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WAMSI NODE 1
Western Australian Marine Ecosystem Research

SUMMARY REPORT

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Important Disclaimer

Acknowledgements

A detailed list of the many people who helped carry out and complete the WAMSI Node 1 projects is given in the project final reports. Mizue Iijima and Lucy Kay helped in compiling the information for this Node summary.

Contents

NODE DETAILS

Node 1.Western Australian Marine Ecosystem Research
Node Leader: John Keesing (CSIRO)

Project 1: Southwest Australian Coastal Biogeochemistry
Project Leaders: John Keesing, Peter Craig, Graham Symonds, Jim Greenwood, Mat Vanderklift, Peter Thompson, Martin Lourey (CSIRO)
Total Project Funding: $12,418,000 incl. $ 6,275,000 (CSIRO) and $ 4,183,000 (WAMSI)

Project 2: Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules
Project Leaders: John Keesing, Russ Babcock, Mat Vanderklift, Phillip England, Peter Craig (CSIRO)
Total Project Funding: $3,663,000 incl. $ 2,126,000 (CSIRO) and $ 1,417,000 (WAMSI)

Project 3: Benthic habitat surveys of potential LNG hub locations in the Kimberley region Project Leaders: Gary Fry (CSIRO) and Andrew Heyward (AIMS)
Project Funding: approx $500,000 (WA Government)

1. NODE OUTCOMES AND SUCCESS MEASURES

WAMSI's Node 1: Western Australian Marine Ecosystem Research, was undertaken to better characterise the south west Australian marine coastal and shelf ecosystem structure and function, and enhance our shared capacity to understand, predict and assess ecosystem response to anthropogenic and natural pressures.

The success measures for WAMSI Node 1 were to achieve the outcomes established in 2006 for Node 1 in the WAMSI Node 1 Science Plan (see Annexure 2). These were as follows:

1. Improved understanding of the importance of offshore/onshore exchange, longshore transport, and upper-ocean physical processes on nutrient supply to the shelf.

2. Improved understanding of hydrodynamic influences on benthic habitat, and the exchange of water, nutrients and particles between the lagoon and outer shelf.

3. Improved quantification of the nutrient budget for coastal waters and representation of benthic primary production and bentho-pelagic coupling at both lagoon and shelf scales.

4. Improved prediction of the impact of hydrodynamics and nutrient enrichment on benthic habitats.

5. Improved understanding of physical and anthropogenic impacts on ecological interactions.

6. Better understood key ecosystem processes across gradients of human use or disturbance

7. Improved access by management agencies to data and model outputs building on the development of Data Interrogation and Visualisation Environment (DIVE).

All these outcomes were achieved. A further success measure was the training of 8 PhD students. Despite the early period of WAMSI coinciding with a period of difficulty in attracting students to postgraduate study in Australia, as a result of record levels of employment, WAMSI Node 1 achieved its target of training of 8 PhD students and 1 Honours student was also trained.

2. RESEARCH PLAN/SCIENCE PLAN

Four high level questions, as outlined in the original WAMSI Node 1 Science Plan were used to guide and focus the research:

1. What are the large scale influences on the southwestern Australian coastal environment?

2. How can we account for the highly productive characteristics of the southwestern Australian coastal ecosystem in an oligotrophic environment?

3. How does the southwestern Australian coastal marine ecosystem respond to potential anthropogenic forcing (with nutrients and sediment as a key focus)?

4. What physical and ecological interactions are important determinants of southwestern Australian coastal marine benthic habitats?

Guided by these high level science questions and the desired outcomes (listed above) the following objectives (worded here as deliverables) were established:

1. Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions.

2. Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales.

3. Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling

4. Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment

5. An assessment of the importance of physical forcing and ecological interactions among key functional groups in determining patterns of spatial mosaics in benthic habitats.

6. An assessment of ecosystem processes with particular relevance to contrasting fished and non-fished areas.

7. An assessment of likely dispersal patterns for marine organisms based on hydrodynamic and population genetic models.

8. Electronic delivery of data and models to management agencies, building on the development of Data Interrogation and Visualisation Environment (DIVE)

These objectives were delivered through two projects: *Southwest Australian Coastal Biogeochemistry* (WAMSI 1.1) and; *Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules* (WAMSI 1.2) which all began on 1 July 2007. Note that the WAMSI Node 1 Science Plan sets these out in 3 projects, these were later reorganised into the two projects).

A third project: *Benthic habitat surveys of potential LNG hub locations in the Kimberley region* (WAMSI 1.3) was undertaken over a short period between June and October 2008 to support the WA government's strategic assessment of the proposed Kimberley LNG industrial precinct.

3. RESEARCH ACTIVITIES

Node 1 research projects entailed a large multidisciplinary research effort. A wide array of physical, biogeochemical and ecological approaches were taken to collecting data and a similarly wide range of analytical, statistical and modelling approaches were taken to analyse the data. These methodologies are too extensive and varied to describe them all here. However each of the methodologies used are provided within each of the main chapters which comprise the Project Final Report – Research Chapters (Annexure 3).

4. RESEARCH FINDINGS

4.1 Overall Research Findings

4.1.1 Ocean Systems Forecasting

- WAMSI Node 1 has developed hydrodynamic models at nested scales for the SW Australian continental shelf (2 - 5km resolution) down to lagoon scale (50-100m resolution) in Marmion Marine Park. These models have been shown to have close agreement with independently derived measurements such as from satellite and in water instrument data and can help in understanding the mechanisms which transport particles and nutrients through the water. The models have a wide range of applications in fisheries and marine park design and management. The models are relocatable to other parts of the WA coastline.

- WAMSI Node 1 has developed nutrient budgets which identify the source of nutrients and their pathways to benthic and primary production. The importance of benthic productivity in these budgets has been demonstrated with benthic productivity off the southwest (e.g. from kelp) being 3 times higher than previous estimates. Between 80 and 90% of primary production on the continental shelf is dependent on recycling of nitrogen on the shelf rather than new supplies from the open-ocean or terrestrial runoff. This information is important in understanding the carrying capacity and productivity of coastal fisheries such as that for the western rock lobster.

- WAMSI Node 1 discovered a combination of important mechanisms for supply of nutrients to fuel the annual autumn phytoplankton bloom which occurs off the entire mid and southwest shelf of WA. The annual autumn strengthening of the Leeuwin current mixes nutrients from deep water off the coast and this southward flow also entrains thin layers of nutrient rich, low oxygen water – sourced from deep waters offshore to the northwest of WA – into the euphotic zone making it available to phytoplankton to bloom. These sources are augmented with wave generated nutrient resupply from the sediments on the shelf. This knowledge is important for fisheries and marine parks by enabling an understanding of how climate variability and climate change can affect the productivity of WA coastal and shelf waters.

- WAMSI Node 1 has undertaken extensive instrumentation of the Marmion Marine Park lagoon showing for the first time that water circulation and exchange is largely driven by wave forcing over reefs which fringe the lagoon. Waves pump water into the lagoon and set up currents which we found can flush the lagoon in 15 hours or less emphasising the rapid rate of exchange between coastal and shelf waters. The information has implications for how we forecast the impacts of coastal developments such as sewage treatment plants and desalination plants. The models and research instrumentation approaches used can be relocated to other parts of the WA coastline.

- WAMSI Node 1 has identified a range of indictors of ecosystem health based on an assessment of the ecology and biogeochemistry of soft sediment habitats across a gradient of human impact. These indicators can be used to monitor and predict the impacts of coastal developments based on a given range of nutrient input and wave/swell exposure regimes.

4.1.2 Biodiversity Conservation

- WAMSI Node 1 research has shown that, in the southwest (Marmion, Jurien, Rottnest), the effectiveness of marine sanctuaries is dependent on both the time the sanctuaries have been in place and their size. The research showed that small sanctuaries are ineffective at protecting biodiversity and that even large sanctuaries must be in place for many years before they have a positive impact.

- WAMSI Node 1 has identified an important feature of the way the Leeuwin current transports particles southwards along the WA coast. Researchers found transport was not latitudinally uniform between northwest Cape and Cape Leeuwin and that different parts of the coastal shelf waters “retain” and “disperse” water and the particles it carries at different rates. Particles are rapidly flushed from some sections of the coastal shelf while in others they are retained longer. This information has important implications for how marine parks and fisheries are designed and managed as this requires a knowledge of how eggs and larvae of marine animals and their food will be dispersed or retained along the WA coast. The research has shown that WA's productive coastal scallop fisheries coincide with areas of high “retention” while those areas that lack scallop fisheries are in high “dispersal” areas.

- WAMSI Node 1 research has highlighted both the high biodiversity of WA flora and fauna and how little we know about our biodiversity. Even very short surveys conducted off Marmion and in the Kimberley have resulted in the discovery of previously unknown species.

- WAMSI Node 1 researchers working offshore of Marmion Marine Park has made the first discovery anywhere in the world of deep water sponges which possesses high levels of photosynthetic symbiotic cyanobacteria. Researchers also discovered that sponges from Marmion excrete significant amounts of nitrogen in the form of nitrate. These important findings suggest that sponges in temperate waters off WA may play a critical role in producing and recycling carbon and nitrogen. Sponges (like corals in the tropics) are long lived animals and thus may store and recycle large amounts of nutrients and maybe critical in helping maintain the high productivity of WA’s coastal reefs and benthic fisheries such as that for western rock lobster.

- WAMSI Node 1 researchers have overcome an important obstacle to understanding the timeline of some important ecological features of WA's productive coastal reefs by determining how kelp canopy patches and kelp free patches are maintained and replaced after storms. Understanding the longevity of transient features of the marine habitat like kelp beds is critical for the design and management of marine parks. WAMSI researchers found that most bare patches free of kelp canopy last an average of 6-10 years before the kelp canopy recovers. Thus we need to take into account that any climate change induced change in the strength or patterns of storms which tear up kelp beds will impact the resilience of kelp beds, which we know are the most productive parts of the southwest WA marine ecosystem and the highest store of carbon in living organisms in coastal waters.

- WAMSI Node 1 researchers discovered deepwater (50-60m) kelps beds off southwest WA but their importance remains a mystery given the difficulties carrying out research at these depths.

- WAMSI Node 1 researchers showed by combining two sophisticated technologies; hydrodynamic modelling and molecular ecology, that population connectivity exists over very large spatial scales indicating west and south coast parts of some species ranges can be linked genetically by Leeuwin Current-mediated larval dispersal. In widely dispersing species, the south west coast of WA potentially spans a single evolutionarily significant unit. This has implications for how spatial management units such as those used in zoning marine parks are designed and for how species may change their distribution in response to climate change induced modifications to marine environments and oceanography.

4.1.3 Natural Resource Management

- WAMSI Node 1 undertook surveys in the Kimberley in the vicinity of Gourdon Bay, Quondong – Coulomb Point, Perpendicular Head and Packer Island. The data, providing improved knowledge on biodiversity, habitat complexity and bathymetry were used as part of the WA government's strategic assessment of the region and formed part of the basis on which James Price Point was chosen as the location for the LNG industrial precinct. At the time of the surveys, the marine benthic communities at these prospective sites were largely undescribed. The surveys resulted in the discovery of at least 4 new species and numerous new records for Australia and Western Australia.

- WAMSI Node 1 research found that the open-ocean swells are critical in transporting and retaining biological particles, especially the western rock lobster puerulus off the west coast of Australia. Since the puerulus are slightly buoyant, they are pushed by the swell (in a process called Stokes drift) towards the shore. This conclusion has been successfully developed in an associated FRDC western rock lobster recruitment project with Node 4 researchers.

4.2 Specific Research Findings/Outputs

4.2.1 Project 1 South West Australian Coastal Biogeochemistry

Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions

Eastern Indian Ocean Scale

By modelling the connectivity among regions of the WA coast we have identified key source and sink areas for the larvae of commercial and recreationally important species of finfish, lobster and scallops. Connectivity varies with season and is also influenced by factors such as ocean swells and larval behaviour.

Numerical models are key tools for our understanding of hydrodynamics of the ocean boundary current systems and their impacts on marine ecosystems. In this study, the primary source of large-scale and regional ocean circulation information is a global ocean model, OFAM (Ocean Forecasting Australia Model), which has 0.1 degree (~10 km) resolution in the Australasian region. OFAM was developed as part of the BLUElink partnership between CSIRO, the Bureau of Meteorology, and the Royal Australian Navy. To prove the accuracy of the model in simulating the Leeuwin Current along the shelf break of the WA coast, we have validated the BLUElink Reanalysis (BRAN) product of OFAM with field data. The validation against observations from research vessels and shelf moorings suggests that the BRAN product provides good qualitative representation of the Leeuwin Current and its associated eddies. This comparison gives confidence for nested ocean modelling, biophysical investigations, and ocean connectivity analysis, based on the BRAN product, in this WAMSI project as well as in other projects in Node 2 and Node 4.

The BRAN model output has been used to assess the seasonal variations of the Leeuwin Current and its eddy field. It has confirmed the two pathways for tropical waters entering the southward Leeuwin Current during the autumn and winter seasons. The study has developed particle-tracking based on the BRAN model output that can be used to track the movements of passive particles representing fish and invertebrate larvae, as well as marine pollutants. The retention and connectivity of shelf waters off the west coast of WA have been assessed using the particle tracking, to provide indication of fisheries recruitment processes. The shelf regions off the west coast of WA can be classified into several sections of alternating low and high retention, to a large extent determined by the magnitude of alongshore velocity. Shelf regions identified to have significantly higher retention rates than their standard deviations were: Carnarvon (24º-25.5ºS), the broad Abrolhos region (26.5º-29.5ºS), between Perth and Geographe Bay (32-33.5°S), and south of Cape Leeuwin (34.5-35ºS). In addition to North West Cape, low retention shelf regions were identified off Shark Bay

(~26°S), near Jurien Bay (30-31°S), and off Cape Leeuwin (~34ºS). With the exception of the Shark Bay scallop fishery (which occurs inside the shelter of an almost continuous island chain), the shelf areas with sufficient scallop populations to support commercial saucer scallop fisheries occur in close association with regions with high levels of particle retention rates.

Particle tracking suggests that alongshore dispersal is dominantly southward in April-June when the Leeuwin Current is strong, but more north-south symmetrical in October to December. Thus, the direction of fish larval transport along the coast will depend on the spawning season.
From the particle modelling, larval behaviour has been found to be important in determining eventual recruitment. For example, the open-ocean swells have been found to be critical in transporting and retaining biological particles, especially the western rock lobster puerulus off the west coast of Australia. Since the puerulus are slightly buoyant, they are pushed by the swell (in a process called Stokes drift) towards the shore. This conclusion has been successfully developed in an associated FRDC western rock lobster recruitment project.

Western Australian Continental Shelf Scale

At the Continental shelf scale, we developed an intermediate scale model capable of resolving sub-mesoscale processes on time scales ranging from hours/days to seasonal cycles, with resolution down to around 2 km, centred on Perth and extending from the coast to the continental slope and nested within the regional scale model.

The Regional Ocean Modelling System (ROMS) was implemented on a domain extending from the coast offshore to 108°E and from 35°S (Cape Leeuwin) to 21°S (North West Cape). ROMS is a widely-used open-source model (developed at Rutgers University) that has also been implemented in WAMSI Nodes 3 and 6. On this southwestern domain, the horizontal resolution in cross-shore direction varies between 2 km and 4 km from the coast to the 1000 m isobath and then increases to 8 km at the oceanic boundary. The alongshore resolution varies from 3 km to 8 km. This horizontal resolution is considerably higher than the uniform 10 km used in previous (SRFME) studies, and in BLUElink (BRAN). In the vertical, there are 30 levels with refinement in the top 200 m. The model was driven by the same air-sea flux forcing as the BLUElink model and was one-way nested into BRAN at the open boundaries. This nesting ensures that the consequences of large-scale forcing, including the Leeuwin Current itself, are captured by the model.

The model was integrated for 4 years from January 2000 to December 2003 and the solution for 2003 is selected to represent "typical" (i.e. neither El Nino nor La Nina) conditions for the region. The model reproduces defining features of the Leeuwin Current System, including the seasonal variability seen in BRAN and satellite observations, but the finer-scale features such as eddies are better represented in ROMS. For example, ROMS produces a much stronger northward Capes Current than BRAN, and the Leeuwin Current is also significantly stronger. Both models reveal a seasonal cycle of eddy kinetic energy (EKE), with higher EKE in austral winter and lower EKE in austral summer, but EKE is higher in ROMS than in BRAN due to the improved eddy resolution. The shelf-scale hydrodynamic model was developed primarily to examine the nutrient balance and primary productivity of the region (see below). The higher resolution of the model addresses the underestimation of velocities (including cross-shore fluxes) in the 10 km models like BRAN. This is obviously critical to the biogeochemical balances over the shelf, which are driven by physical processes, including eddies, as discussed below.

Lagoon Scale (Marmion Lagoon)

At the lagoon scale our objective was to develop a model with horizontal resolution of order 100m for the Marmion lagoon region in an area of order 10km x 10km. Time scales of interest vary from seconds to weeks and it was important that the model incorporate the influence of surface waves.

At the lagoon-scale, wave driven currents were incorporated (for the first time) in a very high resolution (30 m) hydrodynamic model of the WA coast, leading to significant improvements in accuracy. This will enable much more accurate predictions of processes such as dispersal, mixing, and connectivity of these reef and lagoonal systems.

