies can be widely applied as marine management tools, there is a need to understand the uncertainties inherent in using remotely sensed products.

Approach

A review of management requirements for remotely sensed data compared with the technical and operational constraints of remote sensing technologies available identified turbidity and its impact on the in-water light field as the highest priority property to evaluate for management.

Reference data sets of in-water constituents, chlorophyll-*a* (Chl-*a*) and TSS concentration, as well as optical data sets measuring apparent optical properties (e.g. diffuse ocean reflectance) and inherent optical properties (i.e. light absorption and scattering) were collected *in situ* to understand uncertainty of the products.

The remotely sensed products tested were all derived from the Moderate Resolution Imaging



Approximate boundaries of the six regions identified by analysis of spatial patterns in annual anomalies. (1) Broome and surrounds, (2) King Sound, (3) Collier Bay and surrounds, (4) Kalumburu, (5) the region north of Berkeley river, and (6) the region extending beyond the Western Australian border to capture the Joseph Bonaparte Gulf.

Spectrometer (MODIS) on the US Government's Aqua and Terra satellites.

A regionally-tuned algorithm for TSS, developed in waters of the Pilbara region, was compared with two different global scale algorithms.

The 16-year archive of TSS data from the MODIS satellite sensor produced with the regional algorithm was statistically analysed to describe the patterns of spatio-temporal variability.

Analysis of an *in situ* dataset of inherent optical property measurements taken from low turbidity water was completed in order to separate the relative contribution of different optically-active constituents on light absorption in the wider Kimberley marine region (40-2000 metres depth range).

Key Findings

A combination of empirical orthogonal function and anomaly analysis identified six regions along the Kimberley coast that may be considered different in terms of variability, impact of extreme TSS, and influence of tidal forcing.

Time-series analysis showed two seasonal peaks in TSS concentration in the water column; one in the early part of the year (February to March) coinciding with peak river discharge in the wet season (November to April), and a second larger one during the months of June and July.

Closer examination revealed that TSS also fluctuates on a fortnightly time-scale consistent with tidal cycles.

These findings suggest an important role for mixing in determining the vertical distribution of suspended sediments.

The highest concentrations of TSS were found in King Sound and Collier Bay in the vicinity of major rivers such as Fitzroy River. Patches of relatively high TSS were also observed further from shore.

A light at depth (LAD) product was also derived after incorporating TSS, bathymetry and modelled tidal range and can highlight changes in the marine light environment.

The LAD is expressed as a percentage of the 'at-surface light' that reaches the depth of the substrate and is useful for determining regions where the impact of TSS decreases the light levels to such an extent that the potential for photosynthesis is decreased.

Management Implications

Remote sensing has been shown to be useful in providing data appropriate for detecting and quantifying turbidity and TSS concentration, as well as for visualizing spatial patterns and identifying change from time series analysis.

Through the provision of near-daily retrospective views of the environment, an assessment of baseline environmental conditions can be made against which past and future change can be measured.

These technologies have provided data coverage for the complete Kimberley region highlighting the spatio-temporal patterns of remotely sensed TSS and identifying six different coastal regions in the Kimberley.

Although remote sensing represents the lowest cost approach for routinely collecting scientific data at a regional scale, it is important to note that provision of high quality regional remote sensing products relies on the availability of regional *in situ* measurements for tuning and validating algorithms.

Future Focus

The reference datasets used to assess the uncertainties of the remotely sensed products were too sparse to allow a rigorous assessment of algorithm accuracy. Additional *in situ* measurements and datasets are required to monitor algorithm performance and in turn to further understand the variability under different environmental conditions.

Future exploration of regional algorithms that account for the range of optically active constituents in marine waters (i.e. types, concentrations ranges, seasonality, tidal cycles, water depths and proportions of organic and inorganic substances) is needed to create "locally tuned" algorithms, or more advanced analytical algorithms which would produce more reliable results than generic empirical approaches.

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Climate Change: Knowledge Integration and Future Projection

Historical data and numerical models have been used to identify the climate sensitivity of the Kimberley coast to climate variability in the Pacific and Indian Ocean over the past several decades.

Overview

Ocean climate is largely defined by temperature, salinity, circulation and the exchange of heat, water and gases with the atmosphere and exhibits significant interannual and decadal variations, mostly due to the dominant modes of climate variability in the coupled atmosphere-ocean system, such as El Niño-Southern Oscillation (ENSO).

Understanding the impacts of interannual and decadal climate variability and long-term climate change on regional ocean climate, its temperature, salinity, and ocean circulation, is crucial for effective marine environment management.

The Kimberley coast, situated in tropical northern Australia, is strongly influenced by the Australian monsoon and ENSO variability, and to some extent by the Indian Ocean dipole and Madden-Julian oscillation (MJO).

Sea surface temperature of the Kimberley coast appears to be warmer during El Niño, compared to the rest of the west coast of Australia where temperatures are warmer during La Niña.

The ocean temperature of the Kimberley coast has been rising due to climate change at a moderate rate of 0.05 to 0.1˚C per decade, which is lower than the rate of ocean warming observed off Australia's southwest. However, the Kimberley coast also appears to have experienced more frequent extreme hot temperature events during summers over the past 30 years.

Given the climate sensitivity of the Kimberley coast, it is likely that climate change will have significant impacts on the region's marine physical environment in coming decades with flow on effects to biodiversity and ecosystems.

Therefore, it is important to better quantify climate sensitivities and develop modelling tools that:

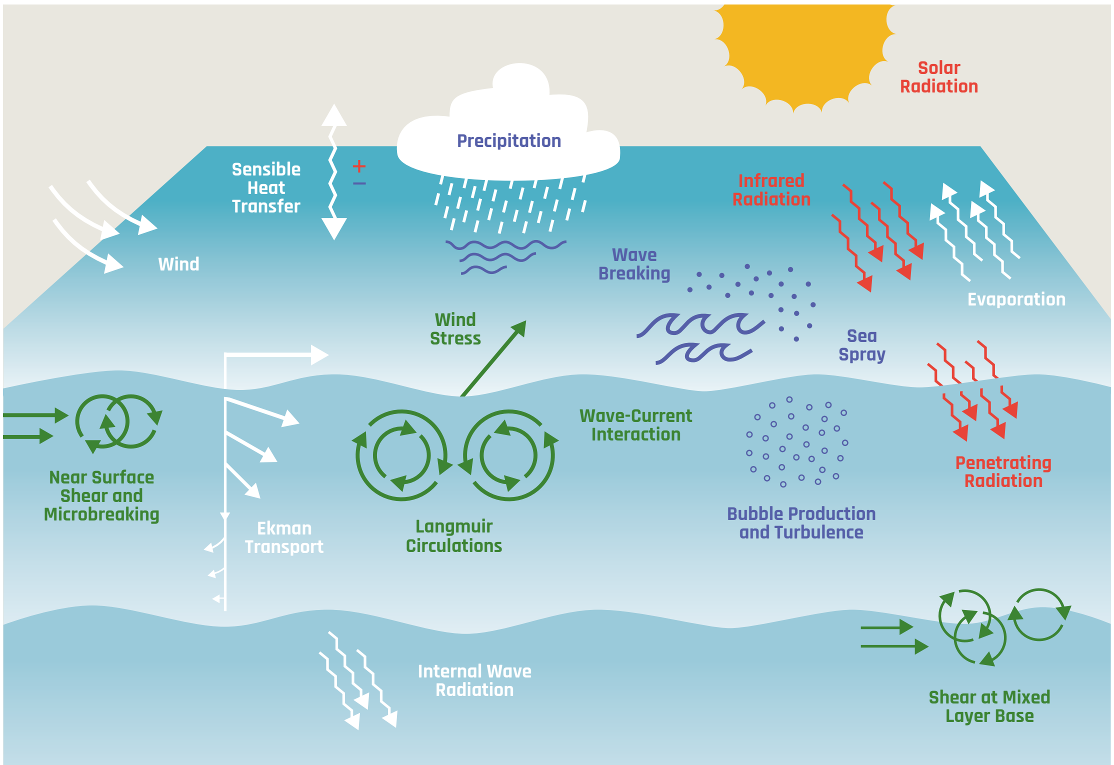
i. will improve the predictability of climate-driven environmental variability and changes, such as marine heat-waves; and
ii. can project future changes to the marine environment in areas like temperature and internal wave characteristics.

Approach

Ocean downscaling models were used to project future climate change impacts on the marine environment such as the ocean temperature and internal wave characteristics.

A ROMS shelf model was built for the Kimberley region and nested in the Ocean Forecasting Australia Model version3 (OFAM3) model outputs to simulate the coastal circulation off the Kimberley during 2009-2012.

A regional downscaling model utilised the existing ROMS model simulation for the period 2009-2012 as the current climate, which has captured some extreme ENSO climatic events. For the future climate, an equivalent period during 2066-2069 was used to nest the ROMS model within the OFAM3 simulation under the RCP8.5 climate scenario. The OFAM3



Processes affecting the upper ocean heat balance and SST.

model provides the initial and open boundary condition for ROMS, and the ROMS model was forced with the same reconstructed atmospheric fields.

Key Findings

Precipitation variability of the Kimberley coast is highly sensitive to ENSO variability in the Pacific.

High precipitation tends to occur during La Niña and low precipitation during El Niño, due to ENSO modulation of the strength of the Australian monsoon and atmospheric convection activities.

The salinity of water in the Indonesian throughflow and the coastal Kimberley reduced by more than 0.2 psu during the extended La Niña conditions in 2010-11, mostly due to unusually high precipitation rates in the region during this time. A decadal trend of reduced ocean salinity is apparent in the region which may have implications for marine biota.

Coastal sea level variability in the Kimberley coast is also influenced by ENSO, through the ocean waveguides.

High sea levels during La Niña and low sea levels during El Niño are influenced by ENSO-related trade winds and sea level anomalies in the western Pacific, transmitted through the Indonesian archipelago. High sea level anomalies off the Kimberley coast during La Niña often align with stronger water movement through the Indonesian throughflow.

Sea surface temperature off the Kimberley coast is higher during summer and cooler during winter with seasonal ranges of about 4-5˚C.

Unlike the sea surface temperature off the Pilbara coast, the Kimberley is warmer during El Niño events than La Niña events. This may indicate that sea surface temperature is more influenced by air-sea exchanges on the shelf instead of coastal currents.

During El Niño, increased solar radiation (due to less cloud coverage) and a weakened Australian monsoon warm the ocean surface.

There has been an increase in frequency of marine heatwaves off the Kimberley coast during austral summers over the last three decades, with most occurring during El Niño events. This warming can be strong without the co-occurring influence of the Indian Ocean dipole, which can dampen this warming tendency.

The climatic trend of more frequent El Niño events in the Pacific during the 1960s to 1990s has reversed with more frequent La Niña events

over the last two decades, which have affected the occurrence of extreme climatic events off the Kimberley coast and may have masked some long-term climate change signals.

Climate projections suggest that the ocean temperature of the Kimberley coast will warm by more than 1 °C in the next 50 years. The future climate projection using a high-resolution shelf model suggests that internal wave energy on the continental shelf will likely increase due to surface warming leading to increased water column stratification on the shelf. Hence, increased cross-shelf exchange may occur in the future which could bring more deep nutrients onto the shelf.

Management Implications

Ocean temperature and salinity fluctuations affect the growth and health of marine species.

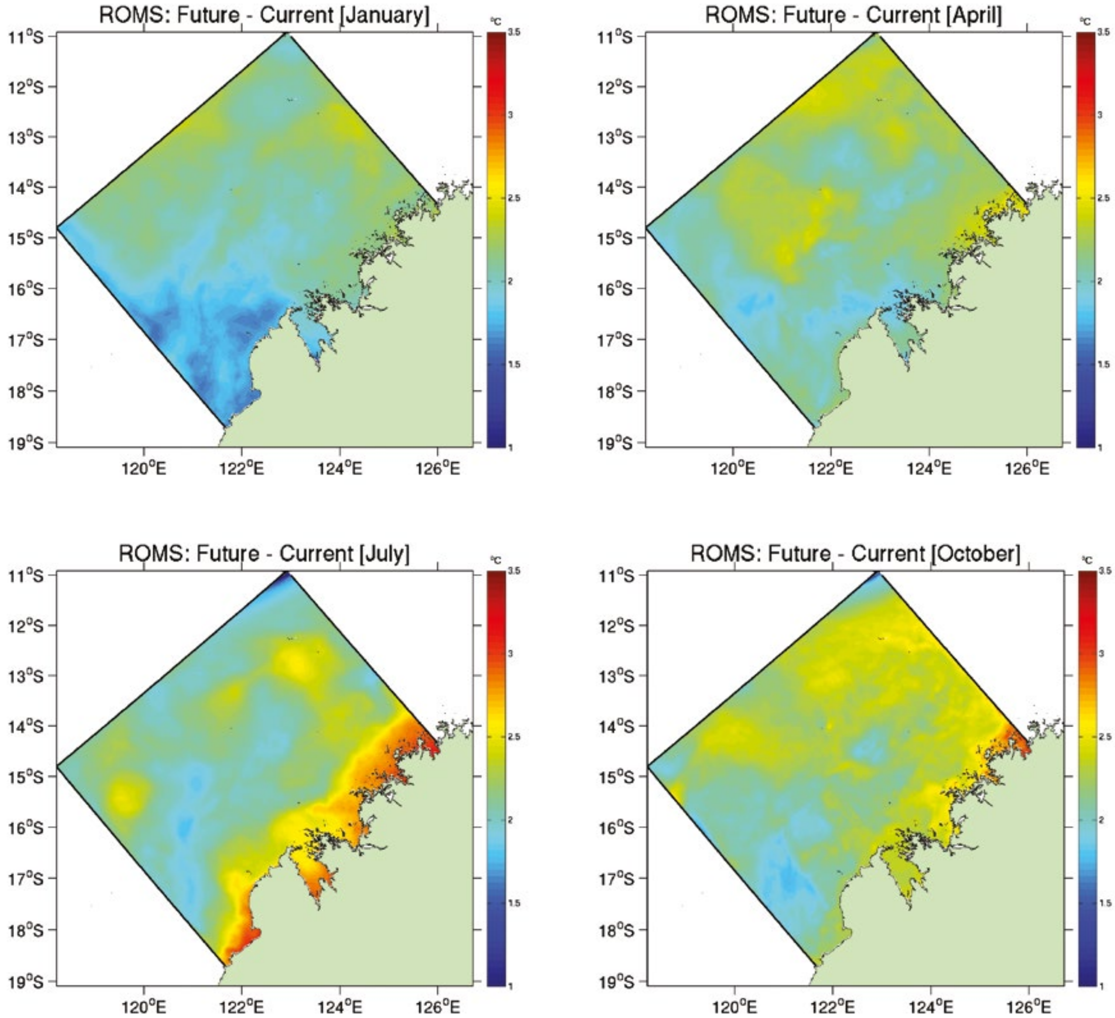
Fisheries and aquaculture industries of the Kimberley region must understand the climate-driven influences of temperature and salinity variation in the region, such as warming during El Niño events and reduced ocean salinity resulting from heavy precipitation during La Niña events.

It is recommended that these industries use tools such as ENSO predictions hosted on the Bureau of Meteorology website and the CSIRO Bluelink model results hosted on the Integrated Marine Observing System (IMOS) website to monitor the current climate information and oceanographic conditions off the coast and prepare adaptation responses.

Coral bleaching is one of the key threats to coral reef communities and the highest risk of coral bleaching occurs during extreme events (i.e. marine heatwaves). Off the Kimberley coast, these are more likely to occur after the peak of an El Niño event, particularly in years without a corresponding Indian Ocean dipole. Variability of the Australian summer monsoon and other weather variability like the Madden-Julian Oscillations are also likely to trigger the occurrences of marine heatwaves.

Ocean temperature off the Kimberley coast is likely to warm by more than 1 °C in the next 50 years due to human-induced climate change, which would exceed the thermal tolerance of many marine species such as seagrasses and macroalgae.

Sea level will continue to rise due to the ocean temperature warming and ice sheet melting. Under predicted climate change circumstances, extreme ENSO events are likely to occur more often, causing more marine heatwaves. These changes will affect marine ecosystems off the Kimberley coast.



Generally, the sea surface temperature warming along the coast in the next 50 years is about 1-3°C, with fast warming trend during austral winter season. (Sea surface temperature differences between 2066-2069 average and 2009-2012 average using ROMS downscale model [Climate Change].

Although the tropical Pacific climate will assume an increasingly El Niño-like condition under future climate projections, precipitation changes off the Kimberley coast are uncertain due to the competing climate impacts of factors like an increase in greenhouse gas, but potential reduction of Asian aerosol influence.

Future Focus

While the prediction of regional ENSO influences have greatly improved in recent years, broad-scale predictions of the Indian Ocean remain limited.

Although ocean temperature of the Kimberley coast is often warmer during an El Niño event, the magnitude of the warming remains unpredictable, and the timing and severity of marine heatwave events is sometimes related more to short-term climate variability. An additional regional model experiment for the Kimberley coast using the CSIRO regional model and targeting a few MJO events in austral summer would further enrich our knowledge and capability on the predictability of shelf current and temperature responses to the MJO forcing.

Climate change will not only induce warmer ocean temperatures, it will also affect the water column stratification in coast regions. The stratification change may affect the vertical mixing of nutrients and limit coastal sediment resuspension. The mechanisms of how the physical environment changes will affect the biology and marine ecosystem remains largely unknown and should be further explored.

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Resilience of Kimberley Coral Reefs to Climate and Environmental Extremes: Past, Present and Future

Corals in the Kimberley have shown remarkable stress resistance to the natural extremes of this environment through adaptations to their physiology, which is critical for their ongoing survival under changing climate conditions.

Overview

The Kimberley region is a naturally extreme environment that features abundant and highly diverse coral reefs.

Nearshore corals in some Kimberley locations are exposed to average monthly temperatures of around 22˚C in July to over 31˚C in December, and which may exceed 30˚C on average for around five months each year.

They are also subject to diurnal tidal amplitudes of up to 12 metres that can expose corals to potentially stressful and damaging levels of temperature and light for extended periods. Exposed tidal pools can become stagnant, lowering the availability of oxygen and further increasing the stress on corals.

Corals living in naturally extreme environments can provide important insight into the mechanisms underlying coral resistance to thermal stress. Thus, intertidal and near-shore environments along the Kimberley coast provide a challenging thermal environment to which corals have adapted.

In 2015/16, unusually high ocean temperatures associated with one of the strongest El Niño events on record resulted in a global mass bleaching event (NOAA 2015) with the greatest heat stress in Australia occurring along the northern WA coast including the remote Kimberley region.

This project has established an understanding as to how corals in the Kimberley, the key ecosystem engineers on tropical reefs, have adapted and will respond in the future to the extreme variations in physical (e.g. light, temperature, water motion) and chemical (e.g. pCO_2, oxygen, and nutrients) conditions characteristic of the Kimberley coastal region.

Approach

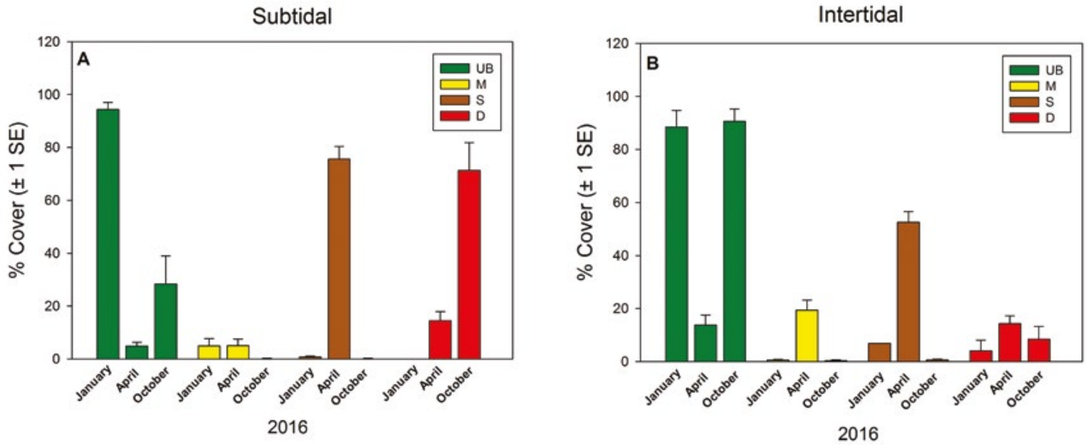
Present-day calcification rates on seasonal time scales:

Calcification rates of the common Kimberley corals *Acropora aspera* (branching), *Dipsastraea favus* (massive) and *Trachyphyllia geoffroyi* (massive) were studied in Cygnet Bay at three experimental sites with varying degrees of tidal influence to examine the influence of season, tidal exposure and region on calcification rates. A comparative study was conducted on corals of the same genus or species at Coral Bay in the southern part of Ningaloo Reef.

Thermal tolerance and bleaching thresholds of Kimberley corals:

A controlled mesocosm experiment was conducted to assess the thermal tolerance and bleaching thresholds of branching *Acropora aspera* and massive *Dipsastraea* sp collected from a tide pool and a subtidal environment, in Cygnet Bay.

The photochemical efficiency of all corals was monitored daily and the health status of each fragment was assessed at the end of the experiment to determine the effects of time and/or temperature and environment on the physiological variables.



Changes in coral health (per cent of coral cover) pooled for all coral genera between January, April and October 2016 in the A) subtidal and B) intertidal, respectively. U = unbleached, M = moderately bleached, S = severely bleached, D = dead.

During the extreme 2015/16 El Niño, coral health monitoring was conducted in intertidal and subtidal habitats near Cygnet Bay to assess the impacts of a potential marine heatwave on coral health.

Historic records from coral cores:

A coral core, approximately 1.2 metres in length, was collected from a *Porites* colony in the subtidal zone of Shell Island near Cygnet Bay, comprising skeletal growth from 1919 to 2015.

High-resolution and annually-resolved geochemical measurements were conducted to measure skeletal trace element ratios and stable isotopes to provide an understanding of the influence of changes in seawater temperature and other environmental factors in reef growth at a mechanistic and physiological level, as well as its responses to climate change.

The Ba/Ca ratio and oxygen isotopes ($\delta^{18}O$) were compared to the nearby Fitzroy River discharge and cyclone records to evaluate the influence of cyclone-induced sediments loading and runoff input.

Key Findings

Present-day calcification rates on seasonal time scales:

While Kimberley corals generally exhibit high resilience of calcification to extreme temperature variations, the exact mechanisms of adaptation and/or acclimatisation vary strongly between taxa.

Common Kimberley corals calcified at rates that were comparable or faster than those from similar corals at Ningaloo Reef.

The effects of tidal exposure and season were highly species-specific: branching *A. aspera* grew more slowly in the environmentally more extreme intertidal than in the subtidal, whereas massive *D. favus* and *T. geoffroyi* grew faster in the intertidal environment.

Thermal tolerance and bleaching thresholds of Kimberley corals:

Physiological measurements showed that Kimberley corals are highly susceptible to heat stress and coral bleaching despite being adapted to a naturally extreme temperature environment.

In the branching *Acropora* corals, ~20 degree heating days resulted in up to 75 per cent mortality or severe losses of symbiont cells and chlorophyll-*a* while massive *Dipsastraea* corals also experienced significant loss of symbiont cells and chlorophyll-*a*, but all corals survived and symbiont losses were not as pronounced.

The best estimate of a coral bleaching threshold for Kimberley corals is ~32°C average daily temperature for only a few days, only ~1°C higher than maximum monthly mean (MMM) temperatures. This confirms that Kimberley corals are living precariously close to their physiological limits for enduring thermal stress which are remarkably consistent at 1-3°C above regional MMM, regardless of location.

Intertidal corals of both species were generally more resistant to heat stress than the subtidal corals.

Since all corals harboured the same genetic type of *Symbiodinium* (clade C) independent of origin or treatment, this indicates that the native thermal environment plays a critical role in shaping coral thermal tolerance.

These findings were confirmed during the first documentation of a regional-scale bleaching event in the Kimberley during March/April 2016 which indicated that bleaching in the subtidal environments was more severe and widespread than the intertidal and six months later most corals in the intertidal environments had recovered, whereas the subtidal corals suffered significant mortality.

Historic records from coral cores:
The calcification rates of massive *Porites* spp. coral have been relatively stable (~1.2 to ~1.6 g/ cm^2/yr) for the past ~100 years.

No significant trend was observed, despite a slight warming trend in the reconstructed annually-resolved seawater temperatures since 1919 and more variable temperatures since the 1970s.

Key calcification mechanisms in Kimberley corals are not compromised by the extreme environmental conditions, resulting in high and stable calcification rates as observed in corals from less extreme reef environments.

Management Implications

Although Kimberley corals have been shown to be resilient to the natural extremes of their environment, the regional heatwave in the 2015/16 summer highlights the increasing threat of ocean warming and marine heatwaves to the Kimberley marine environment. Hence, management should focus where possible on minimising local stressors to maximise ecosystem resilience, particularly during heat stress events.

Intertidal coral communities, having shown higher resilience to these events, should be the focus of awareness and protection efforts as their naturally higher heat resistance resulted in significantly higher survival and recovery than the less tolerant subtidal coral communities during the first documented mass bleaching event in the region.

Given the negative impacts of increased sediment and nutrient concentrations on water quality and coral health, monitoring of sediment/nutrient input into the Fitzroy River catchment should be a key priority to ensure that terrestrial management limits any increase in the sediment input into river catchments particularly during severe river discharge events.

Future Focus:
Due to their resilience, Kimberley corals should be prioritised for long-term coral health monitoring and further research into the mechanisms enabling such remarkable stress resistance in reef-building coral.

This should include assessing the physiological, genetic, genomic and biogeochemical mechanisms that enable the high resilience of Kimberley corals to heat and other environmental stressors. It should also include determining whether their capacity to acclimate and/or adapt to ongoing climate change and ocean acidification can be used for proactive management approaches.

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Historical Reconstructions of Water Quality in the Kimberley Using Sediment Records

Suspended sediments derived from marine and terrestrial environments settle out onto the substrate to form layers that capture information on the environmental conditions of the time, and form a record of those conditions in marine and terrestrial environments.

Overview

Water quality and the pelagic biological oceanographic environment is influenced by natural climate variability, greenhouse induced climate change and other anthropogenic influences e.g. nutrients from grazing, agriculture and other catchment uses including those in coastal towns and cities.

Understanding impacts from local and global pressures on the environment is difficult without extended and consistent time-series data which rarely exists for remote areas like the Kimberley.

The remote Kimberley coast is one of the few marine environments relatively unaffected by human use, but the region is undergoing increasing economic importance as a destination for tourism and significant coastal developments associated with oil and gas exploration. As a result, there is a need to gain an understanding of the historical and baseline environmental conditions.

This project has reconstructed a timeline of water quality changes using paleoecological and biogeochemical techniques on sediment cores for selected sites in the Kimberley with contrasting human uses and/or environmental influences to better understand the impacts of different pressures on the marine environment.

The results provide an indication of the level of variability and change in water quality over the last 100 years and provide a baseline against which future changes can be measured.

Approach

A suite of paleoecological approaches were used to reconstruct a chronology of change in coastal water quality over the last ~100 years at Koolama Bay (King George River), Cygnet Bay and Roebuck Bay in the Kimberley.

Sediment cores up to 1.5 m deep were collected from each site and tested for a set of parameters every 1-2 cm including 210Pb, 15N, 13C, C/N ratio, sedimentation rate and grain size, total organic carbon and nitrogen, biosilicates and biomarkers.