The numerical model XBeach was used to simulate the depth-averaged wind and wave-driven circulation. The wave field is obtained using a simplified time-dependent wave-action balance that includes wave refraction, shoaling, current refraction, bottom friction and wave breaking. The model is forced at the offshore boundary with observed significant wave height, wave period and direction. The model domain is 13 km alongshore and 8 km across-shore, covering the Southern portion of the Marmion Marine Park with a grid size of 30x30 m. The wave model provides the spatial distribution of wave action, and therefore wave energy, which is then used to evaluate the radiation stress terms in the depth-averaged, shallow water equations for the mean flows.

Comparison of observed and modelled time-series of currents showed good quantitative agreement at some locations but at other locations the model failed to capture the stronger currents seen in the observations. Numerical results for the case with a significant wave height of 2.2m revealed the high spatial variability in the currents in the vicinity of the reefs due to the spatial variability in forcing associated with wave breaking on the reefs. Examination of the dominant terms in the momentum balance showed that, through the surf zone over the reef crest, the radiation stress gradient opposes the pressure gradient. The cross-reef current is forced by the combination of radiation-stress gradient and pressure gradient. In the lagoon behind the reefs radiation-stress gradients were small and the flow is governed by a balance between the pressure gradient and bottom friction.

The second part of the lagoon scale work was to undertake a field measurement program with the following aims:

(i) to provide data to help tune the numerical model
(ii) to examine the linkages between the hydrodynamic and biological environments

In situ measurements of coastal hydrodynamics provided insight into the interactions of physical and biological processes at a range of spatial scales validating predictions of the lagoon scale model, as well as revealing how algal canopies influence fine scale turbulence and mixing.

Waves and currents at 11 sites across Marmion lagoon were measured by a variety of point current meters, acoustic doppler current profilers (ADCP) and wave gauges. Bio-fouling is a major problem in these shallow waters and, to ensure the highest quality data, the array was deployed for approximately 6-8 weeks and then recovered to download data, replace batteries and clean sensors and mooring frames. The array was deployed four times during the course of the year. Additional data on water quality, temperature, salinity and nutrient distributions were also collected. The observations show primarily wind-forced alongshore currents shorewards and seawards of the reefs during periods of low waves. This result is consistent with earlier studies in a region just a few kilometres north of the current work. However, during high wave events, currents in the vicinity of the reefs and at sites several kilometres removed from the reefs are correlated with offshore wave height. During periods of high waves the observations showed onshore flow over the reefs, offshore flow through gaps between reefs, and alongshore flow in the lagoon behind the reefs. The strongest currents were observed during periods of high waves, sometimes even with opposing, or light winds.

As part of this study, UWA PhD student, Eloise Brown, completed a study of boundary-layer hydrodynamics in submerged canopies. With an array of 4 acoustic Doppler velocimeters (ADV), sampling at 8 Hz, and an acoustic wave and current profiler, water velocities were measured in the field at fixed heights through the kelp canopy and on bare reef over a 3-week period spanning several winter storms. Flows through the canopy were also examined in the laboratory using a synthetic canopy of varying density. Turbulent Kinetic Energy (TKE) was parameterized as a function of reef roughness, canopy density and distance from the canopy edge. Profiles of the flow field were measured with paired ADVs sampling at 25 Hz over bare reef, over five densities of model kelp canopy, and at five distances away from the edge of the model canopy. The results are to be reported in her thesis.

Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales

Continental Shelf Scale

Primary productivity over the southern western WA continental shelf, particularly as viewed in satellite ocean colour, shows variability on space scales of km, and time scales of days. The variability is caused mainly by the underlying physical dynamics. The main source of nutrients to support the productivity appears to be the deep nutrients off the shelf, but the biological dynamics on the shelf itself appear to be largely self-sustaining. In this component of the program, the observations are explained with coupled physical-biological models that improve understanding of the shelf biogeochemical dynamics, and quantify both the fluxes of nitrogen onto and off the shelf, and the patterns of primary production and chlorophyll biomass over the shelf. Four separate model studies contributed to meeting this objective.

First, a nitrogen box-model was constructed for the Western Australian shelf from Shark Bay to Cape Leeuwin based on a range of observations throughout the region. The budget shows that terrestrial and atmospheric inputs to the continental shelf off western WA are small (<1%) compared to preliminary estimates of nitrogen derived from Leeuwin Current advection and eddy activity (8%) and seasonal upwelling along the shelf (7%). By closure, the budget suggests that 84% of primary production is recycled on the shelf, including a large contribution from the sediment.

Second, the seasonal evolution of chlorophyll *a* at the continental shelf break was investigated using a one-dimensional (vertical) model. The model suggest that in years of high Leeuwin Current flow vertical mixing associated with the current could support the increase in chlorophyll a concentration at the shelf break. In addition, inter-annual variation in the timing and magnitude of the winter increase is shown to relate to the strength of the Leeuwin Current. In years when the Leeuwin Current flow is weak surface cooling and convective mixing could explain the winter increase in chlorophyll *a*.

Third, the relative influence of temperature and passing surface-waves on the seasonality of the sediment nutrient flux was examined using a one-dimensional coupled pelagic-benthic biogeochemical model. The results suggest that enhanced sediment pore-water flow associated with large amplitude surface waves during the winter increases the sedimentary mineralisation rate of nitrogen in the sediment, which releases dissolved nitrogen to the overlying water column. The seasonal increase in sediment nitrogen flux is shown to drive pelagic phytoplankton production, accounting for an observed correlation between chlorophyll *a* concentration and surface-wave height. During the summer months the sediment mineralisation lowers again, allowing organic matter to accumulate in the sediment balancing the annual sediment nitrogen budget.

Fourth, a high-resolution coupled hydrodynamic-biogeochemical model was configured for the continental shelf from North-West Cape to Cape Leeuwin, and used to construct a seasonal nutrient budget for the shelf. The model has provided information for the first time about the likely spatial extent and temporal nature of both the deep-chlorophyll maximum, and the biological response to wind-driven upwelling along this coast during the summer. Although the region has its lowest standing stock of chlorophyll *a* during summer numerous small upwelling events were predicted by the model along the shelf between Shark Bay and Cape Leeuwin. These predicted upwelling events during summer were short-lived and associated with model predictions of increased chlorophyll in surface waters along the shelf-break and coast. The model also confirmed the role of anti-cyclonic eddies in the entrainment and export of phytoplankton from the shelf during autumn months, and the potential importance of the sediment nutrient flux in shaping the seasonal variation in chlorophyll biomass on the shelf. An annual nitrogen budget constructed for the model showed that particulate nitrogen production on the shelf was largely fuelled by nutrients released from the seafloor (~90%), with offshore supply of nutrients (via upwelling and advection) supporting the remaining 10%. Deposition of particulate nitrogen on the shelf was underestimated by the model, with about 60% of the particulate nitrogen produced on the shelf exported offshore.

Lagoon Scale (Marmion Lagoon)

Persistent high nitrate concentrations were discovered in the vicinity of limestone reef during the biophysical sampling of the Marmion Lagoon. The main objective of this part of the project was to identify the source of the nitrate, and explain the spatial and temporal variability in the measured distributions. The objective was met by conducting a series of simulated dye release experiments using a high resolution three-dimensional model, and constructing a simple box model of the reef.

The results of the dye release experiments indicated that the observed nitrate distributions in Marmion Lagoon could be reproduced by the release of nitrate from two separate locations on the seabed. In addition, rapid change in the modelled surface dye fields, in response to changes in circulation, provided evidence that the observed nitrate fields were highly transient features, and the spatial variation between observations was largely due to changes in the hydrodynamic conditions. The model was unable to identify the mechanism responsible for the release of nitrate at the seabed. Bacterial nitrification associated with sponges, and the infiltration of nitrate-rich groundwater are suggested as two possible explanations.

Published rates of sponge mediated nitrification (from elsewhere) are an order of magnitude smaller than the two point sources used in the model experiments. However, it is estimated that a reef area of 50,000 m^2 could potentially supply the required amount of nitrate. Box-model calculations showed that the nitrate results could be explained by a groundwater infiltration velocity of 5×10^{-6} ms^{-1} and a groundwater nitrate concentration of 200 mmol N m^{-3} similar to values previously reported for Marmion. The calculations also show that the flow rate is small enough to explain why a salinity signal was not identified.

Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling

Lagoon Scale (Marmion Lagoon)

Research at the lagoon scale resulted in greatly improved understanding of the principal environmental influences on variability in nutrients, primary and secondary production. The research also resulted in improved representation of benthic primary production and bentho-pelagic coupling. Wave climate variability at scales of hours to days was shown to be a key driver of nutrient concentrations in the coastal lagoon. This observation is particularly important in the context of laboratory studies which revealed that nutrients were rapidly consumed – likely by sediment biota including benthic microalgae. Laboratory studies of production by benthic microalgae and by different species of macroalgae revealed that the highest rates of mass-specific production (i.e. production per unit biomass) were yielded by several species of relatively small red macroalgae, but despite the relatively high rates of production by these species, the biomass of benthic autotrophs in Marmion Lagoon is dominated by kelp *Ecklonia radiata*, and this dominance means that benthic production is also very likely dominated by this single species. Field studies of production by *E. radiata* showed that production was highest when water temperatures were coolest and water clarity was highest.

The biomass and the identity of benthic fauna were quite different among habitats for the benthic invertebrate groups studied. In general, reefs supported much higher biomasses than seagrass beds, which in turn supported higher biomasses than unvegetated sand. Patterns in growth and nutrition of mussels were consistent with a model of high contribution by detritus of benthic origin. The high biomasses of filter feeders on reefs and in seagrass beds, the high growth rates we observed inshore, and the high rates of filtration all indicate that suspension feeders are very likely play a key role in detrital food webs and nitrogen cycling in nearshore ecosystems in Western Australia.

Continental Shelf Scale (Pelagic)

The objective was to improve our descriptions and conceptual models for shelf waters including understanding of seasonal and interannual variability.

In the pelagic realm WAMSI has provided the glue to bring together scientists from many institutions including local (especially UWA and Murdoch Universities) and international scientists, post doctoral fellows and PhD students to achieve this objective. Between them they attracted millions of dollars in ship time and support from other agencies (e.g. ARC). The results have been impressive with many publications on the physical, chemical and biological oceanography of the region. The general approach been to describe and understand the spatial and temporal variation in physics, chemistry and biology so that our natural resources can be managed in an environmentally sustainable manner that considers all aspects of the pelagic ecology. The data collected on the two Marine National Facility cruises in 2006 and 2007 have supported many other studies not reported on here including topics as diverse as larval fish dispersal, rock lobster genetics and microzooplankton grazing. The focus within CSIRO has been on understanding the source of nutrients to support pelagic primary production and how this is manifest at higher trophic levels. The sum of this research exceeds the requirements of the objective.

A simple empirical model described 74% of the variation in chlorophyll *a* as a function of seasonality. The residual anomalies were found to be a function of the Southern Oscillation Index (65%) and wind (11%).

Long term trends in the marine environment have been observed at the Rottnest Island Station over the last ~ 40 years including a warming trend of 1.23°C $century^{-1}$, a rise in salinity of ~ 0.41 parts per thousand $century^{-1}$, a fall in dissolved oxygen (-49 µM $century^{-1}$), and a rise in nitrate (0.4 µM $century^{-1}$) and phosphate (0.3 µM $century^{-1}$).

The dominant phytoplankton have been identified and their abundance quantified using a range of methods. We now know that 67% of the biomass is < 2 µm cells, primarily *Synechococcus* and *Prochlorococcus* with their dominance decreasing with latitude and proximity to shore. This represents a considerable change in the previously reported phytoplankton communities in this region.

Regions of high primary production along the west coast of Australia are associated with features of the Leeuwin Current such as a productive eddy-forming meanders, thin and shallow layers of high nitrate offshore at ~ 22 to 24°S and the LC transport and entrainment of this thin layer into the photic zone at latitudes > 28°S.

In the first large scale survey of zooplankton along the west coast of Australia they were found to be > 5 times more abundant nearshore providing a relatively rich coastal environment for the growth of planktonic carnivores such as larval fish.

Regions of high productivity had a more diatom based food web but the majority of zooplankton feed in the microbial food web where heterotrophic dinoflagellates are the keystone species.

The growth of zooplankton was measured for the first time and found to be associated with mesoscale features of the Leeuwin Current such as eddies and edges.

During the autumn of 2007 the greatest abundance of larval fishes was found at the continental shelf break where the fast moving surface layer of the Leeuwin Current delivers a flow of phytoplankton and zooplankton. Successful recruitment of neritic larvae to the location of spawn probably requires behaviours such as vertical migration out of the surface current.

New technology made it possible to observe thin layers of high nitrate water being advected south in the Leeuwin Current. Given the extreme nitrogen limitation (factor 10) for the pelagic ecosystem and the estimated magnitude of this source the shelf wide phytoplankton bloom that occurs each winter appears to depend largely this source.

Continental Shelf Scale (Benthic)

The importance of bentho-pelagic coupling to the ecology of west coast pelagic and benthic ecosystems was highlighted by a combination of empirical and modelling approaches. The presence of extensive primary producer habitats across the shelf out to depths of >70m and rapid nutrient uptake at the benthic boundary layer was shown by modelling to have the potential to maintain low nutrients in the water column.

The project has provided a description of the shelf habitats by categorising the range of benthic habitats encountered and their relative coverage of the shelf region from 20-200 m. Improved methods of analysing acoustic backscatter data to more rapidly characterise benthic habitat types were developed as part of the project. We also describe the distribution of animal and plant abundance and biomass on the shelf and their association with particular habitat types.

We provide models which enable estimates of benthic primary production by depth, benthic irradiance by depth and model which highlights the importance of bentho-pelagic coupling to ecosystem function and resilience and the potential impacts of human impacts such as increased nutrients and associated consequences such as increased light attenuation. Lastly we provide spatial estimates of biomass, carbon and nitrogen distribution and of primary production on the shelf out to 200 m deep off the Marmion coastline. In this region we estimate primary production rates of 122.9 gC per m^2 per year of which benthic primary production comprises 42.7 gC per m^2 per year. This is much higher than previous estimates of benthic primary production in this region and thus has important implications for nitrogen budgets. In revising these budgets we confirmed the importance of benthic resupply of nitrogen to productivity of shelf waters and our model estimates a requirement for a benthic nitrification flux of 9.53 gN per m^2 per year. This is higher than other estimates made for the entire shelf region south of Northwest Cape (6.24 gN per m^2) but is similar to the flux of 10.9 gN per m^2 per year measured at Marmion.

Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment

We aimed to develop a conceptual understanding of ecosystem responses to forcing factors (primarily anthropogenic nutrient load) with the ultimate aim of improving our capacity to predict the impacts of anthropogenic activities which alter the physical dynamics and level of nutrients in nearshore systems. We focussed on an existing gradient of sediment nutrient content as a proxy for nutrient enrichment. We believe sediment nutrient content is a useful indicator because it integrates over time probably best reflecting the nutrient loading at each site much better than water column nutrient loading which can be highly variable in time.

The research was conducted at multiple sites in Marmion lagoon and Cockburn Sound and in between these two locations. This design presented a gradient of sediment nutrient enrichment in nearshore soft sediment habitats from low (Marmion) to high (Cockburn Sound) and gradients from sheltered (nearshore) to exposed (offshore) to determine the importance of wave induced seabed forcing in mediating the impact of sediment nutrient enrichment.

We measured a wide range of physical and biogeochemical parameters and a series of ecological and physiological responses across these gradients. Sediment carbon and nitrogen content were the most significant factors controlling benthic chlorophyll distribution and infaunal and macrofaunal biomass. These findings confirmed our view that sediment nutrient levels were an important driver of the physiological, biological and ecological dynamics of soft bottom benthic habitats.

The sediments of Jurien Bay and the mid and outer sites in the Marmion lagoon had the lowest sediment nutrient levels and those of Northern Harbour, Southern Flats and Jervoise Bank in Cockburn Sound and the Swan River had the highest. Of these the Northern Harbour site was significantly degraded. Primary producer and heterotrophy biomass and diversity was greater at many of the sediment-enriched sites when compared to low sediment nutrient sites in both Marmion lagoon and in Cockburn Sound. However the enriched sites in Cockburn Sound had the highest respiration rates and high counts of heterotrophic bacteria and the results suggest that if soft sediment habitats become overly enriched such as we observed at Northern Harbour then they become highly degraded with low levels of benthic primary production, high levels of heterotrophic bacteria and sediment community respiration and low levels of infaunal and macrofaunal biomass and diversity.

The roughly equivalent measures of microphytobenthos production, Pmax adjusted for differences in biomass (measured by oxygen evolution) and ETRmax (measured by PAM flourometry) tend to be higher outside Cockburn Sound than within and the was an ETRmax gradient across a series of stations distributed along a transect between an “impacted” (Northern Harbour) and offshore (Carnac Island) station suggesting that production efficiency is suppressed in Cockburn Sound possibly due to poor water quality or lower light penetration in the sound. The majority of mean nutrient fluxes (in both illuminated and dark treatments) encountered outside Cockburn Sound were negative suggesting that consumption of nutrients by microphytobenthos dominates the nutrient dynamics in these sediments. Inside the Sound there was pronounced summer time ammonium release from sediments in the dark treatments suggesting that higher respiration and remineralisation of organic matter during summer releases more nutrients than dark uptake by MPB can consume. A large overall efflux of ammonia relative to nitrate suggests nitrification may have been inhibited (possibly by low dissolved oxygen) or that nitrate generated by nitrification may be lost via coupled denitrification or anammox. The ammonia oxidising bacteria and ammonia oxidising archaea are more numerous and form a larger percentage of the total DNA in winter than summer. The higher abundance of nitrifiers in winter compared to summer coincides with lower efflux of ammonia at the corresponding sites, suggesting that this winter increase in nitrifier biomass may also generate an increase in nitrification rate.

4.2.2 Project 2 Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules

An assessment of the importance of physical forcing and ecological interactions among key functional groups in determining patterns of spatial mosaics in benthic habitats

Ecologically sustainable management of resources requires the ability to rapidly address the current state of resources as well as key ecological processed which maintain these resources. Increasingly, resource managers also require information on the relative importance of physical versus biological processes in order to predict how ecosystems may respond to environmental variability including a changing climate. In order to better characterise the south west Australian marine coastal and shelf ecosystem structure and function, and enhance our shared capacity to understand, predict and assess ecosystem response to anthropogenic and natural pressures we assessed the relative importance of physical forcing and ecological interactions among key functional groups in determining patterns of spatial mosaics in benthic habitats.

The project focused on the habitat dynamics of temperate algal communities on reefs off Western Australia. These algal communities display a complex mosaic of different algal assemblages, or habitat types, broadly characterised as either canopy or gap habitats. This mosaic structure has a strong influence on the overall biodiversity of rocky reefs in temperate south west Australia. Changes in this pattern and the relative proportion of the two habitat types will therefore have profound implications for the biodiversity and productivity of coastal marine ecosystems in the region. In order to understand the dynamics of this habitat mosaic structure, the project employed three complimentary approaches. First we described natural patterns of habitat variation and correlate these patterns with physical and ecological variables. Second we undertook ecological manipulations to better understand the ecological processes underpinning patterns in habitat mosaics. Finally we developed habitat models of ecosystem dynamics in order to begin developing predictive ability to predict environmental change under varying physical or ecological conditions.

Mosaics of habitat dominated by canopy-forming macroalgae and canopy-free (open-gap) habitat are prominent features of temperate subtidal reefs on the south and west coasts of Australia, with the proportion of reef occupied by canopy forming algae ranging between 40% and 60% based on diver transects. However, the persistence of this mosaic structure and mechanisms underlying this pattern are not well understood. We described patterns in the proportion of reef covered by each of these habitats, and the length of patches of each habitat, at 20 sites encompassing a gradient in wave exposure in south-western Australia. Our aims were to characterise patterns, and the strength of associations with potential influences, in order to develop models of habitat mosaic generation and maintenance. Modelled seabed orbital velocities explained approximately 35% of the variation in the length of open-gap patches with less canopy cover at higher wave exposure sites. This observation supports the hypothesis that waves create open-gaps by dislodging canopy algae. Herbivorous damselfish (*Parma* spp.) were 5.6 times more likely, and the sea urchin *Heliocidaris erythrogramma* was 20 times more likely, to be encountered at sheltered inshore sites than at exposed sites further from shore. *Parma* were 8.2 times more likely to be found in open-gap habitat. However, there was no relationship between the occurrence of either herbivore and the proportion of open-gap habitat among sites. These observations do not support a hypothesis that grazing by herbivores creates open-gaps. Massive sponges were three times as likely to be found in open-gap habitat, and hard corals were 91 times more likely to be encountered in open-gap habitat. The strength of these associations suggests that canopy algae might negatively influence sessile invertebrates. Further, the large size and likely old age of sessile invertebrates, particularly hard corals, indicates that patches of open-gap habitat can persist for decades. The patterns observed suggest that wave-induced disturbances create open-gaps and that these gaps are persistent features of temperate reefs.

The results of artificial clearance disturbances indicate that open-gap habitat macroalgal assemblages are strong competitors for space and that canopy is slow to establish, with most canopy clearances remaining as open-gap habitat after 3 years. However where returns to canopy habitat were observed, they were more likely to occur when clearances were within or adjacent to canopy habitat. Modelling of habitats using observed probabilities of transitions in habitat state indicated that in undisturbed habitats the average residence time (longevity) of open-gaps was 3.7 yrs and for canopy 2.8yrs, while in disturbed habitats average open-gap residence time was 12 years, of the same order as the average estimated age of coral populations within gaps, while with canopy habitats had much shorter residence times of 2.4 yrs. When canopy habitats were differentiated into *Ecklonia* and *Sargassum*, the two principal canopy forming taxa, the residence times were 6 and 1.6 yrs respectively and open-gap residence times remained unchanged. Projections of proportional composition of the habitat mosaic indicate that, because of the asymmetrical response to disturbance, any increase in the frequency of gap creation is likely to have long term and disproportionate negative impacts on overall canopy cover.

Whether they are observational, experimental or modelling based, studies of the natural environment are characterised by their ‘grain’ and ‘extent’, the smallest and largest scales represented in time and space. These are imposed scales that should be chosen to ensure that the natural scales of the system are captured in the study. We developed a simple cellular automata model of habitat to represent the presence or absence of vegetation, with global and local interactions described by four empirical parameters. Such a model can be formulated as a nonlinear Markov equation for the habitat probability. The equation produces inherent space and time scales that may be considered as transition scales or the scales for recovery from disturbance. However, if the resolution of the model is changed, the empirical parameters must be changed to preserve the properties of the system. Further, changes in the spatial resolution lead to different interpretations of the spatial structure. In particular, as the resolution is reduced, the apparent dominance of one habitat type over the other increases. The model provides an ability to compare both field and model investigations conducted at different resolutions in time and space. The model allows us to better interpret our observations and also forms the basis for ongoing modelling studies.

An assessment of ecosystem processes with particular relevance to contrasting fished and non-fished areas

One of the processes most likely to change the structure of marine ecosystems on the temperate west coast of Australia is fishing by humans. Our approach to examining this was to conduct a series of surveys designed to contrast management units established to prevent fishing (i.e., sanctuary zones in DEC- and RIA-managed marine parks). Surveys of abundances and sizes of fish, rock lobsters, and large invertebrates were conducted at 28 sites during 2007 and 2008 – 13 in Sanctuary zones, and 15 in 'General Use' or 'Recreation' zones. These sites encompassed six sanctuaries across three different regions, two each at Rottnest Island, Marmion Lagoon, and Jurien Bay. Sanctuaries included a range of sizes from 5 ha to >1,300 ha, and a range of ages at date of surveys from 4 years to 19 years. Where possible, surveys encompassed reef, and seagrass and bare sand habitats. Analyses focussed on trends in biomass, density, size and species richness as the most frequently-used indicators of the condition of ecological resources.

Results of the surveys were generally consistent with the expectation of higher abundance and biomass inside Sanctuary Zones (SZs) where fishing is prohibited, although we did not find a ubiquitously higher biomass or density inside SZ for all the metrics evaluated. An important finding was evidence that for several of the metrics large SZs better achieved the goals of higher biomass and density than small SZs, with a trend for higher density inside large SZs of western rock lobsters, and higher biomass of targeted species on reef habitat. This pattern is consistent with the pattern expected if individuals inside small SZs are more susceptible to fishing mortality, and with expectations arising from the fact that both groups are heavily fished in Western Australia. In the case of western rock lobsters, a higher biomass and density was found in both small and large SZs than adjacent fished areas, but the magnitude of the difference in density was much greater for large SZs. In the case of targeted fish, the difference in biomass between SZs and adjacent fished areas was only detected in large SZs, and was not detected in small SZs.

An assessment of likely dispersal patterns for marine organisms based on hydrodynamic and population genetic models

Gaining an understanding of patterns of dispersal within marine systems is fundamental to the identification of fishery stocks and the design of effective management strategies such as marine protected areas, but in practice is difficult to achieve. Hydrodynamic modelling is a rapidly developing and increasingly sophisticated application that has the potential to predict patterns of connectivity among marine populations in great detail. However, without empirical validation it is difficult to determine how well particle modelling is able to realistically represent biological processes. Genetic analysis has the potential to provide such empirical validation in a timely manner. This project employed a multidisciplinary approach incorporating analysis of DNA genotypes and hydrodynamic modelling to characterise dispersal during the larval stages of development in multiple sea urchin species. Sea urchins are useful model organisms for investigating connectivity in marine systems because whilst adults have similar sedentary life-histories, there is extensive variation in the larval life-history of different species allowing the contribution of passive, current-driven larval dispersal to be assessed.

Sea urchins were sampled at Jurien, Perth, Albany and Esperance for assessment of population structure using DNA sequence variation. This phylogeographic analysis was compared with hydrodynamic dispersal modelling to determine biological connectivity under the influence of the Leeuwin Current system.

A deterministic particle tracking model was implemented in Matlab for the BLUELink Re-analysis (BRAN) model outputs during 1997-2002. Particle tracking experiments were carried out to quantify the fate of the Leeuwin Current waters and the modelled larval dispersal patterns among the four urchin sample sites.

Results show that a significant portion of the Leeuwin Current particles, representing more than one third of the Leeuwin Current southward volume transport, were advected around Cape Leeuwin and eastward into the Great Australian Bight. The rest of the particles were dispersed by the Leeuwin Current eddies and interaction with the continental shelf. Particle dispersal from sampling sites was generally southward on the west coast and eastward on the south coast, however, substantial northward dispersal was also observed in summer from the west coast sites when the Leeuwin Current flow is weakest and eddy activity is greatest. Dispersal distances were greater in winter when Leeuwin Current activity is greatest. Areas of higher retention or lower flushing rates were visible at several points along the coast indicating potential for the accumulation of larvae. The ecological implications of this result invite further investigation.

Three genes in *H. erythrogramma* and two genes in *P. irregularis* were sequenced in individuals from all four localities, revealing substantial levels of variation among individuals. Sequence diversity at nuclear genes was higher than for the mitochondrial gene COI. Substantial diversity exists within sites and most of the variation is partitioned among individuals rather than among sites as reflected in Φst values close to or below zero in most genes.

Genetic differentiation among sites (two west and two south coast sites spanning 1130 km of coastline) was observed in nuclear but not mitochondrial genes, consistent with faster rates of intron evolution. Stronger structure and isolation by distance was apparent in *H. erythrogramma* compared to *Phyllocanthus irregularis*, suggesting the latter may have a longer lived larva than the 3-4 day duration measured in *H. erythrogramma* or some other adaptation counteracting population differentiation over the scale of this study.

Coalescent-based directional estimates of genetic exchange rates were consistent with overall predictions from hydrodynamic particle models that incorporated spawning time and larval duration in *H. erythrogramma* where northward gene flow from Perth predominated. Similar findings in *P. irregularis* imply a similar spawning time and this needs experimental investigation.

Electronic delivery of data and models to management agencies, building on the development of the Data Interrogation and Visualisation Environment (DIVE) in SRFME

DIVE is a data access and visualisation package that has been developed through CSIRO's partnership with the WA Government. DIVE enables scientists and managers to view the diverse data sets that have been generated in WAMSI. The data are multidisciplinary and multidimensional, and range from relatively small numbers of field samples through to 4d model output occupying gigabytes of computer storage. DIVE can be installed onto all platforms supporting Java. It is functional on Windows, Linux and Mac OSX computers.

DIVE supports the display of spatial maps, time-series plots, vertical profiles and cross-section plots. The spatial data are represented as coloured maps, contoured plots, vector maps or as habitat maps. The full functionality of DIVE is described in the user manual. DIVE's features include:

- Selection and display of arbitrarily directed cross-section plots
- Display of data from multiple sample points through the use of distinguishing colour and line styles
- Display of scalar and vector variables
- Expansion of individual panels by utilising a "lift-out" function to assist with examination of the data: the lift-out option is invoked by clicking on the small plus sign at the top-right of each plot, to make the panels appear in their own windows
- User–selection of the time-zone in which the data are displayed: most commonly, this will be UTC, or the local time-zone of the user.
- Single-step viewing through the time-series or vertical layers: that is, the time-slide and depth-slide can be clicked through individual time or depth intervals in the data file.
- Output of animations, over either the whole time-range or user-defined subsets: animations can be saved in AVI, Flash and animated gif formats.
- Ability to read folder-based datasets: if data are held in multiple files within a single folder/directory (as is common with output from large model runs), DIVE can interpret the files as a single data source, enabling, for example, faster access and continuous plots (rather than a new plot for each separate file).
- Display of underway datasets including high-resolution glider data, in which hovering the cursor over the track produces detail of the data

DIVE accepts data in self-describing format, in particular NetCDF, which is the standard for oceanographic data and model output. For model results, it has been tailored to handle:

- box-model output, for example from CSIRO's ecosystem model (Atlantis)
- z-coordinate models, such as CSIRO's SHOC,.
- sigma-coordinate models, such as Rutger's University's ROMS. (ROMS is one of the hydrodynamic models used in WAMSI, in Nodes 1, 3 and 6. The vertical sigma coordinate varies in time with the surface elevation.)

DIVE can also read:

- HTF (Hydrographic Transfer Format), see www.hydro.gov.au/tools/htf/htf.htm
- CFF (Column File Format Files) an in-house CMAR text-based spreadsheet-like format. This format is described in an appendix to the DIVE manual.

DIVE can connect to MEST (Metadata Entry and Search Tool) servers, select from available on-line datasets, and download and plot these datasets. MEST servers are based on OGC (Open Geospatial Consortium) Catalogue Services standards to access data sets across the web. This capability will enable DIVE to access data sets archived by the Australian Oceanographic Data Network (AODN), and the Australian Integrated Marine Observation System (IMOS), which have both adopted OGC standards. The capability will be available in DIVE when the national MEST servers are fully functional.

The DIVE installer can be freely downloaded from the WAMSI website http://www.wamsi.org.au/category/region/research/data-management which links to http://software.cmar.csiro.au/

The DIVE Manual is available on the web site: http://software.cmar.csiro.au/www/en/software/dive.html

4.2.3 Project 3. Benthic habitat surveys of potential LNG hub locations in the Kimberley region

The Northern Development Taskforce (NDT) approached the Western Australian Marine Science Institution (WAMSI) to co-ordinate a rapid assessment of the marine benthic communities within four locations along the Kimberley coast. These four locations were surveyed to describe the substratum type, biohabitat type and the bathymetry of the seabed. The survey locations were in the vicinity of Gourdon Bay, Quondong – Coulomb Point, Perpendicular Head and Packer Island. The data, providing improved knowledge on biodiversity, habitat complexity and bathymetry, was used by the Northern Development Taskforce as part of a selection process to rank the suitability of a range of locations for a proposed common-user liquefied natural gas hub precinct.

Sounding data were collected by each vessel during the survey to validate the existing bathymetry contour data. Depth soundings were recorded with four standard single beam echo sounders. These data were adjusted to local tide datum using a tide gauge deployed at each location. Bathymetric contours at depths of 5, 10, 15, 17 and 20 m were calculated from the interpolated grid using the ARC GIS spatial toolbox. The three locations positioned off prominent headlands; Gourdon Bay, Perpendicular Head and Packer Island, had similar bathymetric features. The 5 and 10 m depth contours run within a couple of kilometres from the shoreline at these headlands. Most of the seafloor within these survey locations was between 10 and 15 m deep, with the outer extent of the survey boundaries in about 17 m water depth. At the Packer Island location, there is a steep drop-off, down to 15 – 17 m, close to shore at the northern end. This location is also the deepest of the four locations surveyed; with most of the offshore region in waters greater than 20 m deep. Most of the area in the Quondong – Coulomb Point location is shallow, less than 10 m deep and can extend out to 10 km offshore. The outer survey boundary of this location is in about 15 – 17 m water depth.

Three vessels worked simultaneously in each of the four locations to complete video transects from the intertidal zone out to approximately 20 m depth. A gridded sample design with stratification based on a range of available biophysical parameters was used to select transect sites within each of the four locations. The relative abundance of the main functional groups of benthic organisms and substratum types were recorded along 500 m transects at 757 sites using underwater towed video cameras and analysed in real time. The two habitat classification systems used by AIMS/DECWA and CSIRO were calibrated prior to the survey to ensure standardised data collection. Percent composition data for each of the substratum and biohabitat types were used to produce benthic habitat maps of each of the surveyed locations and supplementary transect lines.

The substratum and biohabitat composition data were extrapolated across the entire extent of each of the four locations using appropriate statistical treatments e.g. cluster analysis and Voronoi tessellations. The biohabitat data was clustered into eight components; Algae (turf /microphytobenthos); Algae (turf / microphytobenthos) and no biohabitat; Algae (other); Bioturbated; No biohabitat; Bioturbated and no biohabitat; Mixed filter feeding community garden (medium); and Seagrass. The substratum data was clustered into four; Sand; Coarse sand; Sand waves/dunes; and Low relief reef.