The biogeochemical proxies addressed phytoplankton composition and biomass, temperature and terrestrial influences.

Where possible these were matched to historical land/water use, meteorological or hydrological observational records.

Each sampling location provided a contrast with which to evaluate changes over either a spatial or temporal gradient of human or natural influences and was used to answer specific management questions.

Key Findings

Cygnet Bay:
The impact of pearl farming on water and sediment quality: With a 50-year history in Australia, pearl oyster aquaculture has been regarded as an activity with low environmental risk. Sediment cores taken in Cygnet Bay, Western Australia, from both inside and outside

a pearl farm lease were used to assess the long-term environmental effects of pearl oyster farming through spatial comparison of multiple proxies (grain size, TOC, TN and BSi, C/N ratio, $\delta^{13}C$ and $\delta^{15}N$).

Significant increases in organic matter, diatom biomass and fine-grained sediment displayed at the oyster farm site coincided with the advent of modern long-line culture methods and the expansion of oyster stocking indicating that oyster farming results in small environmental changes over long periods of time that can be detected using these methods.

In contrast, the only changes outside the pearl farm area were variations over time in response to climatic signals (rainfall and temperature).

The rapid development of modern long-line culture since the late 1980s was presumed to be the dominant driver of environmental changes in sediments.

The results provide insight to the magnitude of environmental change, which can occur over decades resulting from even apparently benign industries and activity.

Although sediment quality in King Sound did not reach a eutrophic level, the study showed that small environmental disturbances accumulating over a long period of time may cause detectable changes in marine ecosystems, particularly in sensitive oligotrophic waters.

Koolama Bay (King George River)

The impact of riverine inputs and climate change: The large freshwater output into Koolama Bay from the King George River offered the opportunity to compare sediment cores from two embayments; one influenced by the river catchment and large freshwater outflows and an adjacent embayment without direct riverine input, to determine the influence of these freshwater pulses.

There was no evidence of sedimentary differences attributable to differential freshwater flows and little evidence that the contribution of carbon from land-based plant material had changed over time.

The cores did show significant evidence of an increasing contribution of marine organic matter over time and a coincident increase in diatom and dinoflagellate biomarkers which is interpreted as indicating an increasing biomass of marine phytoplankton resulting from ocean warming.

Broome – Roebuck Bay

influence of outflow from Dampier Creek on water and sediment quality: The potential to detect any influence of historical or recent anthropogenic input from urban runoff from Broome via Dampier Creek as well as direct intentional or accidental inputs from other sources (e.g. wastewater treatment plant, the old abattoir and the golf course) was investigated through the measurement of nitrogen and coprostanol, a biomarker of sewage.

Levels of ^{15}Nitrogen increased gradually to the present, but significantly at sites closest to Broome from about 1960 (20 cm core depth), highly suggestive of a real increase in anthropogenic nitrogen discharges from Broome.

Coprostanol was at levels close to the limit of detection in the samples and thus there was no evidence of significant sewage pollution.

Both biomarkers of increased terrestrial influence and various indicators of increased productivity show a relationship with rainfall increase. Thus, the changes detected, while probably more related to urban growth rather than specific event(s), also coincide with climate change impacts.

Impact of climate change on phytoplankton biomass: While increased rainfall since the late 1990s and the passing of tropical cyclone Rosita in 2000 is likely to have had an influence on the amount of land-based plant material incorporated into sediments, increased temperature rather than increased rainfall had the greatest influence on phytoplankton biomass, total organic carbon and total nitrogen detected in cores at both sites.

It is likely that ocean warming has led to a significant increase in primary production in the region based on these results.

Management Implications

The results of the suite of investigations indicates that measurement of selected biomarkers in sediment cores can provide useful information for a range of potential environmental pressures.

They provide a historic pattern that can be compared with external measurements and assist in understanding chronic and acute changes to the environment and predication of future environmental impacts to aid in the application of mitigation measures.

In particular these studies have indicated that:

i. Climate change, especially temperature increases, has had a significant influence on phytoplankton biomass and this is expected to continue. This may be of benefit to pearl farming but may have other, yet unrealised, impacts on ecosystem dynamics.

ii. Increased nutrient pollution in Roebuck Bay is occurring and the potential impacts need to be better understood so that they can be managed to avoid enduring detrimental impacts.

iii. Small but accumulating changes in the environment associated with pearl farming are detectable even from minimal anthropogenic activity and may require mitigation measures.

Future Focus

There are a number of useful improvements to the methodology used in this study that would assist with future questions.

For example, there is a need for improved spatial coverage of rainfall measurements and records of river discharge in the Kimberley to link hydrological and meteorological forcing with ecological data sets.

Also, examination of microfossils in sediments compared with phytoplankton in the water column would reveal whether there has been a change in species composition associated with the biomass increases providing an additional line of evidence for temporal changes in the sediments.

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Can black carbon from bushfires be detected in sediment cores?

Black carbon (BC) or elemental carbon is produced exclusively from incomplete combustion of biomass and fossil fuels, and is ubiquitous in the environment.

BC from bushfires can make its way into marine sediments by two pathways: it can settle from the atmosphere; or it can be transported from the site of the fire through river runoff.

The potential for using BC analyses of coastal marine sediment archives to reconstruct the time course of, or to reflect the temporal variability in, bushfires in the Kimberley was investigated.

BC in the cores showed peaks in the (approximate) years of 1974, 1980, 1996, 1999, 2010 and 2012 and lows in 1986, 2002 and 2006.

We found that a model incorporating early season area burnt (with a one-year lag, i.e. the year before) and rainfall explained a significant amount of the variability in BC (R2=0.812, p=0.035).

This result is intuitive but needs to be regarded with caution as the sample size was small (bush fire data matched to BC from 2002-2013) and the rainfall record was from an adjacent catchment.

Nevertheless, the result is encouraging and suggests that a study which sought to optimise the spatial and temporal matching of good time series of explanatory data (area burnt and rainfall) and a sediment core location with a good sedimentation rate and good age preservation would yield results which could be regarded with greater confidence.

Future work on BC could focus on King Edward River catchment as it has a good rainfall record (since 1940), it has a very large catchment area (84,000 km2) and a much larger area burnt each year (> 600,000 ha compared to <250,000 ha in King George River).

In addition, the King Edward River flows into a semi enclosed embayment (Napier Broome Bay) which will offer the likelihood of a higher sedimentation rate and less sediment disturbance.

The targeting of locations for sediment cores based on hydrological and sedimentological considerations would benefit detection of black carbon BC to link to bush fire history.

Modelling the Future of the Kimberley Region

Understanding the response of the Kimberley marine system to a range of potential climate and socio-economic scenarios under a suite of management strategies assists decision makers when considering future development and climate change pressures in the region.

Overview

The future of the Kimberley will be determined by the interaction of many pressures (economic, ecological and social processes, climate change, human population dynamics, resource extraction and others) and the effectiveness of strategies used to manage them.

Management decisions for the Kimberley marine environment aim to find a sustainable compromise between protecting one of the few remaining near pristine coastal and marine environments in the world, while supporting the region's social and economic development needs.

Effective management decision making requires an understanding of the system in question and some predictive capacity guided by visualising future scenarios.

Computer models allow us to integrate numerous and often large datasets, while also accounting for uncertainty and missing information to understand probable future scenarios.

Models are currently the best tools available to explore the possible consequences between a large number of natural processes and human actions that can help managers to understand a system and make optimal decisions.

This project represents the first attempt to integrate a large volume of data, knowledge and state-of-the-art understanding of the biophysical, ecological and social processes that act on the Kimberley marine environment, including the incorporation of new information generated by several KMRP projects.

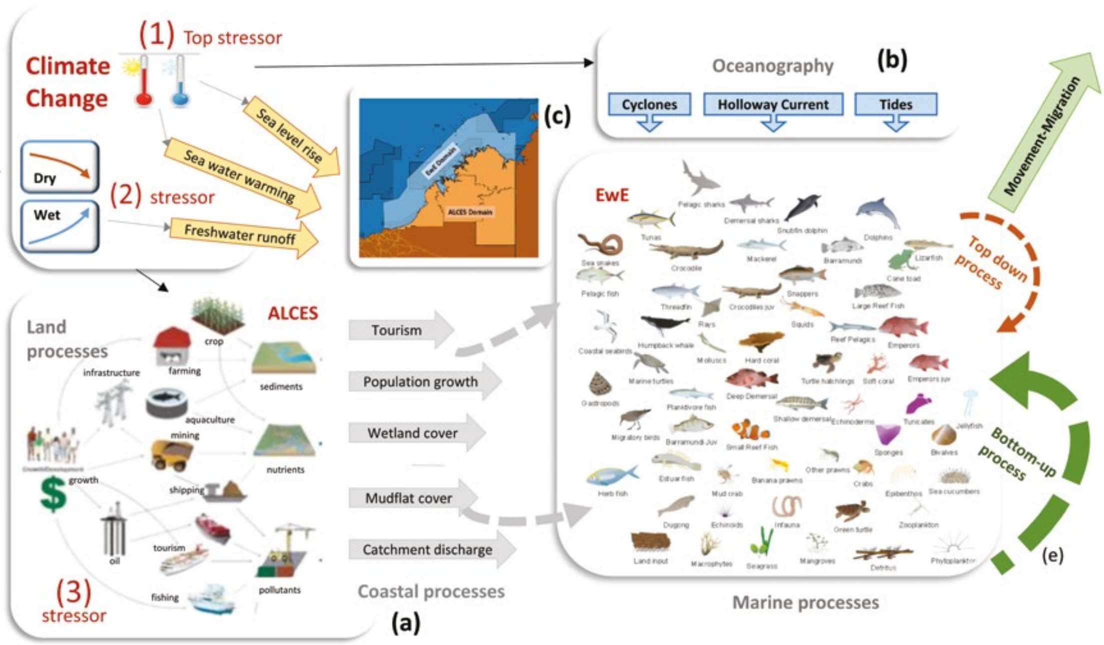
Although a model simulation is not an absolute prediction (a 'prophecy') of how the Kimberley region will be in the future, it is an attempt to describe how the system may respond to the specific conditions summarised in the scenarios and management strategies, which is consistent with the current scientific knowledge and understanding of how the Kimberley ecosystem functions.

While insight on system behaviour gained from consideration of these scenarios can provide guidance on potential patterns of response, care must be taken when considering circumstances outside the specifics of the scenarios and management strategies modelled and particular account must be made of the uncertainty associated with current knowledge.

Approach

We employed the Management Strategy Evaluation framework to engage key stakeholders in designing and imagining likely and desired regional futures to explore the consequences of different management options through a number of climate and socio-economic scenarios that the Kimberley region may experience in decades to come.

Ecopath with Ecosim (EwE) and ALCES computer models were used to integrate existing and new knowledge about the Kimberley and to provide an estimation of the likely impacts of different stressors on the terrestrial (ALCES) and marine (EwE) environments. The model boundaries were



The marine ecosystem (EwE panel) receives pressure from both natural and anthropogenic land-based processes (ALCES panel) mediated by a number of coastal processes and socio-economic processes (a). The marine ecosystem is also driven by oceanographic processes (b). All these processes act at a regional scale, which motivated the choice of the model domains (c). These models have been used to test the system's response to specific conditions (scenarios) and management options which the project stakeholders have recognised as most plausible and of management significance.

set based on existing information and data collected from KMRP projects.

EwE has been used to characterise the impact of fishing, tourism, other human uses and climate change on the Kimberley marine ecosystem as well as how different management options, such as controls on fishing effort and spatial closures, can mitigate these pressures.

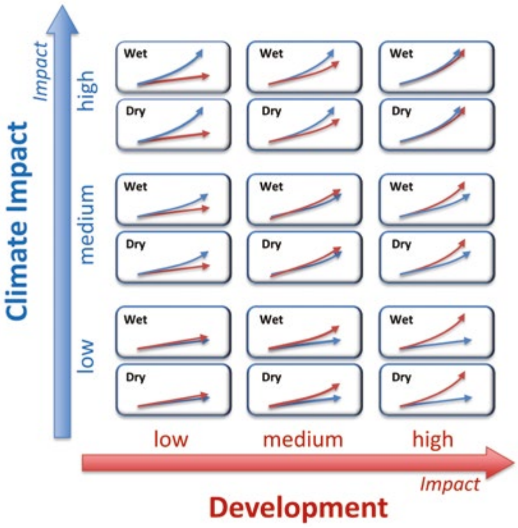
The ALCES model has been used to characterise terrestrial land use and landscape dynamics and how these connect with the marine ecosystem.

Based on available information on likely future trajectories for types of land use in the Kimberley (e.g. mining, energy, aquaculture, commercial fishing, crops, livestock, settlements, tourism, transportation), ALCES simulates how land-based processes affect the marine environment via sediment and pollution flows, infrastructure and localised human pressure.

Scenarios and Management Strategies: A 'double uncertainty' approach was used in the development of scenarios in which trends in climate change and economic development were identified as the two most critical and uncertain drivers of change in the Kimberley region. These drivers were acknowledged as the most important stressors on the Kimberley marine environment by most of the stakeholders engaged in this exercise.

The selected climate change scenarios were based on the simulations produced by the KMRP climate change project. The development scenarios were generated from the ALCES model and account for many sectors including: population, housing, tourism, agriculture, cattle farming, aquaculture, transport, infrastructure, mining and oil and gas.

Management strategies include actions which can be taken to pre-empt or react to stressors and events which may affect the Kimberley marine environment. Interventions under management control are based around existing and proposed marine parks, including their associated restrictions, regulations on commercial and recreational fishing practices and regulation of other human uses in the region including tourism and mineral, oil and gas exploration and extraction.



Modified '3 by 3' future plane consisting of the climate change and development axes. Each climate change scenario has been divided into a 'drier' and a 'wetter' sub-scenario, reflecting the uncertainty of how climate change may affect Kimberley precipitation regimes.