Most of the seabed surveyed within the four locations was fine sand with mean percent coverage ranging between 56 and 62% within each location. Fine sand was most prominent in the deeper regions of the locations. The other key seabed types were sand waves or dunes (from 4 to 22% mean seabed coverage at each location) and coarse sand (6 to 25% mean coverage). Coarse sand was predominantly found in shallow waters around the headlands, with the sand waves or dunes generally occurring in patches between low and high relief reef areas, except for the Quondong Point – Coulomb Point location. At this location, there were extensive areas of sand waves or dunes found in the northern offshore region and along the shallow nearshore stretch at the southern extent.

There was very little mud or silt substratum throughout any of the four locations surveyed. All four locations showed some presence of low to high relief reef structure, predominantly around the shallow waters off the headlands at the two most northern locations surveyed (up to 4% mean percent coverage). At the three northern locations, low and high relief reef habitat were found extending along most of the length of the survey area in the shallows (around 5 m). Within the Gourdon Bay survey location, low relief reef was in a more patchy distribution around the shallows of the headland and around the isolated shoals in the offshore waters.

The distribution of hard substratum type influenced the abundance and distribution of biohabitats and benthic animals within these locations. Where there was low relief solid structure present, there were generally diverse filter feeding communities, such as sponges, whips and gorgonians. These communities were very patchy even at the scale of within transects and most common among the fine sand substrates where they were attached to hard substrates just below a thin sand layer. The filter feeding communities were dominated by sponges, followed by whips and gorgonians. Soft corals and hard corals were recorded within each location; however their abundances were generally low and variable. There were some isolated medium to dense patches of alcyonarians at Coulomb Point and medium to dense patches of *Turbinaria* sp (flowerpot coral) at Perpendicular Head and Packer Island.

Transect sites with higher proportions of low or high relief reef in deeper waters were most strongly associated with mixed filter feeding communities; sponges, gorgonians, whips and alcyonarians and hard coral gardens. With a few exceptions, live reef coral, seagrass and algae (micro- and macroalgae) biohabitats were generally found in the shallower depths.

Halophila sp seagrass was present at all of the four locations surveyed, but generally only found in small sparse patches in the shallow nearshore regions of the small bays (mean percent coverage of between 1 and 6% of the seabed surveyed). There were extensive seagrass beds at the Quondong – Coulomb Point location in deeper offshore waters, 10 m depth. These beds were found interspersed between the filter feeding communities on the fine sand substrates.

Macro- and microscopic algae were the most abundant benthic primary producers encountered, with scleractinian corals and seagrass mostly minor contributors. Green, red and brown macroalgae were common, but were mostly restricted to the shallow areas at Gourdon Bay, Perpendicular Head and Packer Island locations. Along the coast off Coulomb Point, there were extensive patches (mean coverage of 7%) of the brown macroalga *Sargassum* sp extending into the deep waters, almost to the seaward extent of the survey boundary. In the deeper waters with sand substrate, green turf algae and microphytobenthos was most dominant especially in the three northern locations, Quondong – Coulomb Point, Perpendicular Head and Packer Island, with mean percent coverage of 7 to 22%.

In areas characterised by sandy substrate with a significant coverage of microphytobenthos, heart urchins and crinoids were found to be the most dominant animal groups, often in dense patches numbering in the thousands. At Perpendicular Head and Packer Island, a more diverse range of benthic animal species were observed. These two northern locations also had much higher abundances of filter feeding animals such as hydroids, ascidians and seapens. The analyses show that small areas of low and/or high relief hard substrate in a location provide the basis for diverse animal and plant assemblages.

In overview, there are many similarities across all locations in both the types of seabed substrate and the species encountered, but also some differences in the spatial distribution and extent of particular habitat types at each of the four locations. The sites are dominated by a small number of components; mostly bare seabed (no biohabitat), but where there is some biohabitat type present, it is most commonly bioturbated substratum, algae or sponge.

The Gourdon Bay location has a wide band of mixed filter feeding communities (sponge, gorgonian and whip gardens) offshore, an extensive patch of bioturbated seabed in the middle of the survey location and some seagrass close inshore at a few sites. The Quondong – Coulomb Point location, which has the most biohabitat, consists of algal habitat inshore and to the north, bioturbated seabed offshore and in the south and an extensive patch of seagrass in the middle and north of the location.

There are some isolated gardens of mixed filter feeding communities located in a band between these algae and bioturbated areas. The Perpendicular Head and Packer Island locations are broadly similar and consist of algal communities inshore and mixed filter feeding gardens offshore, but also have large areas offshore with either no biohabitat present at all or mostly bioturbated seabed.

The diversity and biomasses of the benthic fauna is generally consistent with other tropical locations along the Western Australian coast such as Ningaloo Reef and the Dampier Archipelago. For example, the sponges collected during the survey contained examples of species that, based on gross morphology at least, are widely distributed along the Western Australian coast and were also collected by AIMS in deeper areas of Ningaloo. However the study found at least four new species and numerous new records for Australia and Western Australia.

4.3 Inter-Nodal Scientific Outcomes

Node 1 had strong and explicit links with Nodes 2, 3 and 4 both in terms of of the compatibility of the science approaches and the key scientists involved in the programs.

WAMSI Node 1 validation of hydrodynamic models against observations from research vessels and shelf moorings suggests that the BRAN product provides good qualitative representation of the Leeuwin Current and its associated eddies. This comparison gives confidence for nested ocean modelling, biophysical investigations, and ocean connectivity analysis, based on the BRAN product which was used in Nodes 2, 3 and 4. For example, the open-ocean swells have been found to be critical in transporting and retaining biological particles, especially the western rock lobster puerulus off the west coast of Australia. Since the puerulus are slightly buoyant, they are pushed by the swell (in a process called Stokes drift) towards the shore. This conclusion has been successfully developed in an associated FRDC western rock lobster recruitment project with Node 4 researchers. The multidisciplinary approaches employed in WAMSI Node 1 projects included high-resolution genetic analysis and hydrodynamic modelling of larval transport, has been extended to two applied projects involving exploited demersal fishes in Western Australia and a study of the potential connectivity as part of the establishment of a national Marine Protected Area network. The first, (WAMSI Project 4.4.2-2a in collaboration with Fisheries WA) evaluated the appropriateness of existing spatial management for the west Australian Dhufish, *Glaucosoma hebraicum*. The second, (CSIRO and Rangelands NRM funded and in collaboration with Fisheries WA), characterised the extent of dispersal in adult, juvenile, and larval spangled emperor (*Lethrinus nebulosus*). This project also evaluated the suitability of existing spatial management for this species. In addition, the hydrodynamic predictions of connectivity made for the dhufish are currently being incorporated into ELFSim models of population dynamics of this species within the West Coast Bioregion as part of WAMSI project 4.4-3. Hydrodynamic simulations have also been conducted for the baldchin groper (SPP) within the West Coast Bioregion as part of the WAMSI project 4.4.2-2b, which incorporates research by a PhD student enrolled at Murdoch University. DIVE is a visualisation tool that is available for all WAMSI projects and data sets in all Nodes, subject to the formatting requirements described above.

5. IMPLICATIONS FOR MANAGEMENT

5.1 Project 1 South West Australian Coastal Biogeochemistry

Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions

Key points

- *WAMSI Node 1 has developed hydrodynamic models at nested scales for the SW Australian continental shelf (2 - 5km resolution) down to lagoon scale (50-100m resolution) in Marmion Marine Park. These models have been shown to have close agreement with independently derived measurements such as from satellite and in water instrument data and can help in understanding the mechanisms which transport particles and nutrients through the water. The models have a wide range of applications in fisheries and marine park design and management. The models are relocatable to other parts of the WA coastline.*

- *WAMSI Node 1 research found that the open-ocean swells are critical in transporting and retaining biological particles, especially the western rock lobster puerulus off the west coast of Australia. Since the puerulus are slightly buoyant, they are pushed by the swell (in a process called Stokes drift) towards the shore. This conclusion has been successfully developed in an associated FRDC western rock lobster recruitment project with Node 4 researchers.*

- *WAMSI Node 1 has identified an important feature of the way the Leeuwin current transports particles southwards along the WA coast. Researchers found transport was not latitudinally uniform between northwest Cape and Cape Leeuwin and that different parts of the coastal shelf waters “retain” and “disperse” water and the particles it carries at different rates. Particles are* *rapidly flushed from some sections of the coastal shelf while in others they are retained longer. This information has important implications for how marine parks and fisheries are designed and managed as this requires a knowledge of how eggs and larvae of marine animals and their food will be dispersed or retained along the WA coast. The research has shown that WA's productive coastal scallop fisheries coincide with areas of high "retention" while those areas that lack scallop fisheries are in high "dispersal" areas.*

- *WAMSI Node 1 has undertaken extensive instrumentation of the Marmion Marine Park lagoon showing for the first time that water circulation and exchange is largely driven by wave forcing over reefs which fringe the lagoon. Waves pump water into the lagoon and set up currents which we found can flush the lagoon in 15 hours or less emphasising the rapid rate of exchange between coastal and shelf waters. The information has implications for how we forecast the impacts of coastal developments such as sewage treatment plants and desalination plants. The models and research instrumentation approaches used can be relocated to other parts of the WA coastline.*

Eastern Indian Ocean Scale

This project has established a model-based description of retention and dispersal patterns of biota along the coast of WA, with results that can be readily applied to larval transport, fisheries recruitment, invasive species, and other ecological studies off the coasts. The study has demonstrated the importance of ocean dynamics in shelf-water transport and retention. Off the west coast, interaction between the ocean boundary-current and coastal geometry was found to be important for the spatial heterogeneity of retention and dispersal patterns. Low-retention shelf regions tend to experience high alongshore currents, owing to the nearshore influence of the Leeuwin Current (narrow shelf), protruding coastal geography, or formation of mesoscale eddies, whereas high-retention regions were sheltered by coastal geographic features from the direct influence of the Leeuwin Current. This information is crucial for the management of marine species, particularly those that have a larval phase. Further, ocean swell has also been shown to be important for buoyant larvae, providing a mechanism for returning larvae to shore. These results have already been applied in a (FRDC-funded) extension of this project, applied to western rock lobster.

The study has shown the value, for WA coastal marine management, of a global model like BRAN, which takes into account the large-scale ocean features, such as the Indonesian Throughflow that have a significant impact, even at the shelf and costal scale on the currents and temperature, and thus on the health and distribution of biota.

Western Australian Continental Shelf Scale

Ocean models provide information on spatial and temporal variability that cannot be determined from measurements. Ocean-physics models are coupled to biogeochemical and connectivity models, to describe the advection of nutrients, phytoplankton and larvae, and thus determine the strength and distribution of productivity along the WA shelf region. ROMS, downscaled to resolutions of 2 km inshore, produces stronger and more realistic currents than the coarser (10 km) BRAN model in which it is nested. Based on the present comparisons with data, ROMS reproduces more faithfully the spatial structure and seasonal variability of the hydrodynamics, particularly of the Leeuwin Current, its eddies, and the inshore wind-driven currents. The implications of these dynamics on shelf productivity are explained in following sections. The hydrodynamic model is a tool for determining the distribution of nutrients and biota (and potentially also pollutants) over the shelf, and for examining the influence and impacts of coastal development and of climate variability and change.

Lagoon Scale (Marmion Lagoon)

The limestone reefs offshore from Perth sustain high macroalgal biomass, while the reef lagoons support temperate sea-grass beds. These systems provide critical nearshore habitat for marine fauna, and yet the source of their productivity is not fully understood, given the low nutrient levels in the water. Field measurements show that currents and dissolved nutrients vary in the lagoonal systems on horizontal scales of tens of metres. Macroalgae thrive under wave conditions on the reefs, while seagrasses require the shelter of the lagoons. As at larger scales, the distribution of nutrients and biological connectivity of reefs and lagoons is determined by the current systems.

The WAMSI Node 1 study, featuring both measurement and modelling components, demonstrated the importance of waves on the circulation over the reef and in the lagoon. The study has shown that models used both to understand nearshore nutrient and productivity distributions in, and to predict the impacts of climate change and coastal development on inshore waters need to incorporate coupling between waves and currents.

Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales

Key Points:

- *WAMSI Node 1 research has provided improved understanding of the influence of offshore/onshore exchange, long-shore transport and upper-ocean physical processes on the nutrient supply to the shelf. This has included new information about the influence of vertical mixing, Leeuwin Current transport, ocean swell, wind-driven upwelling, and cross-shelf transport by meso-scale eddies, on the biological oceanography of the region. The existence of links between these physical processes and phytoplankton production has important implications for the response of the WA ecosystem to climate change, and thus has implications for managing marine natural resources and protecting biodiversity.*

- *WAMSI Node 1 research has shown the significant role recycling of nutrients on the shelf plays to ecosystem function. A nitrogen budget for the western Australian shelf from Shark Bay to Cape Leeuwin shows that terrestrial and atmospheric inputs to the continental shelf off western WA are small (<1%) compared to preliminary estimates of nitrogen derived from Leeuwin Current advection and eddy activity (8%) and seasonal upwelling along the shelf (7%). By closure, the budget suggests that 84% of primary production is recycled on the shelf, including a large contribution from the sediment and other benthos. Thus the productivity of our coastal systems, including fisheries are dependent on protecting the health of benthic coastal environments.*

- *WAMSI Node 1 researchers found new evidence that elevated levels of nitrate in the vicinity of Marmion reefs originate from multiple locations on the seabed. Likely sources are biologically mediated nitrification of organic matter and/or the infiltration of nitrate-rich groundwater. Both possibilities have implications for management. For example, damage to reef organisms, such as sponges, involved in biological nitrification, and/or increased inland removal of groundwater could result in a drop in overall biological productivity.*

- *WAMSI Node 1 researchers have produced biogeochemical models of ranging complexity and spatial scale and include models coupled to hydrodynamics. These models are useful for helping understand the complex physical and biogeochemical interactions which define ecosystem function and these models are relocatable to other parts of WA ecosystem.*

Continental Shelf Scale

This work has provided improved understanding of the influence of offshore/onshore exchange, long-shore transport and upper-ocean physical processes on the nutrient supply to the shelf. This has included new information about the influence of vertical mixing, Leeuwin Current transport, ocean swell, wind-driven upwelling, and cross-shelf transport by meso-scale eddies, on the biological oceanography of the region. The existence of links between these physical processes and phytoplankton production has important implications for the response of the WA ecosystem to climate change. This work has emphasised the importance of surface sediments in the seasonal nitrogen balance of the mid- and inner-shelf ecosystem, highlighting the potential sensitivity of the ecosystem to future dredging operations.

The shelf-scale biogeochemical model developed, together with the hydrodynamic model, during this project represents a valuable tool for on-going investigation of the biogeochemical dynamics of the WA shelf. For example, tracer experiments are already underway to investigate the supply of deep-water nitrate to the shelf. The model shows that wind-driven upwelling of nitrate and eddy export of phytoplankton are significant processes in the supply and removal of nitrogen from the shelf. For much of the time, the presence of the Leeuwin Current at the shelf-break suppresses the upwelling. Further, large Indian Ocean swell appears to drive recycling of nutrients through the sediments. Most of the nutrients on the shelf appear to be recycled, rather than renewed from offshore (or inshore).

As noted above, all of these physical phenomena – upwelling, the Leeuwin Current and its eddies, and Indian Ocean Swell – are likely to be affected by climate change, and are affected by climate variability. There is clear interannual variability, and significant spatial structure, in the surface-water productivity across and along the shelf, as observed by satellite imagery. The model will enable climate variability in the primary production to be explained, and the impacts of climate change to be assessed. Further, although there are local sources of nutrients inshore, much of the nutrient supply to the coastal zone is likely to come from offshore. The model will be the only tool to allow a regional assessment of the offshore impacts of climate change on inshore (reef and lagoonal) productivity.

Lagoon Scale (Marmion Lagoon)

This work provides new evidence that elevated levels of nitrate in the vicinity of Marmion reefs originate from multiple locations on the seabed. Likely sources are biologically mediated nitrification of organic matter and/or the infiltration of nitrate-rich groundwater. Both possibilities have implications for management. For example, damage to reef organisms, such as sponges, involved in biological nitrification, and/or increased inland removal of groundwater could result in a drop in overall biological productivity. Conversely, since such organisms are more abundant in open-gap habitats, their contribution of nutrients may provide a negative feedback on processes such as wave disturbance, that can reduce macroalgal canopies, thereby stabilising the composition of temperate reef ecosystems.

Measurement of nutrients in the Marmion lagoon throughout the year suggested groundwater seeps of nutrient-rich water into the reef system. Modelling shows that the plume-like distribution of nutrients in the water is consistent with relatively small-area seeps. However, seeps are yet to be definitively identified in field measurements, and other influences, such as the draw-down of phytoplankton by filter-feeding sponges, may contribute to the structure of the nutrient distribution. The modelling is preliminary at this stage, but indicates that ground-water management may contribute to the health of the reef system. Meanwhile, the lagoon-scale coupled physical-biological model developed during this project is a valuable tool for future understanding of the nearshore biogeochemical dynamics at Marmion and elsewhere along the coast. The model incorporates benthic macroalgal and sea-grass production, although this has not been run seriously because of uncertainties about the lagoonal nutrient balance. There will be major challenges in the modelling, for example, in capturing the wrack cycle, and the dependence of the macroalgae on the wave environment. It will also be challenging to deliver the observations required to calibrate and validate the model. However, the model will be a critical tool for understanding, predicting and managing the impacts of both climate change and the various human activities along the coast on the rich near-shore ecosystem.

Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling

Key points:

- *WAMSI Node 1 has developed nutrient budgets which identify the source of nutrients and their pathways to benthic and primary production. The importance of benthic productivity in these budgets has been demonstrated with benthic productivity off the southwest (e.g. from kelp) being 3 times higher than previous estimates. Between 80 and 90% of primary production on the continental shelf is dependent on recycling of nitrogen on the shelf rather than new supplies from the open ocean or terrestrial runoff. This information is important in understanding the carrying capacity and productivity of coastal fisheries such as that for the western rock lobster.*

- *WAMSI Node 1 discovered a combination of important mechanisms for supply of nutrients to fuel the annual autumn phytoplankton bloom which occurs off the entire mid and southwest shelf of WA. The annual autumn strengthening of the Leeuwin current mixes nutrients from deep water off the coast and this southward flow also entrains thin layers of nutrient rich, low oxygen water – sourced from deep waters offshore to the northwest of WA – into the euphotic zone making it available to phytoplankton to bloom. These sources are augmented with wave generated nutrient resupply from the sediments on the shelf. This knowledge is important for fisheries and marine parks by enabling an understanding of how climate variability and climate change can affect the productivity of WA coastal and shelf waters.*

- *WAMSI Node 1 research has highlighted both the high biodiversity of WA flora and fauna and how little we know about our biodiversity. Even very short surveys conducted off Marmion and in the Kimberley have resulted in the discovery of previously unknown species.*

- *WAMSI Node 1 researchers working offshore of Marmion Marine Park has made the first discovery anywhere in the world of deep water sponges which possesses high levels of photosynthetic symbiotic cyanobacteria. Researchers also discovered that sponges from Marmion excrete significant amounts of nitrogen in the form of nitrate. These important findings suggest that sponges in temperate waters off WA may play a critical role in producing and recycling carbon and nitrogen. Sponges (like corals in the tropics) are long lived animals and thus may store and recycle large amounts of nutrients and maybe critical in* *helping maintain the high productivity of WA's coastal reefs and benthic fisheries such as that for western rock lobster.*

- *WAMSI Node 1 researchers discovered deepwater (50-60m) kelps beds off southwest WA but their importance remains a mystery given the difficulties carrying out research at these depths.*

Lagoon Scale (Marmion Lagoon)

Nearshore ecosystems along the coast of Western Australia support very high benthic primary productivity from macroalgae, seagrasses and microalgae, despite typically low nutrient concentrations. Our results suggest that this high production is facilitated by episodic release of nutrients from the benthos (probably due to the action of waves), and favourable light and temperature environments. In addition, our research suggests that food webs are supported by this primary production through detrital food chains rather than grazing food chains. Benthic suspension feeders likely play a key role in cycling the detritus and making the production available to higher trophic levels. The key implications for management are therefore that actions that substantially change the nutrient, light, temperature or wave climate will likely change the rates of benthic primary production, and that such changes would propagate through nearshore food webs.

Information for improved ecosystem based management was provided in the quantitative understanding that actions which substantially change the nutrient, light, temperature or wave climate will likely change the rates of benthic primary production, and that such changes would propagate through nearshore food webs.

Continental Shelf Scale (Pelagic)

Processes that introduce nutrients into the euphotic zone determine the overall productivity of ecosystems. In this research we resolved a long standing (> 40 years) question about why the west coast of Australia is productive when there is no upwelling or obvious nutrient sources (e.g. significant river runoff). This new understanding makes it possible to have a mechanistic, rather than empirical, relationship between physical forcing factors (e.g. Leeuwin Current flow) and biological responses (e.g. primary production). Future biogeochemical models will be able to include significant nutrient input from the Leeuwin Current and should be substantially better at predicting ecological responses. This will be especially valuable to future predictions of productivity along the west coast in response to forcings such as the Southern Oscillation Index and the Indian Ocean dipole.

The improved descriptions of biological oceanography on the west coast are the most comprehensive to be found anywhere around Australia. They provide the fundamental understanding to underpin pelagic ecosystem based management and improve our capacity to manage our aquatic resources in a sustainable manner. We link from physical attributes of the Leeuwin Current through to changes in phytoplankton community composition, to increases in primary production and standing stock through greater zooplankton and larval fish. The abundance of small phytoplankton cells and the fatty acid profiles of zooplankton suggest that most of the carbon cycles through the microbial pathway with heterotrophic dinoflagellates as a key species.

Early in WAMSI the proposed nutrient budget for the shelf was developed by Feng and Wild-Allen. This budget challenged pelagic scientists to investigate all the possible mechanisms that could deliver nutrients to the euphotic zone and increased our emphasis on understanding nutrient recycling and benthic-pelagic cycling on the shelf. This refocus lead to discoveries about the importance of nutrient resupply from sediments on the shelf and the important potential contribution of nitrate from benthic filter feeders and possibly groundwater, and to the discovery that the Leeuwin Current carries significant nitrate south. The source of the nitrate that is advected south in the Leeuwin Current is not known. It will be necessary to investigate this source and measure some of the dynamics of N cycling if new understanding is to be fully utilized to improve modelling and predictions of future trends.

A great deal of data was collected and analysed as part of this component of WAMSI Node 1. A great deal of this has been published and its existence in the public domain helps to assure sustained use of the data and the concepts. One publication provided extensive maps of phytoplankton distributions from 22° to 34°S. The entire physical data set is archived with CSIRO, WAMSI and IMOS and is available to the public through easy to use web based tools. The majority of the biological data is similarly archived and those components collected by CSIRO have been transferred to publically accessible data bases at CSIRO and IMOS. As documented elsewhere a number of students used the research voyages to collect data and CSIRO personnel to assist with interpretation. All pigment data has been supplied to Australian researchers working on remote sensing and also will be supplied to American and European Space agencies.

Continental Shelf Scale (benthic)

The project has made an important contribution to between understanding a key component of the south-west Australian ecosystem that has largely been ignored. Habitats in this region out to about 20m depth have been fairly well described, but the focus for this part of the study has been to describe the habitat out to 200m which is usually regarded as the continental shelf break. To emphasise the importance of this region consider that the shallow areas to 20m only account for about 15% of the seabed in the photic zone.

In particular the study has highlighted the ecological importance of the extensive region of the shelf between about 20 and 50 m where significant amounts of the total benthic primary production on the shelf occur. We have discovered significant deepwater kelp beds to about 60m and we have found that deepwater brown and red algae have high levels of photosynthetic efficiency. Kelp comprises the biggest single store (34%) of organic carbon on the shelf 90% of it in the shallow 0 – 20 m zone.

The study also highlighted the importance of sediment habitats on the shelf. In particular those in the photic zone because they provide about 30% of total primary production on the shelf and store about 25%of carbon and 46% nitrogen on the shelf. Elsewhere in this study we have shown that these sediments play a critical role in the resupply of nitrogen for pelagic primary production which still comprises 65% of all production on the shelf. In the past these habitats have largely been regarded as lifeless and unimportant, in particular they are dismissed when considering the impacts of coastal development. However this part of the study has shown their importance and our modelling reveals the importance of healthy sediment habitats to healthy ecosystems.

The study has shown the great importance of sponge, ascidian and other filter feeders to the function of the shelf ecosystem. These animals make up 50% of all animal and plant biomass deeper than 20m and are likely to play a key role in storing and recycling the products of phytoplankton photosynthesis on the shelf. We made the first record of deepwater photosynthetic sponges anywhere in the world and future research may yet show that sponges are important primary producers in mesotrophic habitats. Indeed our study highlights the importance of and lack of knowledge about mesotrophic habitats off south-western Australia. It is worth noting that these habitats provide the majority of the catches of rock lobsters in Western Australia. Improved methods of analysis of acoustic backscatter data were developed and applied enabling greater discrimination between different classes of benthic habitats from swath mapping surveys.

Lastly this study provides a significant re-assessment of the nitrogen budget for the shelf by incorporating the high levels of benthic primary production we measured in this study into our model which confirmed that about 90% of nitrogen used in primary production is recycled on the shelf and that to achieve this high levels of nutrient resupply from nitrification at the benthos are required. This again underscores the importance of the sediment microbial communities and those associated with sponges in maintaining a productive southwest Australian shelf ecosystem.

The data and models produced in this part of the study have shown the importance of benthic habitats on the continental shelf and in particular shown that the importance of the very spatially extensive and deeper benthic habitats has been underestimated. Similarly the importance of soft sediment habitats has been underestimated in the past. As such the results have important implications for ecosystem based management of fisheries resources and implications for ecosystem and primary producer habitat protection, with habitats previously regarded as being of low environmental importance now evidently warranting greater protection. It is also clear that our study has demonstrated the need for more extensive studies on the processes which are important in structuring these deepwater habitats and the role they play in primary production and nutrient recycling and resupply, In particular we suggest that the deep water kelp communities warrant study they can tell us about kelp resilience and how to protect kelp resources in shallower eaters in the face of climate change, the role of sponges as nitrifiers and the extent of autotrophy and improved quantification of the contribution of soft sediment habitats to primary production and nutrient resupply functions in southwest Australian ecosystems. Lastly, this study has only looked at a very small section of the western Australian shelf and many of the conclusions are underpinned by assumptions and make use of literature values that should be tested and warrant verifying by targeted investigations. Thus much new work is warranted to quantify the importance of mesotrophic habitats to southwest Australian ecosystems.

Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment

Key points:

- *WAMSI Node 1 has identified a range of indictors of ecosystem health based on an assessment of the ecology and biogeochemistry of soft sediment habitats across a gradient of human impact. These indicators can be used to monitor and predict the impacts of coastal developments based on a given range of nutrient input and wave/swell exposure regimes.*

The motive for the research contained within this part of the study was to develop a conceptual understanding of ecosystem responses to forcing factors (primarily sediment nutrient load) with the ultimate aim of improving our capacity of scientists and managers to predict the impacts of sediment nutrient enrichment. The wide range of parameters measured in this study across a gradient of nutrient enrichment together with studies of the biogeochemical processes have provided an insight in the function of these habitats and their response to nutrient enrichment. A number of simple regression models are used to describe these responses and a conceptual model of transition states for soft sediment habitats subject to nutrient enrichment is provided as an aid to monitoring and managing impacts to these habitats. This project has also demonstrated the utility of measuring variations in the physiology of the organisms (i.e. the photosynthetic performance of microphytobenthos). A change in photosynthetic performance will be reflected in the shape of the production versus irradiance relationship and factors such as Pmax, alpha and Ik may prove useful for management agencies looking for indications of photosynthetic stress resulting from coastal development or climate change.

We have applied novel molecular probes that target nitrifying and denitrifying genes across a range of microbial taxa. These probes are a cost effective tool for identifying the presence and biomass of particular organisms responsible for some of the most important microbial nutrient modification processes. These molecular probes are a powerful new tool for understanding the biological pathways of N cycling in the sediment and we anticipate their ongoing refinement and use will continue to give new insights into N cycling in the Western Australian marine environment. In addition we applied molecular probes for polychaete indicators of sediment nutrient enrichment which show promise of delivering rapid assessment of sediment health and anthropogenic enrichment.

A conceptual model of soft sediment habitat condition or state is proposed based on the large range of physical, biogeochemical and ecological parameters we measured. It suggests that biogeochemical and ecological attributes of sediments can reveal the degree of alteration of sediments between a base state of “typical” or “healthy” sediment habitats and the degraded condition state. Some aspects of the model are simplistic and require qualification but it does present a practical approach to assessing habitats, designing and carrying out monitoring and for predicting the trajectory of sediment habitats where there is concern about the potential for anthropogenic enrichment. The simple relationships derived for production versus irradiance (P versus I) have potential beyond the direct results of this project. These relationships form a baseline of photosynthetic performance for comparison with other regions and if repeated over time could reveal a response to changing climate.

5.2 Project 2 Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules

An assessment of the importance of physical forcing and ecological interactions among key functional groups in determining patterns of spatial mosaics in benthic habitats

Key points:

- *WAMSI Node 1 researchers have overcome an important obstacle to understanding the timeline of some important ecological features of WA’s productive coastal reefs by determining how kelp canopy patches and kelp free patches are maintained and replaced after storms. Understanding the longevity of transient features of the marine habitat like kelp beds is critical for the design and management of marine parks. WAMSI researchers found that most bare patches free of kelp canopy last an average of 6-10 years before the kelp canopy recovers. Thus we need to take into account that any climate change induced change in the strength or patterns of storms which tear up kelp beds will impact the resilience of kelp beds. which we know are the most productive parts of the southwest WA marine ecosystem and the highest store of carbon in living organisms in coastal waters.*

We characterised the proportion and size of canopy and open-gap states at multiple sites along a gradient in wave exposure, and found open-gap patch lengths were positively correlated with modelled seabed water velocities. We also found open-gap patches are naturally persistent features, which likely become even more long-lived in the face of severe disturbance. Given the potential for increasing levels of disturbance from urbanization, climatic factors such as increasing sea temperatures and changing wave intensity regimes, it may be predicted that the relative balance of habitat types on southwest Australian temperate reef ecosystems will change in the future. While this may not necessarily have dire immediate consequences for biodiversity, there may be negative implications for secondary production on temperate reefs, where food webs appear to be disproportionately reliant on brown algae as a food source. The ability of open-gap habitat to occupy space indicates that such changes may be very difficult to reverse, and that we should ensure that we make efforts to manage any processes that may exacerbate the transitions from kelp canopy to open-gap habitats. The relationships between a key environmental parameter, wave intensity, and the dynamics of kelp forest habitat mosaics can now be modelled in ways that, when combined with appropriate climate models, will enable us order to provide general predictions of changes to the productivity, and biodiversity of coastal reefs in south western Australia.

An assessment of ecosystem processes with particular relevance to contrasting fished and non-fished areas

Key points:

- *WAMSI Node 1 research has shown that, in the southwest (Marmion, Jurien, Rottnest), the effectiveness of marine sanctuaries is dependent on both the time the sanctuaries have been in place and their size. The research showed that small sanctuaries are ineffective at protecting biodiversity and that even large sanctuaries must be in place for many years before they have a positive impact.*

Probably the most compelling result from this study is that, where SZs are established with the aim of increasing the biomass and/or density of species targeted by fishers, larger reserves will be most likely to achieve this aim. It also showed that these patterns were strongest for the two most heavily fished groups of species. Although we found some evidence that small reserves did show responses for some metrics, the difference was smaller than that yielded by large reserves, and was present for fewer metrics. One inference from this is that, while small reserves might achieve aims of increasing biomass or density, they are less likely to do so, or will lead to smaller increases seen in fewer species. The results of the SZ comparisons will be important for marine conservation planning in Western Australia. No new tools *per se* have been developed, because conclusions about the benefits of SZs of different sizes are necessarily qualitative - that is, that larger SZs are more effective than smaller SZs. This information is being provided to DEC and to the MPRA, as the two main bodies responsible for marine conservation management in Western Australia. We envisage that the information will be used to support decisions when planning new marine parks, or when assessing the management plans in place for existing marine parks. The findings are particularly relevant for the revision of the Marmion Marine Park Management Plan currently being undertaken by the MPRA.

An assessment of likely dispersal patterns for marine organisms based on hydrodynamic and population genetic models

Key points:

- *WAMSI Node 1 researchers showed by combining two sophisticated technologies; hydrodynamic modelling and molecular ecology, that population connectivity exists over very large spatial scales indicating west and south coast parts of some species ranges can be linked genetically by Leeuwin Current-mediated larval dispersal. In widely dispersing species, the south west coast of WA potentially spans a single evolutionarily significant unit. This has implications for how spatial management units such as those used in zoning marine parks are designed and for how species may change their distribution in response to climate change induced modifications to marine environments and oceanography.*

The main implication for management is that population connectivity has been shown to exist over very large spatial scales indicating west and south coast parts of some species ranges can be linked genetically by Leeuwin Current-mediated larval dispersal. In widely dispersing species, the south west coast of WA potentially spans a single evolutionarily significant unit. This has implications for how spatial management units such as those used in zoning marine parks are designed and for how species may change their distribution in response to climate change induced modifications to marine environments and oceanography.

This work demonstrates the value of combining two sophisticated technologies, hydrodynamic modelling and molecular ecology to elucidate the cryptic but important spatial dimension in marine ecology of which dispersal is a central determinant. Understanding the spatial extent of populations and species is crucial to spatial ecosystem management and our project has yielded information on an important benthic invertebrate but also demonstrated the potential to apply the same approach in other marine taxa reliant upon passive dispersal under the influence of oceanographic processes.

Electronic delivery of data and models to management agencies, building on the development of the Data Interrogation and Visualisation Environment (DIVE) in SRFME

Key points:

- *DIVE is a data access and visualisation package that has been developed through CSIRO's partnership with the WA Government. DIVE enables scientists and managers to view the diverse data sets that have been generated in WAMSI. The data are multidisciplinary and multidimensional, and range from relatively small numbers of field samples through to 4d model output occupying gigabytes of computer storage. DIVE can be installed onto all platforms supporting Java. It is functional on Windows, Linux and Mac OSX computers. DIVE supports the display of spatial maps, time-series plots, vertical profiles and cross-*

section plots. The spatial data are represented as coloured maps, contoured plots, vector maps or as habitat maps.