Key Findings

The number of scenarios tested can be grouped into three main levels of pressure with climate change induced warming being the stressor causing the greatest impact on the system, followed by changes in precipitation regimes and socio-economic development. Invariably these stressors interact such that, given a specific level of climate change warming, socio-economic development can add further significant pressure to a system already under stress.

Irrespective of the modelled scenarios, the system displayed its own internal dynamics intrinsic to the system, including a clear bottom-up dynamic and an oscillation in the distribution of biomass with a main period of around 20 years which has the potential of affecting the system resilience to both major natural and anthropogenic events.

Species in marine food webs are likely to respond differently to the scenarios and management strategies. Some species are 'winners', that are likely to increase in biomass under most modelled scenarios, while others may routinely decrease, regardless of scenario. Additionally, some species are more likely to exhibit sensitivity to scenario variability than others.

Analysis of the available management options suggest that, while species may respond differently to the management strategies modelled, marine reserve sanctuary zones are an important tool to meet conservation objectives and have the potential to considerably alleviate the pressure imposed on the system by the interaction of climate and development stressors.

Careful analysis of model behaviour shows that the benthic primary production associated with seagrass and macroalgal assemblages is a key component in the functioning of the Kimberley marine ecosystem through its role in providing food resources and shelter to a range of biodiversity.

Management Implications

The scenarios generated by this project can be used to assist decision making, planning and monitoring of the likely response of natural resources to increasing human and climate pressure. More specifically:

- Species and groups which are expected to be the most sensitive to different climate and development pressures such as seagrass, turtles and dugongs should have high priority for long-term monitoring as this will provide an indication of the impact of climate change on the system.
- Further research on these species and groups will improve our knowledge of their respective life history, leading to an improved understanding of the drivers of this sensitivity.
- The sensitivity of some marine communities to climate change makes them good indicators for the early detection of system response which can identify the need for management action as well as inform the models to help identify which, among the modelled scenarios, the system is heading towards.
- It is important that the critical role played by seagrass and macroalgal assemblages is accounted for in marine reserve planning and management to ensure these habitats are adequately conserved and managed.
- The value attributed to marine protected area management and in particular sanctuary zones, should be taken into account in future planning exercises, recognising that expansion of sanctuary zones will be more effective for relatively sedentary species such as benthic primary producers and reef fishes than for migratory species and will have increased benefits for exploited species such as barramundi, snapper and emperors.
- This project highlights the importance of adopting a system view to management that recognises the potential impact of relative timing of system perturbations.

- Given that the internal dynamics of the system need to be considered as well as the external pressures, models that take into account a large number of functional groups across a food web can provide a deeper understating of the health and sustainability of the system, which could not be obtained by collating disparate observations of individual species or functional groups.
- Populating the EwE and ALCES models so that they represent the Kimberley land and marine systems to the best of our current knowledge provides a significant legacy for future research with this model that can be improved with new and emerging knowledge.

Future Focus

Despite the advancements resulting from this research, large knowledge gaps still exist which, if addressed, could considerably improve this modelling work.

A prioritisation process was undertaken that looked at the likely impact on the model performance against the expected effort and cost in collecting better data for each of the potential data improvements.

Priority should be given to better characterisation of the dynamics of primary producers, given:

i. the strong bottom up structure of the Kimberley food web; and

ii. their role as main driver of the oscillations in the system.

Similarly, information about distribution, biology and population dynamics of some coastal predatory finfish groups will better inform top-down interaction in the ecosystem.

The impact of climate change on the biology and metabolism of marine species, in particular corals, seagrass, plankton and fish will have important implications for how adaptable these species may be to climate change.

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Glossary

(4WD)	Four-wheel drive
(BC)	Black carbon
(BMA)	Benthic microalgae
(CALM)	Department of Conservation and Land Management
(CTD)	Conductivity, Temperature and Depth
(DBCA)	Department of Biodiversity, Conservation and Attractions
(DNA)	Deoxyribonucleic acid
(DOC)	Dissolved Organic Carbon
(ENSO)	El Niño-Southern Oscillation
(EOF)	empirical orthogonal function
(GBR)	Great Barrier Reef
(GCM)	global climate models
(IK)	Indigenous Knowledge
(IMOS)	Integrated Marine Observing System
(IPA)	Indigenous protected area
(KISSP)	Kimberley Indigenous Saltwater Science Project
(km)	kilometres
(LAD)	light at depth
(LAEA)	Lambert Azimuthal Equal Area
(LAT)	lowest astronomical tide
(m)	metres
(MMM)	maximum monthly mean
(Ma)	(mega-annum) a million years
(MODIS)	Moderate Resolution Imaging Spectrometer
(MJO)	Madden-Julian oscillation
(MPA)	Marine Protected Area
(NIR)	near-infrared
(NT)	Northern Territory
(NWSFTCP)	Northwest Shelf Flatback Turtle Conservation Program
(OFAM3)	Ocean Forecasting Australia Model version3
(PAM)	Passive acoustic monitoring
(PBC)	Prescribed Body Corporate
(PPGIS)	public participation geographic information system
(ROMS)	Regional Ocean Modelling System
(RUV)	remote underwater video
(SBP)	sub-bottom profiling
(TEK)	traditional ecological knowledge
(TO)	Traditional Owner
(TSD)	Temperature dependent sex determination
(TSS)	total suspended solids
(WA)	Western Australia
(WAMSI)	Western Australian Marine Science Institution

KMRP Collaborators

AIMS	Australian Institute of Marine Science
ALCES Group	ALCES Landscape and Landuse Group
ANU	Australian National University
AWSG	Australasian Wader Study Group
Bardi Jawi	Bardi Jawi Niimidiman Aboriginal Corporation RNTCB
BHA	Bush Heritage Australia
CDU	Charles Darwin University, Northern Territory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Curtin	Curtin University
CWR	Centre for Whale Research
DBCA	Department of Biodiversity, Conservation and Attractions
Dambimangari	Dambimangari Traditional Owners
DPIRD	Department of Primary Industries and Regional Development
East China Normal University	East China Normal University, China
ECU	Edith Cowan University
Goojarr Goonyool	Goojarr Goonyool Aboriginal Corporation, Two Moons Whale Research
Griffith University	Griffith University, Queensland
Guangzhou Institute of Geochemistry	Guangzhou Institute of Geochemistry, China
KLC	Kimberley Land Council
KTLA	Karajarri Traditional Land Association
Mosaic Environmental	Mosaic Environmental Consultancy
Murdoch	Murdoch University
MV	Museums Victoria
Ningbo University	Ningbo University, China
Nyul Nyul	Nyul Nyul Rangers
Ocean University	Ocean University, China
Pendoley Environmental	Pendoley Environmental Pty Ltd
Tongji University	Tongji University, China
University of Bremen	University of Bremen, Germany
University of Copenhagen	University of Copenhagen, Denmark
University of La Rochelle	Université de La Rochelle, France
University of Texas	University of Texas, Austin, USA
UNSW	University of New South Wales
UQ	The University of Queensland
UWA	The University of Western Australia
ARC CoE CRS	Australian Research Council Centre of Excellence for Coral Reef Studies, The University of Western Australia
WAM	Western Australian Museum
WAMSI	Western Australian Marine Science Institution
Wunambal Gaambera	Wunambal Gaambera Traditional Owners
Yantai Institute of Coastal Zone Research, Chinese Academy of Science	Yantai Institute of Coastal Zone Research, Chinese Academy of Science, China
Yawuru	Nyamba Buru Yawuru

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Integrating Project 1 – Habitats, biodiversity and baselines

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1.1.2	Key ecological processes in Kimberley benthic communities: recruitment and herbivory
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1.1.3	Ecological connectivity of Kimberley marine communities
Short Title:	Connectivity
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1.2.1	Humpback whale use of the Kimberley: understanding and monitoring spatial distribution
Short Title:	Whales
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1.2.2	Key biological indices required to understand and manage nesting sea turtles along the Kimberley coast
Short Title:	Turtles
Project Leader:	Scott Whiting (DBCA)
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1.2.3	Saltwater crocodiles in the northwest Kimberley
Short Title:	Crocodiles
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1.2.4	Distribution, abundance and genetic connectivity of Australian snubfin and humpback dolphins in the Kimberley
Short Title:	Dolphins
Project Leader:	Lars Bejder (Murdoch)
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1.2.5	Integrating Indigenous knowledge and survey techniques to develop a baseline for dugong management in the Kimberley
Short Title:	Dugong
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1.2.6	Evaluating the impacts of local and international pressures on migratory shorebirds in Roebuck Bay and 80MB
Short Title:	Shorebirds
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1.3.1	Reef growth and maintenance: Reef geomorphology, Holocene growth history and impacts for climate change
Short Title:	Geomorphology
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Short Title:	Resilience
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1.5	Kimberley Indigenous Saltwater Science Project – Navigating knowledge currents through Kimberley Saltwater Country
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Integrating Project 2 – Human use, ecological processes, knowledge integration and prediction

Integrating Project Co-ordinator: Peter Thompson, CSIRO

2.1.1	Human use patterns and impacts for coastal waters of the Kimberley
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2.2.3	Benthic community production and response to environmental forcing
Short Title:	Productivity
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2.2.4	Benthic primary productivity: production and herbivory of seagrasses, macroalgae and microalgae
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2.2.6	Terrestrial- ocean linkages: the role of rivers and estuaries in sustaining marine productivity in the Kimberley
Short Title:	Land Sea Linkages
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2.2.7	Knowledge integration and predicting biophysical response to climate change
Short Title:	Climate change
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Short Title:	Management Strategy Evaluation (MSE)
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2.2.9	Historical reconstructions of water quality in the Kimberley
Short Title:	Sediments
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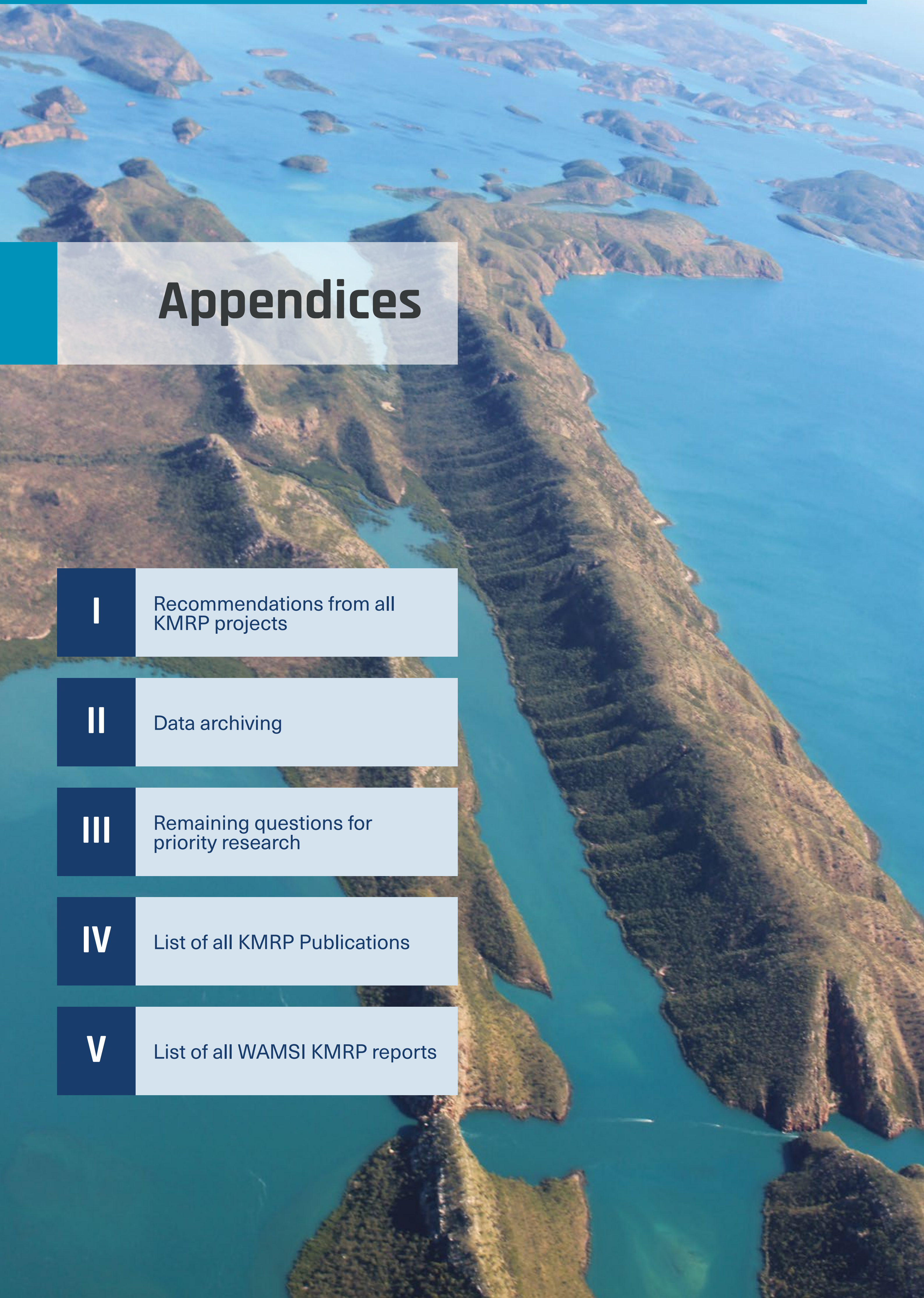

Appendices

I	Recommendations from all KMRP projects
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Appendix I - Recommendations from all KMRP projects