DIVE has advanced considerably over the WAMSI project. It is a versatile, intuitive data access and visualisation tool, developed to assist both researchers and managers in their interpretation of field data and model output. The intention of DIVE was that it be a tool to enable environmental managers to access, look at, and compare the diverse range of data sets collected across WAMSI. It can access data across the web, and should be particularly suitable for interrogating the WAMSI central database. This gives managers access to the actual data, so that they do not have to rely on the subsets and interpretation provided in research reports. DIVE handles data in up to 4 dimensions, from across the marine disciplines.

Unlike physical oceanographic data, there is no standard format for biological data. Further, oceanographic data are stored in 'self-describing format', that allows a data-access program to interpret the content without user intervention. We have established an ascii column-file format to enable data to be read by DIVE. However, in reality, the tool is presently most suited to physical, and some biological, oceanographic data, and to model output. While DIVE has now been set up to interrogate MEST servers, neither WAMSI nor the national servers have yet been established with databases that allow the actual data sets to be accessed. This means that this DIVE capability has cannot, to date, be fully tested. At the start of WAMSI, the adoption of MEST standards by national data agencies had not been anticipated. The ability to connect to MEST servers is a response to the establishment of the Australian Oceanographic Data Network (AODN) and the Integrated Marine Observing System (IMOS).

5.3 Project 3. Benthic habitat surveys of potential LNG hub locations in the Kimberley region

Key points:

- *WAMSI Node 1 undertook surveys in the Kimberley in the vicinity of Gourdon Bay, Quondong – Coulomb Point, Perpendicular Head and Packer Island. The data, providing improved knowledge on biodiversity, habitat complexity and bathymetry were used as part of the WA government's strategic assessment of the region and formed part of the basis on which James Price Point was chosen as the location for the LNG industrial precinct. At the time of the surveys, the marine benthic communities at these prospective sites were largely undescribed. The surveys resulted in the discovery of at least 4 new species and numerous new records for Australia and Western Australia.*

At the time of the surveys, a number of sites in the Kimberley region were being considered for their suitability as a location for a proposed common-user liquefied natural gas hub precinct. The marine benthic communities at these prospective sites were previously largely undescribed. The four locations surveyed were in the vicinity of Gourdon Bay, Quondong – Coulomb Point, Perpendicular Head and Packer Island. The data, providing improved knowledge on biodiversity, habitat complexity and bathymetry were used as part of the WA government's strategic assessment of the region and formed part of the basis on which James Price Point was chosen as the location for the LNG industrial precinct.

6. CAPACITY BUILDING

The following is a list of the WAMSI Node 1 PhD and Honours students and their projects. Abstracts of their work can be found in the Node 1 Project 1 and 2 Overview Reports referred to in Annexure 3.

Adam Gartner (ECU) was awarded a WAMSI PhD top up scholarship and completed his PhD in 2010. Adam is now an associate at Oceanica. His project was entitled: Trophic implications of light reductions for *Amphibolis griffithii* seagrass fauna which is linked to the project 1. Adam was supervised By Professor Paul Lavery (ECU).

Cecile Rousseaux (UWA) was awarded a WAMSI PhD top up scholarship and completed her PhD in 2010. Her project was entitled: Oceanographic forcing of phytoplankton dynamics in the waters off north Western Australia which is linked to the project 1. Cecile was supervised By Professor Anya Waite (UWA) and Dr Peter Thompson (CSIRO).

Eloise Brown (UWA) was awarded a Wealth from Oceans PhD top up scholarship. She is undertaking a project titled "Hydrodynamics of submerged *Ecklonia radiata* kelp canopy in a subtidal reef ecosystem" and is linked to the project 1and 2, to examine the linkages between the hydrodynamic and biological environments. Eloise is supervised by Professor Carolyn Oldham (UWA), Dr Graham Symonds (CSIRO) and Associate Professor Euan Harvey (UWA).

Sharon Yeo (Murdoch) was awarded a WAMSI PhD top up scholarship. She is undertaking a project entitled Population Biology of the sand dollar, *Peronella lesueuri*, Cockburn Sound which is linked to the project 1. Sharon is supervised by Dr Mike Van Keulen (Murdoch) and Dr John Keesing (CSIRO),

Thisara Wilhena (UWA) was awarded a WAMSI PhD top up scholarship. He is undertaking a project entitled: Dense water formation and cross-shelf exchange on the Rottnest Continental Shelf in south-western Australia, which is linked to the project 1. Thisara is supervised by Professor Chari Pattiaratchi (UWA) and Dr Ming Feng (CSIRO)

Thibaut de Bettignies (ECU) was awarded a WAMSI PhD top up scholarship. He is undertaking a project entitled: Spatial subsidies provided by organic matter export from kelp forests: importance of storm-driven pulses versus chronic export which is linked to the project 1. Thibaut is supervised By Professor Paul Lavery (ECU), Dr Thomas Wernberg (UWA) and Dr Mat Vanderklift (CSIRO).

Charulata Singh (ECU) was awarded a WAMSI PhD top up scholarship. He is undertaking a project entitled: Assessing the trophic subsidy provided by kelp wrack in seagrass ecosystems, which is linked to the project 1. Charulata is supervised by Professor Paul Lavery, Assoc. Prof Glenn Hyndes and Dr Mat Vanderklift. At this stage, Ms Singh has taken leave from the project for medical reasons and her research will recommence in 2012.

Natalie Millar (Murdoch) was awarded a WAMSI Honours scholarship to undertake a project entitled Larval Fish Assemblages in the Leeuwin current system, Western Australia which is linked to the project 1. Natalie was supervised by Professor Lynnath E. Beckley from Murdoch University. Natalie successfully completed her thesis in 2009.

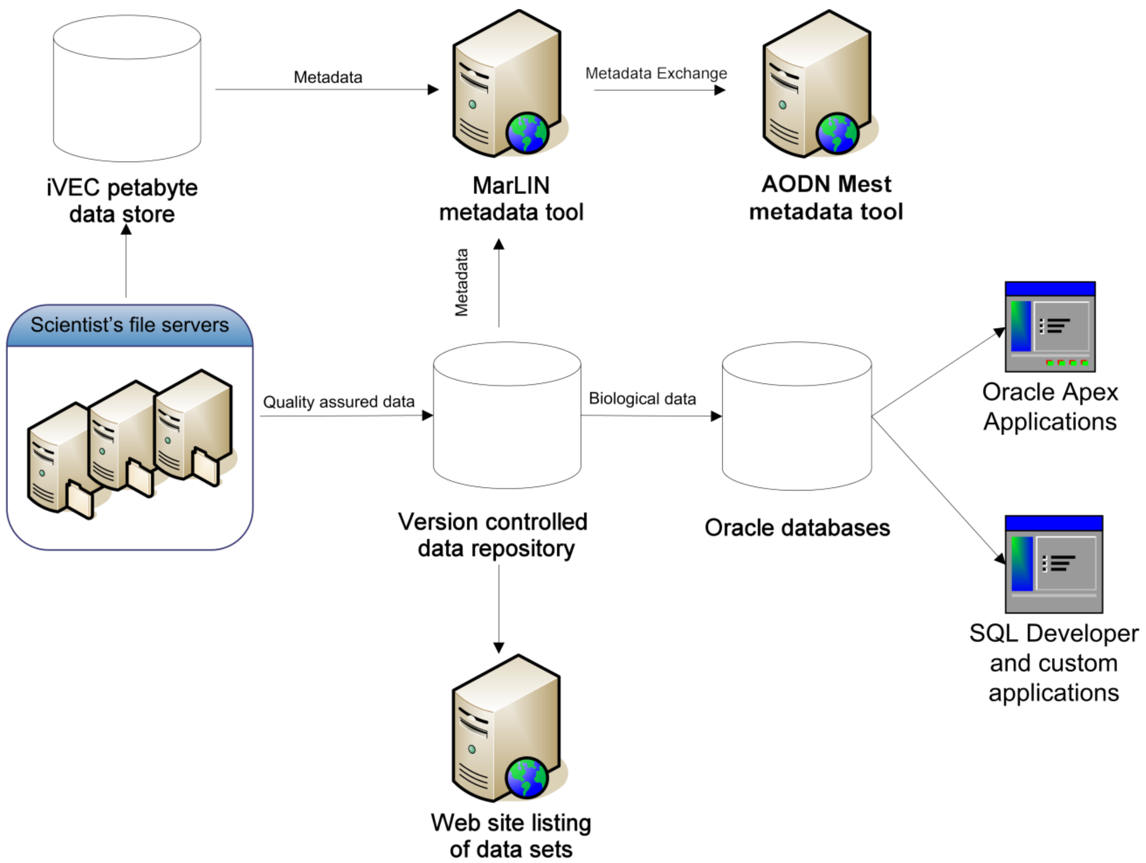
David Rivers (UWA) was awarded a WAMSI PhD top up scholarship. He is undertaking a project entitled: The role of seeding recruitment in maintaining seagrass diversity, which is linked to the project 2. David was supervised by Professor Di Walker (UWA) and Dr John Keesing (CSIRO).

7. DATA MANAGEMENT

The WAMSI program has generated data from a wide range of sources, disciplines and organisations that has resulted in the assembly of a multitude of data formats and data types.

To manage these datasets, a version controlled data repository was established that served as a central data distribution point and is supported by a repository website (http://www.marine.csiro.au/datacentre/SRFMEandWAMSI/) and a publicly accessible metadata tool called MarLIN (http://www.marine.csiro.au/marlin). MarLIN is linked to both the Australian Spatial Data Directory and the Australian Ocean Data Network (AODN). Both these external metadata search services provide international online access to WAMSI metadata records.

Metadata records are published in the public domain, while access to datasets in the data repository is provided via the data repository website.



WAMSI Data Repository architecture

The data repository is mounted on a CSIRO computer with appropriate file restrictions to limit access to CSIRO WAMSI participants only. The repository consists of a directory structure that mirrors the major project components of the WAMSI program. To maintain the integrity of data, only data that has been quality assured by scientific staff is included in the repository. Quality standards are maintained by, and are the responsibility of individual projects. To maintain the currency of data exposed via the WAMSI data repository website, the data repository was placed under an "Apache Subversion" (SVN) version control system. SVN was chosen because of its simplicity and ability to support the needs of a wide variety of users and projects. Most biological data was provided in the form of Microsoft Excel® spreadsheets, the format of which reflected a wide range of datasets, experiments and data manipulation processes. These spreadsheets have been placed directly into the data repository. Quality assured raw data was also entered into an Oracle database so that common attributes such as temporal and spatial information could be merged for different datasets, such as algae, invertebrate, fish species, coral, habitat and substrate datasets. A variety of tools were then used by scientists to further process data. At the time of writing, the data base contained 39,160 biological data items in 1,018 data sets and 11,973 transect images. Where large data sets of terabyte size would have placed an excessive burden on the data repository and its associated infrastructure, this data was placed in the iVEC petabyte data store.

8. MODELING

This project has explored the use of models as tools for environmental understanding and prediction. At the full scale of the continental shelf, the project investigated larval advection along the shelf using the BLUElink reanalysis BRAN. Larval retention rates and early stage larval dispersal by ocean currents are pivotal to population dynamics, genetic structure, and biogeography of many coastal species, especially in the very dynamical and variable marine environment off the west coast of WA. There is observational evidence that fish larvae are transported by the Leeuwin Current and its eddies in and out of their hatching ground and inshore habitats. In this project, we have identified close association between the shelf retention rate and scallop fisheries off the west coast, demonstrating the strong oceanographic influence on fisheries recruitment. Further, we have shown that persistent southwestern swell from the Indian Ocean helps to move buoyant organisms, such as rock lobster puerulus, back towards the shore. In addition, in WAMSI Node 1 Project 2, oceanographers and geneticists worked together using the BRAN product and particle tracking to strengthen understanding of the connectivity of benthic communities off the coast of WA.

BRAN is a multi-year archive of global model results with 10 km resolution, improved by data assimilation. While it demonstrates the features of the circulation off the west coast, it is too coarse to fully represent the fine detail of the Leeuwin Current and its eddies. The second tool used in these studies is a finer-resolution model nested inside BRAN. This is an implementation of the ROMS model, with resolution down to 2 km inshore. At this higher resolution, the modelled currents are considerably more energetic. The model was developed specifically to drive a further model of primary productivity (biogeochemistry) over the shelf. Its primary role in management comes through this application, which is described in the following section.

The third tool is a very high (30 m) resolution model of the Marmion lagoon. In this case, the model is Delft University's XBeach, which predicts both waves and currents, and the coupling between them. The modelling and the accompanying field work demonstrate that, when waves (swell) are high enough to break over the reef, this drives the currents inside the lagoon, with outflow to the north and south, and through gaps in the reef. The productivity of the lagoonal system is very dependent on the wave and current dynamics. While waves appear to enhance access of reef macroalgae to nutrients, seagrasses thrive in the protection of the lagoon. Winter storms break off plant material that becomes wrack, and apparently leads to the recycling of nutrients. There is evidence (see below) that groundwater also introduces nutrients into the lagoonal system. The currents are responsible for distributing nutrients that are resupplied from nitrification in sediments, as well as propagules, through, and beyond the system.

At each of the three scales, eastern Indian Ocean, shelf and lagoon, the models show the importance of physical dynamics to the health and distribution of biological systems. At all scales, the exposed coastal waters of Western Australia show clear responses to climate variability, on time scales of years, and climate change on scales of decades. The physical manifestations of climate change may include changes in: the frequency and intensity of the El Nino-Southern Oscillation (ENSO) cycle; the frequency and intensity of both local storms and distant storms that generate swell; the currents associated with the Leeuwin Current; water temperature; and sea-surface height. Further, coastal waters are affected by coastal population growth and development. Coastal development can change both the physical nature (e.g. through construction) and chemical composition (e.g. through the release of nutrients) of the water. Models provide a mechanism for managing all of these phenomena. They allow cause and effect relationships to be evaluated (e.g. in separating natural and anthropogenic effects), time scales to be separated (e.g. between climate change and variability), and future scenarios to be simulated. Further, through coupling to biological models, they allow quantitative investigation of ecosystem responses to the physical forcing.

9. SOCIETAL BENEFITS

This topic is already sufficiently dealt with under section 5. In addition a series of “Key findings” dot points listed under headings of each of the principal WAMSI outcome areas of Ocean Systems Forecasting, Biodiversity Conservation and Natural Resource Management is provided at the start of section 4.

10. FUTURE RESEARCH

While WAMSI Node 1 has made much progress on understanding the key processes structuring pattern and function on the south west Australian marine ecosystem much remains to be done and it would be unfortunate if the future focus for WAMSI did not include some work on the south-west and mid-west coasts where population pressure remains greatest.

As an example WAMSI Node 1 researchers have made key findings about why the region has such productive benthic habitats (tight nutrient cycling and benthic pelagic coupling) and the importance of different types of primary producers on shelf scale primary production. However, the different sources of nitrate on the shelf and the relative importance of each different contribution remain unresolved. For example we determined that wave generated nutrient resupply from nitrifying processes in sediments and filter feeders are likely to be important. However we also found that ground water maybe an important source of nitrate input into the system and this has important implications for both ground water supplies and nutrient budgets.

The discovery of deepwater kelp beds (50-60 m) and autotrophic deepwater sponges as part of the WAMSI Node 1 research as well as our quantification of filter feeder biomass at these depths raises many questions about the importance of these mesotrophic habitats and their assemblages to productivity on the shelf including to deepwater benthic fisheries such as that for rock lobster. Our limited work in this area revealed unknown species within a few km of Perth’s busiest boat ramp showing how little we still know about the biodiversity of the region

In addition some research requires longer time frames. As the dynamics of algal patch dynamics appear to play out over timescales longer than the life of WAMSI projects it was not possible to follow clearances for as long as would be desirable, however we will seek other opportunities to pursue this work. Nevertheless the approach has proved useful as a means of parameterising habitat models. Such models promise to provide a useful predictive tool, particularly when combined with environmental models of variability and change in temperature and wave climate associated with climate change and variability. Currently, downscaled models of this kind for marine environments do not occur for the southern west coast of Australia. A valuable complimentary approach to the study of habitats we have recently completed would be to construct similar models of coral and sponge populations which would provide an independent means of evaluating the time scales of patch persistence, as well as having obvious importance for understanding and predicting the response of sessile invertebrates such as corals to changing marine climates.

11. PUBLICATIONS

This is the list of the 53 publications and reports and 101 presentations arising from the projects undertaken as part of WAMSI Node 1, Western Australian Marine Ecosystems Research. Most of the publications have arisen directly from the three WAMSI Node 1 projects, however a few of those included have arisen indirectly as part of other studies, reviews or commissioned reports undertaken by WAMSI scientists that have drawn on data collected from WAMSI Node 1 projects. It is envisaged that this list will grow significantly over the next two years as more of the research is published and presented at conferences.

11.1 List of journal publications

Babcock, R.C., N.T. Shears, A.C. Alcala, N.S. Barrett, G.J. Edgar, K.D. Lafferty, T.R. McClanahan and G.R. Russ (2010). Decadal Trends in Marine Reserves: differential rates of change for direct and indirect effects. *Proceedings of the National Academy of Science of the United States of America*, 107 (43)**:** 18256–18261**,** doi:10.1073/pnas.0908012107.