Project	Theme	Recommendation
Benthic Biodiversity	Marine park planning	Consideration should be given to additional marine park areas with sanctuary zones within the Greater Kimberley Marine Park to provide adequate representativeness for subtidal seabed biodiversity, in particular the rich biodiversity areas adjacent to shorelines, near channel margins in between islands or along drowned river channels that extend across the shelf. Areas that include inshore-offshore gradients, such as archipelagos, and that include both sheltered and exposed shorelines, are effective in ensuring a representative sample of coral and other benthic primary producer habitats and species.
Benthic Biodiversity	Marine park planning	The information that habitat and species distribution modelling provides can be used for making informed spatial allocation decisions for conservation, such as determining the placement of protective zones. These models will perform best where detailed bathymetry is available and where model confidence has been assessed so that management decisions can be based on areas that were predicted with high (rather than low) confidence.
Benthic Biodiversity	Research and Monitoring	Remote sensing provides a useful and cost effective tool for assessing the presence, extent and changes to key benthic primary producers such as corals, algae and seagrass in intertidal and shallow subtidal waters to identify and monitor habitats, particularly if used at low tide.
Biogeochemistry	Monitoring	Nutrient and phytoplankton monitoring is recommended in areas that are experiencing increased human activity.
Biogeochemistry	Monitoring	Given emerging land-use development pressures in Kimberley catchments, it is recommended that a strategy for monitoring river nutrient and sediment levels, be developed, particularly where rivers are entering near culturally or ecologically significant coastal areas.
Climate change	General	Ocean temperature and salinity fluctuations affect the growth and health of marine species. The fisheries and pearl aquaculture industry along the Kimberley coast needs to understand the climate driven temperature and salinity variations in the region; warming during El Niño events and reduced ocean salinity resulting from heavy precipitation during La Niña events. It is recommended that these industries use available tools such as ENSO prediction hosted on the Bureau of Meteorology website and CSIRO Bluelink model results hosted on the Integrated Marine Observing System (IMOS) website to monitor the current climate information and oceanographic conditions off the coast and prepare adaptation responses
Connectivity	Marine park planning	To protect hard corals, the crucial habitat forming organisms of coral reef ecosystems, and seagrass, an important food source for dugongs and turtle, and a nursery habitat for fishes, marine and Indigenous protected areas need to incorporate strategies that account for the spatial dispersal of these organisms. Protected areas that are large enough to encompass routine dispersal distances of corals (10–20 km), and are spaced at similar distances, will maintain self-replenishment and aid recovery after disturbance through connectivity between protected areas.

Project	Theme	Recommendation
Connectivity	Marine park planning	The cryptic Acropora coral lineages detected through genetic studies reveal that current assessments of the diversity of hard coral species in the Kimberley are likely substantial underestimates and further integrated taxonomic research is needed to clarify species diversity patterns in all taxon groups.
Connectivity	Marine park planning	Management of trochus *(T. niloticus)* on the Dampier Peninsula and Buccaneer Archipelago should treat the region as being effectively a single stock on the ecological timeframes relevant to harvest management where over-harvested sites will be replenished with recruits from neighbouring sites within years, assuming they exist, and allowing for the slow growth of the species. Conversely management of this species at offshore oceanic reefs should treat each oceanic shoal as being effectively isolated on the ecological timeframes relevant to harvest management and replenishment from outside will not replenish over-harvested stocks at these locations.
Connectivity	Marine park planning	Corals and seagrasses of Buccaneer Archipelago and Dampier Peninsula should be managed as demographically independent populations with some evolutionary exchange. The negligible exchange between the inshore and offshore Kimberley coral reefs and other bioregions means that these populations are reliant on standing genetic variation as the basis of adaptation to climate change or other disturbances.
Connectivity	Marine park planning	Ecological exchange varies between species between the Pilbara, Kimberley and Northern Territory bioregions and this should inform the stock management required for different species.
Recruitment	General	Current estimates of species diversity in corals are likely to be substantial underestimates and further integrated taxonomic research is needed to clarify species diversity patterns in all taxon groups.
Recruitment	Monitoring	The protocol developed for quantifying coral recruitment using frames deployed and retrieved from a small vessel is recommended for future monitoring activity as it does not require SCUBA diving or long periods in the water, to accommodate the hazardous conditions in the Kimberley. Indigenous rangers have assisted using this technique and should be engaged for future monitoring work.
Resilience	General	It is critical to minimize local stressors to boost coral resilience, particularly during heat stress events.
Resilience	General	Sediment input is strongly correlated with river discharge of flood waters during major cyclonic events. Given the negative impacts of increased sediment and nutrient concentrations on water quality and coral health, monitoring of sediment/nutrient input into the Fitzroy River catchment should be a key priority.
Crocodiles	Future Research	The crocodile populations in the Kimberley are considered to be healthy and management should focus instead on human-crocodile interactions as a priority. This will still require addressing knowledge gaps around crocodile abundance and size structure as well as estimating the spatial extent of appropriate nesting habitat.
Dolphins	General	Humpback dolphins in the Kimberley are genetically distinct to those in the Pilbara and should be managed as separate units. The low gene flow between snubfin populations in Roebuck Bay and King Sound indicate that this species may need to be managed on even smaller spatial scales.
Dolphins	Monitoring	Passive Acoustic Monitoring (PAM) can be a cost effective tool to spatially monitor the occurrence of acoustically active species like dolphins, however it has limitations with respect to humpback and snubfin dolphins as it cannot rule out the absence of species that are often silent and is therefore not effective for these species.

Project	Theme	Recommendation
Dugong	Indigenous engagement	The following components of the WAMSI dugong project in the Kimberley should be continued in partnership with CSIRO, Indigenous ranger groups and DBCA-marine parks: the integration of TEK and scientific knowledge; monitoring trends in dugong distribution and abundance, both locally and regionally; and the long-term study of movement ecology.
Dugong	Monitoring	The Bayesian method should be further developed and validated to integrate traditional and scientific knowledge of dugongs along with an integrated monitoring and risk assessment framework to manage cumulative risks to dugong populations from multiple pressures, including customary take.
Dugong	Monitoring	A monitoring program for dugong populations and associated seagrass habitat should be designed and implemented in smaller high priority areas at representative sites across the Kimberley, using standardised methodologies (e.g. small boat-based surveys) and, if necessary, trialling new survey methods (e.g. use of drones or helicopters).
Dugong	Monitoring	A long-term fixed-wing aerial survey monitoring program should be designed for sea country and co-managed marine parks that integrates data from regular (seasonal) small area local surveys.
Dugong	Research	A stakeholder and experts workshop should be held in the Kimberley (Broome) to discuss the potential of close-kin genetic methods to estimate critical population parameters of dugongs for their management.
Dugong	Research	The movement study commenced in the North Kimberley should be relocated to Roebuck Bay in the South Kimberley, based on management need and to significantly reduce logistical costs. This study could underpin a long-term study of dugong spatial ecology in full partnership with all Kimberley ranger groups, DBCA and CSIRO.
Dugong	Research	Research should be implemented that will support Yawuru rangers establish customary take monitoring systems of dugongs and turtles, and to better understand the relationship between dugong population and harvesting dynamics and their seagrass habitats. Yawuru have an immediate need given that Broome is an expanding regional population centre.
Geomorphology	Marine park planning	A scheme of reef classification, with GIS database of habitats, (ReefKIM) includes georeferenced data and location of every significant reef in the Kimberley (Landsat resolution =30 m) and includes detailed substrate & geomorphology maps for 30 Kimberley reefs providing preliminary data on key habitats and the relative significance on the Kimberley Reefs. This database should be used to identify reefs with high conservation value for future planning and management.
Herbivory	Monitoring	Some work is still needed to develop methods for monitoring that can be adopted and applied uniformly by Indigenous ranger groups for Healthy Country Plan monitoring, preferably one consistent with current state-of-the-art methods used for monitoring of marine protected areas.
Herbivory	Marine park planning	Marine plants, especially seagrasses, are important to the diet of Kimberley marine fauna. Notably, seagrass consumption is high, and is a major component of the diet of several herbivores that are important to Indigenous communities as a seasonal food cultural resource (e.g. golden-lined rabbitfish *(S. lineatus)* and green turtles). Management plans for areas that contain seagrass beds or stands of macroalgae should consider these as Key Performance Indicators.

Project	Theme	Recommendation
Herbivory	Monitoring	Given the important ecological role that seagrass consumers play, monitoring abundances of these taxa is desirable. The imperative for monitoring the abundance of green turtles is also supported by their status as a protected species and their high value in monitoring and management of the Indigenous Healthy Country Plans for the region.
Herbivory	Monitoring	The importance of seagrasses to large vertebrate herbivores can be easily monitored through simple tethering experiments which can be useful to assess the resilience of the seagrass and its grazers.
Herbivory	Research	Studies of the movement of green turtles might help identify seagrass beds and other important primary producer habitats.
Human Use	Education and Compliance	Education and compliance activities for those fishing from boats can be directed to the boat launching areas identified in this study.
Human Use	Education and Compliance	This study identified sites of relatively high use that should be used by natural resource managers to guide operational activities (including monitoring, compliance and education) to ensure cultural and environmental targets are achieved.
Human Use	General	The review of potential impacts of human use on coastal habitats in the Kimberley highlighted that visitation to the Kimberley is increasing which may lead to greater pressures to coastal habitats. The most likely environmental impacts will be from litter and rubbish, sewage and other pollution, coastal track formation, fishing, impacts of boating and trampling of coastal vegetation and intertidal reefs. Management should focus attention on sites highlighted 'higher use' to monitor for potential impacts and to implement management strategies including education that will prevent potential impacts from occurring.
Human Use	Marine park planning	Having a benchmark of human use prior to the gazettal of marine protected areas is recommended as a basis from which to detect trends.
Human Use	Marine park planning	The study on the south-western extent of the Kimberley between Port Hedland and Derby provides temporally and spatially explicit data on coastal recreational activities in the nearshore marine and coastal environment that can be used as a benchmark of level of use prior to the implementation of 80 Mile Beach and Roebuck Bay Marine Parks or any major coastal development such as sealing the road north of Broome to Cape Leveque.
Human Use	Marine park planning	The concentration of recreational fishing at specific sites can lead to changes in fish community structure and should be taken into consideration in planning monitoring programs for fish in the marine parks.
Human Use	Monitoring	While aerial survey can be a costly monitoring tool, it can be used on a periodic basis to assess use of marine parks, including to identify new areas of use as they emerge, and to plan operational management.
Human Use	Monitoring	A cost-effective desk top survey method was developed to enable monitoring of tourist visitation by expedition cruise vessels to all sites covered by itineraries along the Kimberley coast and should be used on a regular basis.
Human Use	Monitoring	The method of remote camera surveillance to record vessel launches should be considered for use at boat launch ramps as it allowed cost-effective assessment of vessel activity, requiring fewer resources than traditional surveys and the collection of information after hours, on weekends and holidays without additional cost. This technique would be of particular use at sites where there are planned changes to infrastructure such as One Arm Point.

Project	Theme	Recommendation
KISSP	Indigenous engagement	Navigating knowledge currents in the future requires continued investment in a regional working group to provide a conduit between Indigenous knowledge holders, Traditional Owners, researchers, managers and policy makers concerned with ensuring that Saltwater Country and People are healthy long into the future.
KISSP	Indigenous engagement	All researchers seeking to engage in research in the Kimberley should be encouraged to use the guide for researchers to engage in collaborative science on Kimberley Saltwater Country.
Land Sea Linkages	General	Management of catchments and/or rivers needs to consider the system as a whole and requires a greater understanding of the origins of the material being delivered into the coastal environment.
MSE	General	Functional groups and system indicators may respond differently to different climate and development pressures. By the year 2050, the state of some groups (e.g. seagrass, turtles, dugongs) and system indicators may vary dramatically from scenario to scenario, while others (e.g. corals, snubfin dolphins, mammals, mangroves) may show little variation. Groups and system indicators which are expected to be most sensitive to different climate and development pressures should have high priority for long-term monitoring for two reasons. First, this will improve our knowledge of these groups' life history (such as changes in habitat range, recruitment, growth and survival rates), leading to better model parameterisation and thus an improved understanding of the very drivers of this sensitivity. Second, the sensitivity of some marine communities to climate change provides a good indicator for the early detection of system response which can help identify which, among the modelled scenarios, the system is heading towards.
MSE	General	Some functional groups (corals, snubfin dolphins, pelagic sharks) are consistently losers and others (seagrass, dugongs and turtles) consistently winners under a wide variety of scenarios, while other groups' success depends considerably on the precise scenario which may eventuate. This result can provide managers with an indication of the expected direction and magnitude of a species' response to a specific scenario and thus the extent to which a management intervention targeted at a specific group is likely to succeed. However, this likelihood is also inherently linked to the target and scope of the intervention and cannot be evaluated without information about its purpose. If specific interventions are considered, the models presented in this work can be used to explore their potential impact.
MSE	General	Whatever the final state of the system in 2050, we should not expect the system to transition linearly, or even monotonically, to such state over the coming decades. Rather, we should expect system level indicators, like total biomass and diversity, to display non-linear oscillatory behaviour. While the exact details and timing of these oscillations are largely uncertain, the general form is similar under all modelled scenarios, leading us to conclude that this behaviour is due to internal system dynamics, rather than external forcing and as such deserves further investigation.

Project	Theme	Recommendation
MSE	General	The climate scenarios modelled in this work are the same as recommended by the Intergovernmental Panel on Climate Change (IPCC). These represent expected warming under different pathways of future anthropogenic CO_2 emissions. While there is uncertainty on which pathway will materialise (as well as on the level of warming given this pathway), anthropogenic CO_2 emissions change very slowly and their impact on the climate has a delayed response. This means that the likelihood of each modelled scenario to occur can be assessed in advance and will become better defined in the years to come. This has two implications: i) changes will occur smoothly, time for contingency planning is available and abrupt surprises are unlikely; on the other hand, ii) impact of management actions will also be slow and subject to system inertia, which recommends strategic, rather than reactive, management.
MSE	General	Careful analysis of model behaviour shows that the lower part of the food web is a key component in the functioning of the Kimberley marine system. Benthic primary production associated with seagrass and macroalgal assemblages provide food resources and shelter to diverse communities of invertebrates and finfishes. It is important that the critical role played by seagrass and macroalgal assemblages is accounted for in the MPA planning and management to ensure these habitats have adequate protection.
MSE	Marine park planning	The analysis of the available management options we have explored suggests that a 20% to 30% increase in Sanctuary Zone extension (compared to today) would benefit the system total biomass under most scenarios. These results also suggest that sanctuary zones within the marine parks are an important tool to meet conservation objectives. Sanctuary Zone extension can be particularly beneficial to exploited species such as barramundi, snapper and emperors. Further, the effectiveness of the management strategies varies between functional groups, being more effective for relatively sedentary species such as reef fishes than for migratory species such as sharks, billfishes and tunas.
Recruitment	General	When planning research activities in the Kimberley, it should be recognised that sampling often requires additional resources, as well as development, refinement and testing of established and innovative techniques to ensure they work in this remote and challenging environment.
Recruitment	Monitoring	Some work is still needed to develop methods for monitoring that can be adopted and applied uniformly by Indigenous ranger groups for Healthy Country Plan monitoring, preferably one consistent with current methods used for monitoring of marine protected areas.
Recruitment	Marine park planning	Conservation policy and planning should recognize that all marine habitats provide a unique contribution to the overall pool and diversity of the Kimberley's fish fauna by providing fish nurseries and therefore warrant some level of protection.
Recruitment	Monitoring	Additional sampling of coral recruitment in future years would provide information in a more typical year for comparison as a coral bleaching event occurred in the year of this study. Sampling should encompass several locations and a nested sampling design to further examine spatial variability in recruitment patterns.

Project	Theme	Recommendation
Recruitment	Monitoring	While fish recruitment underlies replenishment of populations and can be used as an indicator of population health, rates of recruitment vary spatially and temporally and comprehensive monitoring of fish recruitment will be expensive, especially in remote locations like the Kimberley. Monitoring of adult fish numbers, which are less variable, may be an easier way to assess the health of the Kimberly's fish fauna and should therefore take priority over recruitment surveys. When monitoring of fish recruitment is possible it should focus on species under the greatest anthropogenic pressure and those that perform key ecological roles and should concentrate sampling in the wet season (March/April) within mangrove, seagrass and coral reef habitats to get the strongest and most comprehensive assessment of juvenile fish recruitment.
Recruitment	Research	Juvenile fish diversity in the Cygnet Bay and Sunday Island group was surprisingly low considering their proximity to the equator and global centre of fish diversity. Further research is needed to confirm this finding and to understand how challenging macro-tidal systems may affect patterns of juvenile fish recruitment.
Remote Sensing	Education and Compliance	High resolution remotely sensed products should be developed that allow communities to visualize change in coastal and seabed topography and processes to better understand impacts of development and climate change on their local environment.
Remote Sensing	General	An archive of remotely sensed data should be maintained and made readily available to end-users along with tools that will enable them to process and analyse data to produce environmental indicator products.
Remote Sensing	Monitoring	Remote sensing data should be used to monitor long term trends, changes and spatial patterns of TSS and other asset-relevant variables such as light attenuation and percentage of light at the substrate.
Remote Sensing	Monitoring	Remote sensing technologies represent the lowest cost approach for routinely collecting scientific data at a regional scale and over long time series, allowing for an assessment of baseline environmental conditions against which change can be measured and should be considered for future research and monitoring programs.
Resilience	General	Kimberley corals are arguably Australia's most stress-resistant corals, have adapted their overall physiology to the naturally extreme environment of the Kimberley and should therefore be considered regional and national priorities for long-term coral health monitoring and further research into the mechanisms enabling such remarkable stress resistance in reef-building coral. Intertidal coral communities, in particular, should be the focus of awareness and protection efforts.
Seagrass	General	While the overall rates of productivity in this Kimberley reef system were comparable to other coral reef habitats worldwide, the environmental conditions under which primary producers survive and grow are extreme. This has implications for the resilience of these producers in the face of climate change across the Kimberley environment. Given the extreme conditions in temperature, oxygen levels and nutrients, management should consider strategies that will ensure any additional anthropogenic pressures that could add stress to the system are minimised and also be aware of environmental conditions that may change over time.

Project	Theme	Recommendation
Seagrass	Monitoring	The following is recommended to monitor seagrasses in the Kimberley: • monthly monitoring to quantify temporal patterns and reveal the likely causes of those patterns. • monitoring programs to include measures of seagrass shoot density, biomass and growth rates. These measurements should be coupled with environmental data to better explain the observed patterns in seagrass growth.
Seagrass	Monitoring	The following is recommended to monitor macroalgae in the Kimberley: • detailed sampling throughout the wet season, and a monthly sampling program. • extending the measurements from Sargassum linear extension to density, biomass and change in biomass (growth). • extending the initial sampling on Sargassum to other macroalgal species, like Turbinaria, Lobophora and Gracilaria.
Sediments	Future Research	Biomarkers in sediment cores can be used as indicators to monitor environmental pressures (both natural and anthropogenic) and assist in understanding chronic and acute changes to the environment and prediction of future environmental impacts to aid in the application of mitigation measures.
Shorebirds	Monitoring	Continued monitoring of shorebird populations in north-western Australia is recommended as roost usage and shorebird numbers in north-western Australia are dynamic. Shorebird counts can provide direct evidence of local pressures on shorebird sites, and the success or otherwise of habitat management.
Shorebirds	Monitoring	Shorebird monitoring should include demographic parameters as well as shorebird numbers such as annual estimates of adult survival and recruitment of immatures to provide early warning of changes and to enable understanding the causes of these changes.
Social Values	Education and Compliance	Management to maintain both biodiversity and the visitor experience is important along the entire coastline and there is community support for this, locally and further afield. Recognition of biodiversity and social values should be promoted through education programs to raise awareness.
Social Values	Indigenous engagement	Dampier Peninsula, Roebuck Bay and northern Kimberley regions are high priorities for management attention to ensure that the broad suite of values associated with Aboriginal culture are adequately recognised and supported in both policy and planning. Engagement of Indigenous groups in regional and local policy and planning would provide consistency across the Kimberley while maintaining localised focus.
Social Values	Indigenous engagement	Opportunities exist for a range of groups including the DBCA, Traditional Owners, Tourism WA and tourism operators to build upon and develop new conservation and tourism-related products that harness stakeholder interest in Aboriginal culture. With additional resourcing and training, Aboriginal ranger groups in particular present an ideal means of combining conservation, tourism and Aboriginal culture in a manner that will help to foster greater understanding of, and support for, cultural values and Aboriginal management of the coastal and marine environment. Initial discussion with PBC or equivalent Indigenous management groups would assist in directing the appropriate direction for the development of any opportunities.

Project	Theme	Recommendation
Social Values	Marine park planning	The importance assigned to both use and non-use social values means that good planning must take both types of values into account when considering changes to management or potential developments.
Social Values	Marine park planning	While residents and non-residents displayed high similarity in values and management preferences, significant differences exist for a small number of value and preference associations. These will require careful consideration in any stakeholder engagement and the weighting of interests according to stakeholder group remains an important policy and planning decision. Similarly, education and interpretive material may need to be made relevant to the different audiences.
Social Values	Marine park planning	The levels of recreation facilities provided on the Dampier Peninsula are a key issue for future policy makers and planners particularly due to the ease of access to this area by residents and non-residents alike. This may be particularly relevant where improved road infrastructure is put in place.
Social Values	Monitoring	Managers should consider repeating the combined methodologies of PPGIS and choice experiments to ensure currency of social information as these tools produce information that can be used to guide decisions about management frameworks for MPAs, assist in developing education and compliance programs that will best suit the values and preferences of the local and visitor community to meet aspirations and enhance experiences and determine if management strategies (including education components) have been effective. A five-year monitoring period is suitable, or monitoring in line with MPA review processes or with any other major change planned for the region (i.e. improved access, new development, etc.) and should take into account the spatial scale of existing MPAs of interest at that time. Further discussion with researchers for regional and localised monitoring over short and longer time frames should be discussed.
Social Values	Research	Managers could consider undertaking a survey of visitors to the Eighty Mile Beach region to determine visitor origin and values associated with the area in comparison to the other regions of the Kimberley. The results of a focused survey may highlight the need for the development of a tourism or conservation product based on the region's rich biodiversity, Aboriginal culture, and pearling and pastoral history. Such research would complement the intensive visitor research conducted in the Port Smith area.
Turtles	General	Six management units, or stocks, of flatback turtles are represented in WA based on a combination of previous and current analyses with two units added based on the Kimberley research (King Sound and north-west Kimberley). The degree of differentiation between these stocks indicates that genetic exchange is limited and that each should be managed as a unit.
Turtles	General	Marked variation in the temperatures of beaches used for nesting by marine turtles in the Kimberley region has been identified and highlights the need to manage populations at the level of individual rookeries. At a regional scale, retaining resilience is a key strategy, which can be achieved by protecting a broad nesting distribution across all habitat types, latitudinal ranges and including mainland and island rookeries. Localised management for female-biased sex-ratios and high mortality at particular nesting beaches could include artificial shading of natural nests (via shade cloth or vegetation plantings), or relocation of egg clutches to cooler sites or beaches. However, before such interventions are undertaken it will be prudent to collect further empirical data on the sex ratios of turtles hatching at major rookeries.

Project	Theme	Recommendation
Turtles	General	There is sufficient genetic separation between green turtles from the Pilbara and Kimberley rookeries to manage them as separate units.
Turtles	Indigenous engagement	Two-way knowledge and the merging of western science, traditional knowledge and local knowledge is essential for continuing to improve our understanding of marine turtles across the Kimberley.
Turtles	Marine park planning	New information on species and seasonal differences in turtle nesting distribution should be used during marine protected area review processes. This spatial and relative density information is also extremely important for any proposed activities in the Kimberley including coastal development.
Turtles	Monitoring	Turtle nesting locations of high management value that are recommended for regular monitoring include summer nesting green turtles at the Lacepede Islands, summer nesting flatback turtles at Eighty Mile Beach, and winter nesting flatback turtles at Cape Domett. Given the high nesting density at the Lacepede Islands, important population information would be gained from an intensive (2-3 week) tagging survey or track count program if partnerships can be developed with regional ranger groups and DBCA.
Whales	Marine park planning	While the importance of the Lalang-garram/Camden Sound Marine Park as a breeding area for humpback whales has been confirmed, all whales may not travel this far north and calving and breeding likely occur at Pender Bay and southwards along the Dampier Peninsula. Additional sites in the Kimberley, like Pender Bay, should be considered important breeding habitat and suitable for additional protection.
Whales	Monitoring	There is no current estimate of the absolute humpback whale population size nor of how population growth may have affected spatial use in the important breeding grounds of the Kimberley. A monitoring program is needed to ensure this population is managed effectively into the future, given the growing pressures of climate change and other anthropogenic pressures in the marine environment. Annual aerial survey of the region (Eighty Mile Beach to Camden Sound) is the best option to monitor trends in population abundance. Given that cost and expertise required is high, it should be undertaken every 5-10 years (at a minimum) to monitor distribution patterns and densities and identify emerging high density areas as the population continues to expand and potentially in response to changing sea temperatures. Annual vessel based surveys can supplement this information. Further, land based viewing platforms can provide a cost-effective means of acquiring data on the us of specific areas (e.g. Pender Bay) by whales with recognised limitations (e.g. limited spatial extent and cannot be used to obtain an abundance estimate).

Appendix II - Data archiving

Links to project metadata for the Kimberley Marine Research Program

Dataset name	Custodian Organisation	AODN metadata link	Embargo release date
Project 1.1.1 - Distribution and predictors of benthic biodiversity	Andrew Heyward, AIMS	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=49791f9e-c8a9-4844-ae31-165f9761cd0f	May 2020
Project 1.1.2 - Key ecological processes in Kimberley benthic communities: coral and fish recruitment	Martial Depczynski, AIMS	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=05f33378-b7df-433f-8019-16e9c7eb8620	June 2019
Project 1.1.2 Key Ecological Processes in Kimberley benthic communities - herbivory	Mat Vanderklift, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=8d910bf0-2f4e-4fc2-8a6e-f0447ed2d996	June 2019
Project 1.1.3 - Ecological connectivity of Kimberley marine communities (ECU - AIMS)	Oliver Berry, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=fb1d80bf-6ef2-4150-9479-22b4240435a7	May 2019
Project 1.1.3 Ecological Connectivity	Oliver Berry, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=0d389dab-d6e2-4895-ba09-389e689b565e	May 2019
Project 1.2.1a - Modelling the movement and spatial distribution of humpback whales in the nearshore waters of the Kimberley	Mark Meekan, AIMS	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=268e7c7e-51e6-4f0e-9c8d-334b7eed9030	Sept 2019
Project 1.2.1b - Monitoring of Humpback Whales (Megaptera novaeangliae) at Pender Bay, southern Kimberley region	Chandra, CMST / Kelly Waples, DBCA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=69907cbd-7e9a-4c7e-b106-a99f563527a0	Sept 2019
Project 1.2.2 - Key biological indices required to understand and manage nesting sea turtles along the Kimberley coast	Scott Whiting, DBCA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=fd1d3645-37f4-4834-a663-92d847cd7460	Nov 2019
Project 1.2.3 - Distribution, abundance, critical habitat and population growth rates of saltwater crocodile populations in the Kimberley region	Will Robbins, DBCA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=e8d33649-bb25-4450-9c22-fba2826c2c3e	April 2019
Project 1.2.4 - Relative abundance, population genetic structure and acoustic monitoring of Australian snubfin and humpback dolphins in the Kimberley	Lars Bejder, Uni of Hawaii	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=665ca349-9270-44d5-8835-cc72917a2392	July 2019
Project 1.2.5 Integrating Indigenous knowledge and survey techniques to develop a baseline for dugong (Dugong dugon) management in the Kimberley	Peter Bayliss, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=ca721225-340c-4415-8027-0ff9d774a1fc	July 2019