Beger, M., R. Babcock, D. J. Booth, D. Bucher, S.A. Condie, B. Creese, C. Cvitanovic, S.J. Dalton, P. Harrison, A. Hoey, A. Jordan, J. Loder, H. Malcolm, S.W. Purcell, C.M. Roelfsema, P. Sachs, S.D.A. Smith, B. Sommer, R. Stuart-Smith, D. Thomson, C.C. Wallace, M. Zann and J.M. Pandolfi (2011). Research challenges to improve the management and conservation of subtropical reefs to tackle climate change threats. *Ecological Management and Restoration* Vol. 12: 7-10.

Caputi, N., R. Melville-Smith, S. de Lestang A. Pearce and M. Feng (2010). The effect of climate change on the western rock lobster (*Panulirus cygnus*) fishery of Western Australia. *Canadian Journal of Fisheries & Aquatic Sciences* 67:85-96.

Caputi, N., S. de Lestang, M. Feng and A.F. Pearce (2009). Seasonal variation in the long-term warming trend in water temperature off the Western Australian coast. *Marine and Freshwater Research* 60: 129-139.

Cook, K. and M.A. Vanderklift (2011). Depletion of predatory fish by fishing in a temperate reef ecosystem leads to indirect effects on prey, but not to lower trophic levels. *Marine Ecology Progress Series* 432: 195-205.

Craig, P.D. (2010). Imposed and inherent scales in cellular automata models of habitat. *Ecological Modelling* 221: 2425-2434. doi:10.1016/j.ecolmodel.2010.07.011.

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Fearns, P.R.C., W. Klonowski, R.C. Babcock, P. England and J. Phillips (2011). Shallow water substrate mapping using hyperspectral remote sensing. *Continental Shelf Research* doi:10.1016/j.csr.2011.04.005.

Feng, M. D. Slawinski, L. Beckley and J.K. Keesing (2010) Retention and dispersal of shelf waters influenced by interactions of ocean boundary current and coastal geography. *Marine and Freshwater Research* 61: 1259–1267.

Feng, M. and K. Wild-Allen (2010). The Leeuwin Current. P197-210. In: K-K. Liu, L. Atkinson, R. Quinones and L. Talaue-McManus (Eds.) *Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis*. IGBP Book Series. Springer, Berlin. 744 pp.

Feng, M. (2009). Eddy induced cross-shelf phytoplankton transport along the downwelling coast off Western Australia. *Journal of Tropical Oceanography* 28(5): 6-10.

Feng, M., A.M. Waite and P.A. Thompson (2009). Climate variability and ocean production in the Leeuwin Current system off the west coast of Western Australia. *Journal of the Royal Society of Western Australia* 92: 67-81.

Feng, M., A. Biastoch, C. Böning, N. Caputi and G. Meyers (2008). Seasonal and interannual variations of upper ocean heat balance off the west coast of Australia. *J. Geophys. Res.* 113: C12025, doi:10.1029/2008JC004908.

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Gartner, A., P. S. Lavery, K. McMahon, A. Brearley and H. Barwick (2010). Light reductions drive macroinvertebrate changes in *Amphibolis griffithii* seagrass habitat. *Marine Ecology Progress Series* Vol. 401: 87–100.

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Greenwood, J. (2009). Shallow water dissolution of settling calcite at station ALOHA. *Limnology and Oceanography*, 54 (5), 1420-1424.

Greenwood, J. and K. Soetaert (2008). Interannual variability in the seasonal cycle of chlorophyll in the Leeuwin Current off the southwest Western Australian coast. *Journal of Marine Research* 66(3): 373-390.

Hanson, C.E., M.J. McLaughlin, G.A. Hyndes and J. Strzelecki (2009). Selective uptake of prokaryotic picoplankton by a marine sponge (*Callyspongia* sp.) within an oligotrophic coastal system. *Estuarine, Coastal and Shelf Science* 84: 289-297.

Hassler, C.S., J.R. Djajadikarta, M.A. Doblin, J.D. Everett and P.A. Thompson (2011). Characterisation of water masses and phytoplankton nutrient limitation in the East Australian Current separation zone during spring 2008. *Deep-Sea Research II* 58: 664-677.

Irvine, T., J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams (2008). West-Central Australian Shelf LME. In: K. Sherman and G. Hempel (Eds.) *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the* *world's Regional Seas*. UNEP Regional Seas Report and Studies No. 182. United Nations Environment Programme. Nairobi, Kenya. p 321-336.

Irvine, T., J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams (2008). Southwest Australian Shelf LME. In: K. Sherman and G. Hempel (Eds.) *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies No. 182. United Nations Environment Programme. Nairobi, Kenya. p 839-852.

Keesing J.K. and T.R. Irvine (in press). Aspects of the biology of an abundant spatangoid urchin, *Breynia desori* in the Kimberley region of north-western Australia. *Echinoderms in a Changing World (Proceedings of the 13th International Echinoderm Conference, Australia, 5-9 January 2009*) Balkema Press

Keesing, J.K., Irvine, T.R., Alderslade, P., Clapin G., Fromont, J., Hosie, A., Huisman, J., Phillips, J., Naughton, K.M., Marsh, L.M., Slack-Smith, S. Thomson, D. and Watson, J. (2011). Marine benthic flora and fauna of Gourdon Bay and the Dampier Peninsula in the Kimberley region of north-western Australia. *Journal of the Royal Society of Western Australia 94:* 285-301 *(Kimberley Special issue).*

Keesing, J.K, Graham F., Irvine, T. and Crossing, R. (2011) Synchronous aggregated pseudocopulation of the sea star *Archaster angulatus* Muller and Troschel, 1842 (Echinodermata: Asteroidea) and its reproductive cycle in south-western Australia. *Marine Biology* 158: 1163-1173.

Kleczkowski, M., R.C. Babcock and G. Clapin (2008). Density and size of reef fishes in and around a temperate marine reserve. Marine and Freshwater Research. 59:165-176.

Lawrence, J.M., J.K. Keesing and T.R. Irvine (in press). Population characteristics and biology of two populations of *Archaster angulatus* (Echinodermata: Asteroidea) in different habitats off the central-western Australian coast. *Journal of the Marine Biological Association UK* Doi:10.1017/s0025315410000871.

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Limbourn, A.J., R.C. Babcock, D.J. Johnston, P.D. Nichols and B. Knott (2009). Spatial and temporal variation in lipid and fatty acid profiles of western rock lobster pueruli at first settlement: Biochemical indicators of diet and nutritional status. *Marine and Freshwater Research*. 60:810-823.

Lourey M.J. and H. Kirkman (2009). Short lived dissolved nitrate pulses in a shallow Western Australian coastal lagoon. *Marine and Freshwater Research* 60: 1068-1080.

Lozano-Montes, H.M., N.R. Loneragan, R.C. Babcock and K. Jackson (2011). Using trophic flows and ecosystem structure to model the effects of fishing in the Jurien Bay Marine Park, temperate Western Australia *Marine and Freshwater Research*. 62:1-11.

Paterson, H. L., M. Feng, A.M. Waite, D. Gomis, L.E. Beckley, D. Holliday and P.A. Thompson (2008). Physical and chemical signatures of a developing anti-cyclonic eddy in the Leeuwin Current, Eastern Indian Ocean. *Journal of Geophysical Research* 113: C07049.

Pattiaratchi, C., B. Hollings, M. Woo and T. Welhena (2011). Dense shelf water formation along the south‐west Australian inner shelf. *Geophysical Research Letters* 38, L10609, doi:10.1029/2011GL046816.

Rivers, D.O., G.A.Kendrick and D.I. Walker (2011). Microsites play an important role for seedling survival in the seagrass *Amphibolis antarctica. Journal of Experimental Marine Biology and Ecology* 401: 29-35.

Rousseaux, C., P. Thompson, J. Greenwood, and J.-P. Descy (submitted). Diel vertical migration of dinoflagellates as a mechanism to decrease the impact of microzooplankton grazing. *Marine and Ecology Progress Series*.

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Thompson, P.A., P. Bonham, A.M. Waite, L.A. Clementson, N. Cherukuru, C. Hassler and M.A. Doblin (2011). Contrasting oceanographic conditions and phytoplankton communities on the east and west coasts of Australia. *Deep-Sea Research II* 58: 645–663.

Thompson, P.A., I. Jameson and S.I. Blackburn (2009). The influence of light quality on akinete formation and germination in the toxic cyanobacterium Anabaena circinalis. *Harmful Algae* 8: 504–512.

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Thomson, D. (2010). Range extension of the hard coral *Goniopora norfolkensis* (Veron & Pichon 1982) to the south-east Indian ocean. Journal of the Royal Society of Western Australia 93:115-117.

Thomson, D.P. and A.J. Frisch (2010). Extraordinarily high coral cover on a nearshore, high-latitude reef in south-west Australia. Coral Reefs 29:923-927.

Vanderklift M.A. and T. Wernberg (2010). Stable isotopes reveal a consistent consumer-diet relationship across hundreds of kilometres. *Marine Ecology Progress Series* 403: 53-61.

Vanderklift, M.A., P.S. Lavery and K.I. Waddington (2009). Intensity of herbivory on kelp by fish and sea urchins varies between inshore and offshore reefs. *Marine Ecology Progress Series.* 376: 203-211.

11.2 List of published and unpublished reports

Fry, G., A. Heyward, T. Wassenberg, N. Ellis, T. Taranto, J. Keesing, T. Irvine, T. Stieglitz and J. Colquhoun (2008). *Benthic habitat surveys of potential LNG hub locations in the Kimberley region.* Client Report to WAMSI. 131 pp.

Graham, F., M. Vanderklift (2010). Indicators of resource condition for selected WA coastal benthic systems. WAMSI Node1 Project 2 Milestone 2.2.3. 28 pp.

Irvine T.R and J.K. Keesing (2009). Identification of epi-benthic sled samples from the Dampier Peninsula and Gourdon Bay, Kimberley region, Western Australia. *Client Report to Woodside Energy Ltd*. CSIRO Marine and Atmospheric Research, Perth. 55 pp.

Irvine, T., F. Parker, J. Strzelecki, M. Vanderklift, J. Keesing, D. Bearham, D. Thomson and R. Downie (2009). *Shelf and Lagoon Biomass and Ecological Sampling Data Report* (WAMSI Node 1 Project 1: Southwest Australian Coastal Biogeochemistry) CSIRO, Australia. 63 pp.

Parker, F., M. Vanderklift and D. Slawinski (2009). *Predator Gradients in Relation to Spatial Management Regimes and Size of Management Units Data Report*. WAMSI Node1 Project 2 Milestone 2.2.2. 36 pp.

Parker, F. and M. Vanderklift (2009). Variation in Ecological Processes in Relation to Spatial Predator Gradients. *WAMSI Node1 Project 2 Milestone* 2.2.2. 20 pp.

Symonds, G. and N. Mortimer (2009). *Marmion lagoon Measurement Program, July 2007 to May 2008*. WAMSI Node 1 Project 1, Southwest Australian Coastal Biogeochemistry, CSIRO Marine and Atmospheric Research Paper 27, 58pp.

Woodley, S., N. Loneragan and R. Babcock. (2010). Report on the Scientific Basis for and the Role of Marine Sanctuaries in Marine Planning. *Report to the Western Australia Department of Environment and Conservation*. 97 pp. Perth Western Australia.

11.3 List of presentations

Babcock, R.C. (2010). Stable habitat mosaics in temperate reef ecosystems; kelp patch dynamics in southern Australia. *WAMSI Node 1: 2nd symposium.* Perth, Australia, July 29, 2010.

Babcock, R.C. (2009). Climate change effects on kelp forest ecosystems. A changing climate: Western Australia in focus. *WAMSI Node 2 Climate change Symposium.* Perth, Australia., March 27, 2009.

Babcock, R.C. (2009). Climate change effects on kelp forest ecosystems. *WAMSI Node 1: 2nd symposium*. Perth, Australia, July 30, 2009.

Babcock, R.C. (2007). Overview of the Jurien shallow water ecology projects. *Western Rock Lobster Ecological Effects of Fishing workshop*, Perth, Australia, August 8-10, 2007.

Babcock, R.C. (2007). Shifting Baselines: the role of marine reserves in a rapidly changing world. *Parks and Protected Areas Forum.* Fremantle, Australia, September 23-26, 2007.

Babcock, R.C., M. Vanderklift, G. Clapin, M. Kleczkowski, K. Cook and J. Phillips (2007). Rottnest Island fished and unfished areas: "Its just a spatial artifact" *Western Rock Lobster Ecological Effects of Fishing workshop*, Perth, Australia, August 8-10, 2007.

Babcock, R.C., M. Vanderklift, M. Haywood, J. Stevens, P. Last, B. Black, E. Harvey, B. Fitzpatrick and G. Hyndes (2007). Ecosystem effects of fishing at Ningaloo. *Australian Coral Reef Society Annual Conference.* Fremantle, Australia, October 9-11, 2007.

Bearham, D. and M. Vanderklift (2010). The influence of light intensity, temperature and water movement on changes in growth of *Ecklonia radiata* in Marmion Lagoon, Western Australia. *Australasian Society for Phycology and Aquatic Botany*. Rottnest Island, Australia, November 17, 2010

Berry, O. and P. England (2009). Complementing oceanographic models of larval recruitment with fine-scale genetic analysis. *WAMSI Node 1 : 2nd Symposium.* Perth, Australia, July 30, 2009.

Campbell, N.A, T. Irvine, J. Keesing, G. Keith and P. Kennedy (2010). Canonical variate plots for categorising benthic classes using EM300 multibeam data. *Geohab 2010*. Wellington, NZ, May 4-7, 2010.

Campbell, N.A., J. Keesing, T. Irvine, G. Keith and P. Kennedy (2010). Distinguishing between benthic Classes - full-ping vs moving-window separation. *Geohab 2010*. Wellington, NZ, May 4-7, 2010.

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Campbell, N.A., J. Keesing and T. Irvine (2009). Canonical variate analysis using contiguous segments of multibeam data, *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

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Campbell, N.A., P.A. Caccetta, J. O'Connell, P. Kennedy, I. Parnum, J. Keesing and T. Irvine (2009). Posterior probabilities images incorporating the backscatter angular response for multibeam data. *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

Craig, P.D. (2009) Connectivity and scale in cellular automata models of marine habitat. *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

Craig, P.D. (2009) Habitat models aren't like ocean models. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

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Denuelle, A. and M. Dunbabin (2010). Kelp Detection in Highly Dynamic Environments Using Texture Recognition. *Australasian Conference on Robotics & Automation 2010*. Brisbane, Australlia, December 1-3, 2010.

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Feng, M. (2009). Long term changes in the Leeuwin Current system in the southeast Indian Ocean. *Greenhouse 2009*. Perth, Australia, March 23-26, 2009.

Feng, M. (2008). Long term changes of the Leeuwin Current derived from an eddy-resolving numerical model. *WPGM*. Cairns, Australia, July 29 – August 1, 2008.

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Feng, M., A. Biastoch, C. Boning, N. Caputi and G. Meyers (2008). Variability and trend of the heat balance in the southeast Indian Ocean. *International Symposium on Effects of Climate Change on the World's Oceans*. Gijon, Spain, May 19-23, 2008.

Feng, M., A. Biastoch, C. Boning, N. Caputi and G. Meyers (2008). The long term trend of the Leeuwin Current derived from an eddy resolving numerical model. *Western Pacific Geophysics Meeting*. Cairns, Australia, July 29 – August 1, 2008.

Feng, M. (2007). Decadal variations and long-term trends in the southeast Indian Ocean. *IUGG*. Perugia, Italy, July 2-13, 2007.

Feng, M. (2007). Nitrogen budget on the continental shelf off the west coast of Western Australia. *IUGG*. Perugia, Italy, July 2-13, 2007.

Feng, M. and K. Wild-Allen (2007). Nitrogen budget on the continental shelf off Western Australia. AMOS conference. Adelaide, Australia, Fubruary 5-8, 2007.

Feng, M., K. Wild-Allen and J. Keesing (2007). Climate Variability and the Marine Ecosystem in the Leeuwin Current off Western Australia. *Continental Margins Open Science Conference: Impacts of global, local and human forcings on biogeochemical cycles and ecosystems*. Shanghai, China, September 17-21, 2007.

Gartner, A. (2008). Trophic implications of seagrass habitat disturbance from reduced light. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Greenwood, J. (2010). 4-d bio-physical modeling at shelf and lagoon scale. *WAMSI Node 1 : 3rd Symposium.* Perth, Australia, June 29, 2010.

Greenwood, J. (2009). Chlorophyll dynamics on the continental shelf. *Catchment to Coasts Workshop*, Brisbane, Australia, May 20-21, 2009.

Greenwood, J. (2009). Continental shelf biogeochemical dynamics. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Greenwood, J. (2008). The underwater light climate off WA. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Greenwood, J. (2008). Evidence for a link between surface gravity waves and nearshore chlorophyll. *Advances in Marine Ecosystem Modelling Research Symposium*. Plymouth, UK, June 23-26, 2008.