Dataset name	Custodian Organisation	AODN metadata link	Embargo release date
Project 1.2.6 - Evaluating the impacts of local and international pressures on migratory shorebirds in Roebuck Bay and Eighty-Mile Beach	Danny Rogers, AWSG	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=bf87eec2-cd06-4748-93cf-54226dac83fd	Sept 2019
Project 1.3.1 - Reef Growth and Maintenance	Mick O'Leary, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=7ab491d2-9507-428c-aed1-091d2aaed521	Completed
Project 1.3.2 - Climate Change Reef Calcification	Malcolm McCulloch, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=ed5a142d-a866-4477-a855-2b5449e94a28	Oct 2019
Project 1.4 - Remote sensing in support of marine environmental monitoring - turbidity	Peter Fearns, Curtin	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=e573dfd6-db4c-4e49-8a86-591a9124215d	May 2019
Project 1.4 - Remote sensing in support of marine environmental monitoring – in situ water quality	Peter Fearns, Curtin	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=491675e2-6853-4738-8ec1-21d8bccc3d0c	May 2019
Project 1.5 - Kimberley Indigenous Saltwater Science Project (KISSP)	Beau Austin, Charles Darwin University	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=8b687a5f-e09c-4c41-8c62-74d877494095	Completed
Project 2.1.1 - Human use patterns and impacts in the coastal waters of the western Kimberley	Lynnath Beckley, Murdoch	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=577dffcc-e88f-4479-aa54-7bf8ac5c5111	Completed
Project 2.1.2 - Human values and aspirations for coastal waters of the Kimberley	Jen Munro, DBCA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=ad78e38d-b5de-40f7-b16c-7c5103be5070	Completed
Project 2.2.1 Physical oceanographic dynamics in the Kimberley	Greg Ivey, UWA / Richard Brinkman, AIMS	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=6b182cf6-fa72-4ab4-a92a-c9d4b0dcbe4f	Completed
Project 2.2.2 - Pathways to production: Biogeochemical processes in Kimberley coastal waters	Matt Hipsey, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=e8cacbe0-6248-4207-a2c8-d3793bc5822a	March 2019
Project 2.2.2 Pathways to production: Biogeochemical processes in Kimberley coastal waters	Jim Greenwood, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=bca5bb63-f93d-4f0d-a9e7-dd4bac9e3ca3	March 2019
Project 2.2.3 - Benthic community production and response to environmental forcing	Ryan Lowe, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=d5b4b157-d0a1-48e3-a916-01aa8cecdf30	Completed

Dataset name	Custodian Organisation	AODN metadata link	Embargo release date
2.2.4 - Benthic primary productivity: production and herbivory of seagrasses, macroalgae and microalgae - Non-CSIRO	Gary Kendrick, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=57590a04-d091-475e-98a8-db436def04ff	Completed
2.2.4 Benthic primary productivity, production and herbivory of seagrasses, macroalgae and microalgae	Mat Vanderklift, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=2f5065eb-0aa1-32ba-e053-08114f8c742d	Completed
Project 2.2.6 - Terrestrial-Ocean Linkages: The role of rives and estuaries in sustaining marine productivity in the Kimberley	Andy Revill, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=fc8bbadc-3242-06db-e043-08114f8c34f5	July 2019
Project 2.2.6 - Terrestrial-Ocean Linkages - Pawsey	Nicole Jones, UWA	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=76d88713-0a15-4936-a0ff-ec9ac259d78d	July 2019
Project 2.2.7 Climate modeling	Ming Feng, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=02396b33-724f-3adf-e053-08114f8cf264	May 2019
Project 2.2.8 - Knowledge Integration and Management Strategy Evaluation (MSE) Modelling	Fabio Boschetti, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=078ffe36-d5f4-0f56-e053-08114f8c04ed	Aug 2019
Project 2.2.9 Historical reconstructions of water quality	John Keesing, CSIRO	http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=03675b95-2f38-761e-e053-08114f8cbf86	Aug 2019

Disclaimer: Some partner institutions may choose to wave the standard 18 month embargo period and release their data earlier.

Appendix III - Remaining questions for priority research

List of the 184 questions identified as remaining areas of priority research for the Kimberley marine environment by a range of scientists, natural resource managers and healthy country managers. This list is not in any order of priority.

1	Does the Kimberley represent the largest naturally occurring turbid coral reef systems in the world?
2	How have extreme tides influenced coral reef development in the Kimberley?
3	Does the Kimberley host unique stress tolerant coral populations?
4	What are the mechanisms that have allowed for the development of the globally unique high intertidal reefs in the Kimberley?
5	What impact are commercial fisheries having on Kimberley marine ecosystems?
6	What impact are commercial fisheries having on marine species of high Indigenous importance?
7	What level of commercial fisheries take is sustainable?
8	How adequate are the zone types of state and commonwealth marine parks/reserves to protect marine ecosystems and the marine species that are sustained by them?
9	What impacts have the products of the Kimberley Indigenous Saltwater Science Project had on research processes in the Kimberley?
10	What improvements are needed in the products of the Kimberley Indigenous Saltwater Science Project to further improve outcomes for western science and Indigenous research partners?
11	How is recreational fishing off major Kimberley coastal communities and other fishing hotspots impacting on targeted fish populations?
12	What restrictions on recreational fishing take would reduce the impact to sustainable levels in the long-term?
13	How effective have early Joint Management systems and practices been at facilitating best practice marine management by respectfully meeting the needs of state government and Indigenous joint management partners?
14	What changes need to be made to improve the Joint Management Systems and Practices in the eyes of the partners?
15	Are the observed patterns of genetic connectivity in the southwest Kimberley representative of the wider Kimberley including the central Kimberley, northern Kimberley and western Dampier Peninsula?
16	Are the observed patterns of genetic connectivity in the southwest Kimberley representative of other taxa?
17	How biodiverse is the Kimberley?
18	How much cryptic diversity exists in corals and other taxonomic groups in the Kimberley?
19	Are the observed spatial patterns of genetic connectivity stable in time in the Kimberley?
20	How do local disturbance, demographic history, reproductive characteristics and climate change influence spatiotemporal patterns of genetic connectivity in the Kimberley?
21	Do Kimberley taxa have a higher adaptive capacity than surrounding regions, and if so, how can this be managed and utilized for conservation outcomes?
22	Can improved predictive tools (e.g. hydrodynamic and dispersal models) for ecological connectivity be developed for the highly complex topographical macro-tidal nearshore regions of the Kimberley?
23	How will climate change affect the biology of different marine taxa in the Kimberley, including their reproduction and metabolism?
24	How will climate change affect the functioning of the Kimberly marine ecosystem as a whole (migrations, extinctions, food webs, etc.)?
25	How will climate change affect the ocean circulation and thus the ecological connectivity and productivity of the Kimberley region?
26	What indicators will best reflect the overall health of the Kimberley marine system?

27	How will future social attitudes affect public and political support for marine conservation in the Kimberley?
28	What are the post-release survival rates of key recreational finfish species in both the Kimberley tidal creek and offshore reef systems?
29	What are the key species targeted by Traditional Owners in the Kimberley and what is the current level of take and is this sustainable?
30	What is the extent and significance of interactions between commercial fishing and Threatened, Endangered and Protected species (crocodiles, sharks, sawfish, turtles, dolphins, whales and sea snakes) in the Kimberley?
31	Are populations of target fish species within the Kimberley marine park sanctuary areas providing recruitment subsidies or spill-over to fished populations outside of sanctuary areas?
32	Are there sites within the newly created Kimberley marine parks that provide critical habitat or important spawning, nesting, resting or foraging areas for key species, and are some of these areas located within highly protected management zones?
33	What actions within the remit of management will actually address the causes of coral bleaching in the Kimberley?
34	What management action(s) are key to building resilience throughout the Kimberley marine system in its entirety?
35	Where are key sites/locations for priority management action(s) that will help to build resilience to change in the Kimberley marine systems?
36	Are management targets and associated monitoring methods sensitive enough to trigger management responses in a timely manner?
37	What is the best and most cost-effective way to monitor upper ocean temperature and salinity variations and changes on annual, interannual and decadal time scale in the Kimberley region?
38	How does the water column stratification in the Kimberley vary on seasonal and interannual time scales?
39	How sensitive is the Kimberley water stratification to greenhouse induced global warming?
40	What are the implications of changing stratifications on the marine productivity and ecosystems in the Kimberley region?
41	What are the nutrient dynamics on the Kimberley continent shelf and how important are offshore contributions of to the nutrient balance?
42	What is the role of internal tides/waves on the onshore transport of deep nutrients in the Kimberley region?
43	Can we predict the peak of the marine heatwaves in the Kimberley region as well as their biological impacts?
44	What are the major factors influencing rates of larval supply (regional scale) and juvenile survivorship (local-scale) in the Kimberley and how do they differ from other regions?
45	How closely does recruitment strength in the Kimberley region reflect local patterns of adult abundance of cultural, ecological and fisheries important species?
46	How stable are fish nursery grounds given they are living habitats which also respond to global pressures personified by climate change in the Kimberley marine environment?
47	Do we have sufficient knowledge of key ecological values to create benthic habitat maps of the Kimberley marine reserves?
48	Do we have sufficient knowledge of key ecological values of the Bonaparte and Cambridge-Bonaparte IMCRA bioregions to adequately manage these parts of North Kimberley Marine Park?
49	Is there adequate knowledge of natural variations in key ecological processes to undertake ecological monitoring of key ecological values across the Kimberley marine reserves?
50	Are sanctuary zones in the Kimberley marine reserves correctly configured by size and location to optimise the outcomes for conservation?
51	What will be the impact of projected climate-related changes on marine conservation values of the Kimberley marine reserves (e.g. coral reef, seagrass, mangrove) and what are the ramifications for management?

52	Given the first documented, regional-scale bleaching event in the Kimberley in 2016, how long will it take for Kimberley coral reefs to recover from this event and how does recovery differ between species and different environments (e.g. intertidal versus subtidal coral communities)?
53	What are the physiological, genetic and biogeochemical mechanisms that enable the high resilience of Kimberley corals to heat and other environmental stressors such as pH fluctuations, and are they indicative of physiological plasticity and thus high acclimation capacity, or do they represent fitness trade-offs?
54	How is cryptic species diversity in corals linked to functional diversity in the Kimberley, particularly with respect to climate change stressors?
55	How do environmental conditions such as seawater temperature and carbonate chemistry change over daily/tidal/seasonal/annual/decadal time scales, both past, present and future in habitats exposed to different tidal influence?
56	What is the capacity of Kimberley corals to acclimate and/or adapt to ongoing climate change and ocean acidification?
57	Is there the potential for proactive management approaches, such as assisted evolution via selective breeding experiments or assisted translocation to restore degraded reefs, for Kimberley corals in the face of climate change?
58	How representative are reef ecosystem processes in the southern/central Kimberley to those occurring in the much more poorly studied north?
59	How would future changes to upstream catchments (e.g. land use changes) impact coastal water quality and inshore reef ecosystems in the Kimberley region?
60	How effectively can remote sensing technologies (including new satellites) be used to monitor shallow reef ecosystem processes in the Kimberley region?
61	What is the abundance of key species of fauna in the Kimberley region, especially harvested species (e.g. fish (barramundi, threadfin salmon, golden snapper), dugongs, turtles), and is it changing?
62	What is the areal cover of key habitats in the Kimberley region (e.g. mangroves, seagrass), and is it changing?
63	What are the sustainable harvest rates of key species of fauna in the Kimberley region?
64	What are the carbon loss/sequestration rates of coastal ecosystems in the Kimberley?
65	What are environmental/biological drivers that determine core habitat for snubfin and Australian humpback dolphins in the Kimberley region and how do they use these habitats?
66	What species do snubfin and Australian humpback dolphins rely on for foraging in the Kimberley?
67	How will the distribution and abundance of humpback whales in the calving grounds of the Kimberley region change with climate change?
68	Do calving females (whales) return to the same locations within the Kimberley to calf in subsequent years?
69	What are the important key sites in the Kimberley for humpback whale breeding, calving and resting outside of Camden Sound and should these areas be considered for additional management measures?
70	What are the key indicators of emerging pressures that can be used for long term monitoring of the health of 80 Mile Beach Marine Protected Area?
71	How can we measure Aboriginal culture and heritage (including social and cultural values) and incorporate this into our long-term monitoring of Kimberley marine park assets?
72	How does the structure of fish communities at the 80-Mile Beach Marine Protected Area vary spatially and temporally?
73	How do we efficiently monitor the condition of invertebrate intertidal communities in the Kimberley where there is often a high tidal range and extensive mudflats?
74	What is the inherent temporal variation in mangrove structure and cover in the Kimberley and how is this influenced by climate change and anthropogenic disturbances?
75	What are the key ecological processes linking water quality, sediment quality and invertebrate communities in the Kimberley and how may these be influenced by anthropogenic disturbances?

76	What is the distribution of the major marine habitats within Yawuru Nagulagun Roebuck Bay Marine Park/Kimberley Marine Park network?
77	What are the local hydrodynamics within Roebuck Bay and how do they influence water quality and connectivity?
78	What is the distribution and temporal variability of seagrass in the Kimberley?
79	How does abundance of dugong fluctuate through space and time in response to natural and anthropogenic pressures in the Kimberley?
80	What is the abundance, habitat associations and distribution of finfish species in Roebuck Bay, particularly those targeted by fishers in Yawuru Nagulagun Roebuck Bay Marine Park?
81	How important are mangals to productivity in adjacent marine systems in Roebuck Bay?
82	What are the key environmental drivers/constraints of a southerly expansion in crocodile populations in the Kimberley and how can we manage the related increases in human wildlife interaction?
83	What is the condition of marine fauna and flora communities in the East Kimberley (i.e. East of Cape Londonderry through to the WA/NT border)?
84	How well connected are marine environments of the Northern Territory to the Kimberley and in turn how well connected is the Kimberley to populations further south?
85	How much of a threat is marine debris, in particular plastics, to the biodiversity and conservation of the Kimberley marine environment?
86	Why are sea snakes declining in the Kimberley?
87	What is the impact of big marine herbivore harvests, such as green turtles and dugong, on the sustainability of marine systems in the Kimberley?
88	How will global warming influence large scale oceanography and what impacts will this have on the inshore Kimberley?
89	What are the essential nursery habitats for sharks and rays in the Kimberley?
90	What are the essential habitats of key fish species in the Kimberley and how do these vary throughout the life-cycle?
91	How does the status of key ecological communities in the Kimberley (Including fish and invertebrates) differ across the continental shelf (from 0-200m) and meso-scales?
92	What is the status of listed (Protected, Endangered, Threatened) species (e.g. sawfish, giant (QLD) grouper, and river sharks) in the Kimberley region that are directly affected by fishing activities?
93	What is the immediate and cumulative impact of seismic and acoustic activity on demersal fish and invertebrate communities in the Kimberley region of Western Australia?
94	What is the scale of coupling of fish replenishment and oceanographic processes in the Kimberley and does this differ between reef and pelagic species?
95	Do Indigenous people in the Kimberley manage saltwater resources for social-ecological sustainability?
96	Can metrics of effectiveness for Indigenous land and sea management be developed for the Kimberley region?
97	Do clearly articulated access and benefit sharing agreements lead to more equitable outcomes from jointly managed marine protected areas in the Kimberley?
98	How can Indigenous knowledges, practices and beliefs be effectively articulated to regional and national policy and management in relation to the Kimberley region?
99	How effective has the zoning of the Kimberley marine parks been in delivering biodiversity conservation and social outcomes?
100	Which key performance indicators are the most relevant and cost effective to measure the health of the Kimberley marine parks?
101	How effective has joint management been in the Kimberley marine parks and what measures should we use to determine the effectiveness of joint management?
102	Do Kimberley marine parks deliver the cultural outcomes that are envisaged?
103	What impacts or benefits has the establishment of the Kimberly parks had on commercial users?

104	What is the connectivity between regional population centres of dugongs throughout the Kimberley? What implications does the extent of connectivity have for management at a range of spatial scales?
105	What are the ecological relationships between the population and harvesting dynamics of dugongs and the dynamics of seagrass habitat (biomass, species composition, productivity)? How can this knowledge be used to manage dugong populations (both harvested & unharvested) in the face of external pressures such as increasing development in the region and climate change?
106	Dugong stories told throughout the Kimberley by hunters, elders and the communities contain ecological knowledge on historical changes in dugong distribution and abundance. How can this information be collated and used for management?
107	What is the quantitative, cumulative risks from multiple threats to dugong conservation in Roebuck Bay?
108	How important is the Kimberley, at national-international scales, for the conservation and management of dugongs?
109	What are the hydrodynamic processes that have shaped the patterns of biodiversity and ecological processes in the Kimberley parks?
110	What are the ecological and social implications of climate change in the Kimberley region and what management measures can be put in place to facilitate adaptation to changing conditions?
111	What is the overlap between megafauna distribution with important areas of industry activity (shipping, seismic, infrastructure, fishing, etc.) and what is the cumulative risk to megafauna from this overlap?
112	What is the relative importance of the Kimberley region as a humpback whale calving and breeding ground compared to other areas (e.g. Ningaloo, Pender Bay, etc.)?
113	What is the importance of offshore reefs, shoals and islands in the Kimberley region for threatened megafauna and birds?
114	What is the extent of genetic and mass transfer connectivity across ecosystems in the Kimberley?
115	How well do spatial and temporal patterns in hydrodynamics explain patterns of benthic productivity in the Kimberley region?
116	How close are seagrasses of the Kimberley living to the edge of their physiological tolerances?
117	How can the cultural values of nearshore habitats in the Kimberley be linked into a socio-ecological and mapping framework?
118	What are the best methods for monitoring turbid waters in the Kimberley region?
119	What impacts has the prawn trawler fishery of Napier Broome Bay, north of Kalumburu, had on the benthic environment (including bycatch) in the Kimberley?
120	How do barramundi growth rates in the Cambridge Gulf vary with respect to fluctuations in wet season rainfalls?
121	How do we best incorporate cultural, social, biological and physical aspects of the Kimberley when zoning marine parks?
122	What is the total catch of all species and associated impact from charter vessels Vs total catch and impact from gill net fishing operators along the Kimberley coast?
123	How much Traditional Owner time (days) is spent engaged in marine management across Indigenous ranger group operations, established marine parks operations and via other agencies (e.g. fisheries, CSIRO etc.) in the Kimberly?
124	How are shorebird populations changing over time throughout the Kimberley region?
125	Is shorebird distribution on the Kimberley coast changing over time?
126	What do the shorebirds of the Kimberley coast eat, and do the food resources available to them change over time?
127	To what extent are seabird population changes on the Kimberley coast driven by local habitat changes such as disturbance of roosts or changes in food distribution?
128	To what extent are seabird populations on the Kimberley coast driven by external factors, such as breeding success in the northern hemisphere or changes in mortality rates during migration?

129	How can Indigenous customary rights in the sea be better defined, understood and recognised in order to influence government policy and collaborative management arrangements in relation to the Kimberley region?
130	To what extent has park zoning (e.g. sanctuary zones) limited the development of Traditional Owner livelihoods and opportunities in the Kimberley?
131	Can marine parks make allowances for future Indigenous livelihood need and build this into Kimberley management plans and operations?
132	What opportunities exist (or have potential) for Indigenous livelihoods based on sea country in the Kimberley and what could be done to establish these opportunities?
133	How do we develop and support research by Indigenous people and empower Traditional Owners to secure their own Traditional Knowledge in relation to the Kimberley region?
134	What is the need for collaborative research and management of marine turtle and dugong that connects different Traditional Owner groups in the Kimberley and Northern Australia?
135	How can we maximise the use of drones and other new technology to monitor dugongs and other focal research species in the Kimberley region?
136	What are the biosecurity risks for the Kimberley sea country, and how should surveillance programs for Indigenous rangers be designed to monitor for these?
137	What are the most cost effective tools for Indigenous rangers to map and monitor the distribution of deep water seagrass and nearshore seagrass in the Kimberley sea country?
138	What effects do terrestrial reserve management have on marine parks in the Kimberley?
139	What are the trends in abundance of dugong/green turtle populations within the Yawuru Nagulagun Roebuck Bay Marine Park?
140	What are the foraging behaviour and habitat use of green turtles and dugong within Yawuru Nagulagun Roebuck Bay Marine Park?
141	What is the spatial distribution and abundance of sea grass beds within the Roebuck Bay Marine Park and South Kimberley?
142	Do the mangrove communities within the Roebuck Bay provide a habitat sanctuary zone for fin fish and marine invertebrates (mud crabs)?
143	How does the mangrove community within Roebuck Bay support viability of key target recreational species?
144	How do we develop a prioritisation process for monitoring and management in the Kimberley region that incorporates priorities from multiple stakeholders (i.e. encompasses ecological, cultural and social values)?
145	What can we learn from trialling the Multiple Evidence Based approach for monitoring the joint management of marine parks in the Kimberley?
146	Are the current tools and indicators proposed for monitoring marine values sensitive to detect the change required to inform ongoing management in the Kimberley environment?
147	What tools or protocols can be developed to support Traditional Owner groups to store, analyse and interpret monitoring data in the Kimberley?
148	How do we best use remotely sensed data sets, ships of opportunity and available field data to improve predictive modelling of benthic habitat in the Kimberley and identify important habitats characteristic of the region?
149	What is the full extent of coastal water marine biodiversity in the Kimberley how does this vary within and among MPA's and what is the correct spatial scales in which management should be applied?
150	How is the distribution of fish communities linked with benthic habitats within the Kimberley?
151	What are the likely threats/pressures to biodiversity in the Kimberley and the management measures that can be applied to protect priority habitats or species?
152	What are the high value habitats that require special protection in the Kimberley and what drives these areas?
153	What is the potential impact from climate change, in particular sea surface temperature, in Lalang Garram Camden Sound Marine Park?

154	Is the special purpose zone and the regulations around interaction sufficient for the management/ protection of humpback whales in Lalang Garram Camden Sound Marine Park?
155	What is the potential impacts of, and management requirements for, large commercial tourism vessels in Kimberley Marine Parks?
156	Are there habitats within the Kimberley marine parks in which humpback whales are feeding?
157	What are the likely implications of increased access via the Dampier Peninsula Rd once it is sealed?
158	What is the spatial and temporal use of habitat by dugong populations in the Kimberley, including foraging, calving, mating?
159	What is the level of Indigenous take and sustainable take of dugong and turtle in the Kimberley?
160	What is the impact of noise from vessels on marine mammals (including snubfin dolphins and dugong) within the confines of Prince Regent?
161	What is the spatial and temporal use of Lalang Garram Camden Sound Marine Park by marine turtles?
162	What are the non-Indigenous cultural heritage sites of the Kimberley?
163	What is the visitor carrying capacity of the marine reserve on the marine assets in the Kimberley?
164	What is the status of nesting green turtles in the Kimberley?
165	What is the importance of freshwater input into the King Sound and the Buccaneer Archipelago on the fish and benthic communities and what are the likely impacts of increased development and reduction of freshwater input?
166	How can traditional customs and practices of management in the Kimberley region be integrated into modern management methods?
167	How can Indigenous hunting be managed alongside tourism visitation interests in the Kimberley?
168	What are the population abundances of the Green, Ridley and Hawksbill turtles (Flatbacks are being studied) that reside on the reefs and in the estuaries of the 80Mile beach Marine Protected Area, especially on Karajarri Country?
169	What is the spatial and temporal abundance of threadfin and blue nose salmon within 80-Mile Beach Marine Protected Area, particularly within Karajarri Country, and what is the sustainable take from cultural and recreational fishing?
170	What is the population abundance of green mud crabs in the Kimberley and what is the sustainable take from cultural and recreational fishing practices?
171	What is the population abundance of targeted shellfish in the Kimberley, (meat shells) particularly in the intertidal areas and what is the sustainable take of these primarily through cultural fishing practices but also any additional recreational fishing?
172	How have fluctuations in nutrient levels from natural and anthropogenic sources influenced the extent and severity of impacts from Lyngbya to key social and ecological values (e.g. seagrass, benthic inverts) in Roebuck Bay?
173	What is the impact of aquaculture activities on surrounding ecosystems (specifically water quality, reefs, oyster and mangrove systems) in the Buccaneer archipelago?
174	Are commercial and recreational fishing quotas in the Kimberley sustainable?
175	How does noise (e.g. boat traffic) impact on turtle/ dugongs population movements/foraging grounds in the Kimberley?
176	What are the gaps in understanding of marine turtles in the Kimberley and how can Indigenous ranger groups assist with the future research and monitoring of turtles in the Kimberley?
177	What are the capacities and current/monthly occupancy rates of coastal camping and accommodation establishments at key sites across the Kimberley?
178	What is the daily pattern of boat launching and mooring at key sites across the Kimberley (e.g. Wyndham, One Arm Point, Middle Lagoon, Cable Beach)?
179	What is the monthly pattern of human use along the Kimberley coast from Wyndham to Kalumburu?
180	What is the effect of septic tanks at coastal campsites and accommodation on Kimberley coastal water quality?

181	What are the catches and fishing effort of recreational vessels fishing in Yawuru Nagulagun Roebuck Bay Marine Park?
182	What is the annual total number of commercial tour operators operating in the Kimberley, their respective sizes, passenger capacities, itineraries and activities offered?
183	How many individual permits to access the coast of the Kimberley are issued annually by the Traditional Owners?
184	How many helicopter/ float plane - facilitated fishing trips take place each year in the Kimberley, what are the target species and what is the total catch?

Appendix IV - List of all KMRP Publications

Bevan E, Whiting S, Tucker T, Guinea M, Raith A, Douglas R. (2018) Measuring behavioral responses of sea turtles, saltwater crocodiles, and crested terns to drone disturbance to define ethical operating thresholds. PloS one doi: 10.1371/journal.pone.0194460

Brown A, Bejder L, Pollock K, Allen S (February 2016) Site-Specific Assessments of the Abundance of Three Inshore Dolphin Species to Inform Conservation and Management Frontiers in Marine Sciencehttp://dx.doi.org/10.3389/fmars.2016.00004

Brown, G, Strickland-Munro, J. Kobryn, H and Moore SA . (2017). Mixed methods participatory GIS: An evaluation of the validity of qualitative and quantitative mapping methods. Applied Geography Applied Geography 79: 153-166. doi:http://dx.doi.org/10.1016/j.apgeog.2016.12.015.

Brown G, Strickland-Munro J, Kobryn H, Moore S (Dec 2015) Stakeholder analysis for marine conservation planning using public participation GIS Applied Geography doi:10.1016/j.apgeog.2015.12.004

Brown A, Bejder L,Parra G, Cagnazzi D, Hunt T, Smith J, Allen S (2015) Sexual Dimorphism and Geographic Variation in Dorsal Fin Features of Australian Humpback Dolphins, Sousa sahulensis Advances in Marine Biology doi:10.1016/bs.amb.2015.08.002

Bufarale G, Collins LB, O'Leary MJ, Stevens A, Kordi M, Solihuddin T (2016). Quaternary onset and evolution of Kimberley coral reefs (Northwest Australia) revealed by high-resolution seismic imaging. Journal of Continental Shelf Research, 123, 80–88 doi:10.1016/j.csr.2016.04.002

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Appendix V – List of all WAMSI KMRP reports

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