Greenwood, J. (2007). Linking waves and nearshore chlorophyll biomass via sediment nutrient recycling. *International Symposium for the Interaction of Sediments and Waters*. Esperance, Australia, February 17-22, 2008**.**

Gusmão, L.F.M, J. Strzelecki and D. McKinnon (2009). The use of Aminoacyl-tRNA synthetases (AARS) activity as an index of mesozooplankton growth off Western Australian coast. *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

Gusmão, F., J. Strzelecki and A. David McKinnon (2011). Mesozooplankton growth as measured by enzymatic activity off the Western Australia coast. *5th International Zooplankton Production Symposium*. Pucon, Chile, March 14-18, 2011

Hanson, C., J. McLaughlin, G. Hyndes and J. Strzelecki (2009). Connecting the benthic and pelagic: picoplankton uptake by a demosponge (Callyspongia sp.). *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

Holliday, D. (2008). Larval fish, eddies and the Leeuwin Current. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Irvine, T. (2008). Shelf scale benthic habitat characterisation by video analysis. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing J.K. (2011). Marine benthic flora and fauna of Gourdon Bay and Dampier Peninsula in the Kimberley region. *Kimberley Marine and Coastal Science Symposium*. Fremantle, Australia, May 20, 2011.

Keesing, J.K. (2010). WAMSI Node1: Strategic Research on Western Australian Marine Ecosystems. Marine *Science in Western Australia. Joint Symposium by WAMSI and AMSA*. Fremantle, Australia, February 9, 2010.

Keesing, J.K. (2010). Node 1 Overview. *WAMSI Node 1: 3rd Symposium.* Perth, Australia, June 29, 2010.

Keesing, J.K. (2010). Understanding the Leeuwin Current Coastal Marine Ecosystem Dynamics. Invited Presentation. *Society for Underwater Technology*. Perth, Australia, August 11, 2010

Keesing, J.K., D. Bearham and T.R. Irvine (2010). Influence of grazing intensity by the sand dollar *Peronella lesueuri* on microphytobenthos and sediment biogeochemistry in a south-western Australian embayment. *7th European Conference on Echinoderms*. Gottingen, Germany, October 2-9, 2010.

Keesing, J.K. and T. Irvine (2009). Distribution, abundance and population biology of a super-abundant spatangoid echinoid in the Kimberley region of north-western Australia. *13th International Echinoderm Conference*, Hobart, Tasmania**,** January 5-9, 2009.

Keesing, J.K. (2009). Node 1 Overview. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Keesing, J.K. (2009). Importance of soft sediment habitats for WA marine ecosystems. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Keesing, J.K. (2008). WAMSI Node1: Strategic Research on Western Australian Marine Ecosystems. *Marine Science in Western Australia. Joint Symposium by WAMSI and AMSA*. Fremantle, Australia, February 26, 2008.

Keesing, J.K. (2008). Node 1 Overview. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing, J.K. (2008). SS 2007/04 Shelf scale benthic processes and benthic pelagic coupling – overview of rationale, objectives and operations. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing, J.K. (2008). Distribution and biomass of continental shelf benthic biota. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing, J.K. (2008). Biological Responses to Physical Forcing in Western Australia's Unique Marine Environment. Invited Presentation to His Excellency Ken Michael, Governor of Western Australia, Government House, Perth, Australia, October 9, 2008.

Keesing J.K., T.R. Irvine and N. D'Adamo (2007). West Central Australian Shelf – LME44: Review of sustainable development indicators. *Second Global Conference* on *Large Marine Ecosystems. Shanghai*, China, September 17-21, 2007.

Koslow J.A., Strzelecki J., Paterson H., and Pesant, S. (2007). Classical food webs and the microbial loop off Western Australia: Test of a new method to estimate simultaneously micro- and mesozooplankton grazing impacts. *4th International Zooplankton Production Symposium*. Hiroshima, Japan, May 28 - June 1, 2007.

Lawrence, J.M., J.K. Keesing and T.R. Irvine (2010). Population characteristics and biology of two populations of Archaster angulatus (Echinodermata: Asteroidea) in different habitats off the central-western Australian coast. *7th European Conference on Echinoderms*. Gottingen, Germany, October 2-9, 2010. Echinoderm Research 2010, Abstracts p64-65. (Poster presentation)

Lourey, M., M.J. McLaughlin, P. Thompson, J.K. and Keesing (2010). Production by Benthic Microalgae. *WAMSI Node 1: 3rd Symposium.* Perth, Australia, June 29, 2010.

Lourey, M. (2009). Benthic biogeochemistry and productivity. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Lourey, M. (2008). A shelf scale phytoplankton bloom. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

McLaughlin, J., A. Slotwinski, F. Coman, C. Davies, G. Hosie, D. McLeod, M. Tonks, J. Strzelecki and A.J. Richardson (2011). Ships of Opportunity – SOOP Part 2, *WAIMOS Science and Data Uptake Workshop*, Perth, February 24, 2011.

McLaughlin, J., M. Lourey, M. Feng and P. Thompson (2009). Latitudinal variation in primary production during a shelf-scale winter phytoplankton bloom. *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

McLaughlin, J., M. Lourey, M. Feng and P. Thompson (2009). Shelf-scale plankton dynamics and productivity during a winter bloom. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Rousseaux, C. (2008). Grazing losses due to microheterotrophs. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Slawinski, D. and M. Feng (2009). Coastal scale connectivity based on particle track modelling, or putting the 'Link' into BLUELink. *Australian Marine Science Conference*. Adelaide, Australia, July 5-9, 2009.

Slawinski, D. and M. Feng (2008). The source and destination of the Leeuwin Current waters. *WAMSI Node 2 Symposium,* Perth, Australia, September 9, 2008.

Slotwinski, A., F. Coman, C. Davies, G. Hosie, J. McLaughlin, D. McLeod, M. Tonks, J. Strzelecki and A.J. Richardson (2011). Plankton observing in Australia: The Australian Continuous Plankton Recorder (AusCPR) survey. *5th International Zooplankton Production Symposium*. Pucon, Chile, March 14-18, 2011.

Strzelecki, J. and S. Wang (2011). Influence of physical oceanography on the diet of size fractionated zooplankton of Western Australian coast: Insight from fatty acids, *5th International Zooplankton Production Symposium*. Pucon, Chile, March 14-18, 2011.

Strzelecki, J (2010). Zooplankton nutrition Zooplankton nutrition and benthic pelagic coupling (2010). *WAMSI newsflash presentation*. Fremantle, Australia, February 9, 2010.

Strzelecki, J (2010). Outcomes from the 1st Australian Zooplankton Taxonomic Workshop. Perth, Australia, April 9, 2010.

Strzelecki, J, F. Gusmao and A.J. Richardson (2010). Zooplankton communities: East vs West. East West Boundary Current Symposium, Hobart, Australia, June 22, 2010.

Strzelecki, J. and S. Wang (2009). Diet of Size fractionated Zooplankton off Western Australian Coast: Insight from Fatty Acids. *Australian Marine Science Conference*. Adelaide, Australia, July 5-9, 2009.

Strzelecki, J., C. Geordie, W. Shaofang and C. Hanson (2009). Zooplankton dynamics and benthic pelagic links off WA coast. *CMAR AIMS joint seminar*. Perth, Australia, December 17, 2009.

Strzelecki, J. (2008). Benthic pelagic coupling: role of filter feeders. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Strzelecki, J. (2008). Zooplankton of the 34 to 22 parallel. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Strzelecki, J., Clapin, G., Greenwood and Hanson, C. (2007) Role of Filter Feeders in Marmion Lagoon, Western Australia. *Ecological Society of Australia 32nd Annual Conference*. Perth, Australia, November 25-30, 2007.

Symonds, G. and L. Zhong (2009). Effects of wave exposure on nearshore benthic habitat and circulation in a complex reef dominated coastal environment off South West Western Australia. *41st International Liege Colloquium on Ocean Dynamics*. Liege, Belgium, May 4-8, 2009.

Symonds, G., L. Zhong and N. Mortimer (2009). Marmion Lagoon Revisited: wind and wave driven currents. *WAMSI Node 1 : 2nd Symposium.* Perth, Australia, July 30, 2009.

Thompson, P., M. Lourey and J. McLaughlin (2009). Primary production by benthic microalgae on the continental shelf of western Australia. *Australian Marine Science Conference*. Adelaide, Australia, July 5-9, 2009.

Thompson, P., A.M. Waite, M.A. Doblin, L.E. Beckley, J. Strzelecki and P. Bonham (2009). The Plankton Ecology of South Western Australia: Temporal and Spatial Patterns. *Australian Marine Science Conference*. Adelaide, Australia, July 5-9, 2009.

Thompson, P., A.M. Waite, P. Bonham and M.A. Doblin (2009). The phytoplankton ecology of Western Australia. *Phycological Society of America*. Honolulu, Hawaii, July 18-22, 2009.

Thompson, P. (2008). Benthic micro algal photosynthetic performance. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Thompson, P. (2008). Pelagic ecosystem productivity & dynamics - rationale, objectives and operations. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Thompson, P.A. (2007). Phytoplankton and Mixing. *Australian Marine Sciences Association Annual Scientific Conference*. Melbourne, Australia, July 9-13, 2007.

Thomson D, R. Babcock and M.V. Vanderklift (2010). Kelp Patch dynamics; patch size, wave exposure, herbivores and patch age. *Australasian Society for Phycology and Aquatic Botany*. Rottnest Island, Australia, November 15 -18, 2010.

Thomson, D., R. Babcock and M.V. Vanderklift (2010). Kelp Patch dynamics; patch size, wave exposure, herbivores and patch age. Invited speaker at workshop entitled Management, conservation, and scientific Challenges on Subtropical Reefs under Climate Change. *Australian Coral Reef Society (ACRS) conference*. Coffs Harbour NSW, Australia, September 10, 2010.

Thomson, D. (2010). Kelp forest patch dynamics in south western Australia. Workshop: Management, Conservation, and Scientific Challenges on Subtropical Reefs under Climate Change *Australian Coral Reef Society Annual Science Symposium*, Coffs Harbour, Australia, September 13, 2010.

Thomson, D., R. Babcock, M.V. Vanderklift (2009). Kelp Patch dynamics; patch size, wave exposure, herbivores and patch age. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Thomson, D. (2008). Patch dynamics at Marmion reef. *Workshop at CSIRO Floreat, addressing staff from the Department of Environment and Conservation, Australian Institute of Marine Science, Western Australian Fisheries Department and CSIRO.* Perth, Australia, February 27, 2008.

Vanderklift, M. (2010). Corals and kelps: The ecological role of herbivores in tropical & temperate ecosystems in western Australia. *Gordon Research Conference on Plant-Herbivore Interactions*. Galveston, USA, February 21-26, 2010.

Vanderklift, M. (2010). A single species, the kelp *Ecklonia radiata*, is disproportionately important in coastal marine ecosystems. *Australasian Society for Phycology and Aquatic Botany*. Rottnest Island, November 15-18, 2010.

Vanderklift, M. (2009) The ecological importance of herbivores in tropical & temperate ecosystems in Western Australia. *Impacts of mesograzers, ARC vegetation Function Network.* Sydney, Australia, 2009. Invited presentation.

Vanderklift, M. (2009). Benthic Ecology. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Vanderklift, M. and T. Wernberg (2008). Stable isotopes show consistent consumer-prey relationships across hundreds of kilometres. *6th International Conference on Applications of Stable Isotope Techniques to Ecological Studies*. Honolulu, USA, August 25-29, 2008.

Wild-Allen, K. (2008). Nutrient sources for phytoplankton in the Leeuwin Current. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Zhong, L. (2009). Wave-driven circulation in a complex reef dominated coastal environment off South West Western Australia. *2009 ROMS/TOMS Asia-Pacific Workshop*. Sydney, Australia, March 31- April 2, 2009.

Zhong, L. (2009). A high resolution shelf hydrodynamic model. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

ANNEXURE 1: LISTING OF PROJECTS, PROJECT STAFF AND STUDENTS

PROJECT 1. Southwest Australian Coastal Biogeochemistry

Project Leaders: *John Keesing, Peter Craig, Graham Symonds, Jim Greenwood, Mat Vanderklift, Peter Thompson, Martin Lourey*
Project Teams:
<u>Physical oceanography, hydrodynamics and biogeochemical modelling</u>
Peter Craig, Graham Symonds, Ming Feng, Jim Greenwood, Liejun Zhong, Karen Wild-Allen, Dirk Slawinski, Nick Mortimer, Jeff Dunn, Ken Ridgway, Uwe Rosebrock, Gary Carroll, Eloise Brown (UWA), Thisara Wilhena (UWA)
<u>Pelagic ecosystem oceanography, biogeochemistry, biology and ecology</u>
Peter Thompson, Martin Lourey, James McLaughlin, Joanna Strzelecki, Pru Bonham, Peter Hughes, David Holliday (Murdoch), Cecile Rousseaux (UWA), Natalie Millar (Murdoch)
<u>Benthic ecosystem characterisation, biogeochemistry, biology and ecology</u>
John Keesing, Mat Vanderklift, Peter Thompson, Martin Lourey, Joanna Strzelecki, James McLaughlin Russ Babcock, Tennille Irvine, Doug Bearham, Lesley Clementson, Fiona Graham, Damian Thomson, Ryan Downie, Hector Lozano-Montes, Jim Gunson, Julia Phillips, Peter Hughes, Stelios Kondylas, Ryan Crossing, Norm Campbell, Kayley Usher, Jane Fromont (WA Museum), Adam Gartner (ECU), Thibaut de Bettignies (ECU), Charulata Singh (ECU), Sharon Yeo (Murdoch), Natalie Millar (Murdoch)

PROJECT 2. Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules

Project Leaders: *John Keesing, Russ Babcock, Mat Vanderklift, Phillip England, Peter Craig*
Project Teams:
<u>Development of DIVE</u>
Peter Craig, Gary Carroll, Uwe Rosebrock, Jason Waring and Irshad Nainar
<u>Connectivity dynamics, hydrodynamic and genetic modelling</u>
Phillip England, Deryn Alpers, Ming Feng, Dirk Slawinski and Oliver Berry
<u>Benthic ecology</u>
Mat Vanderklift, Russ Babcock, John Keesing, Fiona Graham, Damian Thomson, Doug Bearham, Ryan Downie, Geordie Clapin, Joanna Strzelecki, Richard Pillans, Hector Lozano-Montes, Kylie Cook, Natalie Millar, Mat Dunbabin, Peter Craig, Graham Symonds, Eloise Brown (UWA) and David Rivers (UWA).

PROJECT 3. Benthic habitat surveys of potential LNG hub locations in the Kimberley region

Project Leaders: Gary Fry (CSIRO) and Andrew Heyward (AIMS)
Project Teams:
<u>CSIRO:</u> *Gary Fry, John Keesing, Roland Pitcher, Nick Ellis, Tennille Irvine, Damian Thomson, Mat Vanderklift, Sue Cheers, Tonya Ven der Velde, Nick Ellis, Tom Taranto, Greg Smith, Ted Wassenberg, David Brewer, A. Chetwynd, Rob Pendry, Toni Cannard, Ian McLeod*
<u>AIMS:</u> *Andrew Heyward, Jamie Colquhoun, T. Stieglitz, Kylie. Cook, K. Brookes, Simon Woodley, Olwyn Hunt, Peter Speare*
<u>DEC:</u> *Ray Masini, Cameron Sim, Kevin McAlpine*

ANNEXURE 2: THE APPROVED *SCIENCE PLAN* FOR THE NODE

A copy of the approved science plan is held by WAMSI.

ANNEXURE 3: THE FINAL *PROJECT REPORTS* FOR THE NODE

The following projects final reports, comprising over 700 report pages and over 500 published journal pages, have been submitted to WAMSI:

WAMSI NODE 1 PROJECT 1 FINAL REPORT - OVERVIEW
Southwest Australian Coastal Biogeochemistry
Editor: John K. Keesing
Chapter senior authors: Peter D Craig, Ming Feng, Jim Greenwood, Martin Lourey, Peter A. Thompson, John K. Keesing, Graham Symonds and Mat A Vanderklift
30 June 2011
46 pages

WAMSI NODE 1 PROJECT 1 FINAL REPORT - ANNEXURE A – RESEARCH CHAPTERS
Southwest Australian Coastal Biogeochemistry
Editor: John K. Keesing
Chapter senior authors: Peter D Craig, Ming Feng, Jim Greenwood, Martin Lourey, Peter A. Thompson, John K. Keesing, Graham Symonds and Mat A Vanderklift
30 June 2011
487 pages

WAMSI NODE 1 PROJECT 2 FINAL REPORT - OVERVIEW
Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules
Editor: John K. Keesing
Chapter senior authors:
Russ C Babcock *et al.*, Peter D Craig *et al.*, Phillip R England *et al.*, Mat A Vanderklift *et al.*
30 June 2011
23 pages

WAMSI NODE 1 PROJECT 2 FINAL REPORT - ANNEXURE A – RESEARCH CHAPTERS
Coastal ecosystem characterisation, benthic ecology, connectivity and client delivery modules
Editor: John K. Keesing
Chapter senior authors: Russ C Babcock *et al.,* Peter D Craig *et al.,* Phillip R England et al. and Mat A Vanderklift *et al.*
30 June 2011
113 pages

WAMSI NODE 1 PROJECTS 1, 2 & 3
FINAL REPORT – ANNEXURE B
Publications and Presentations
Compiled by: Mizue Iijima and John K. Keesing
30 June 2011
Approx 500 pages

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