Synopsis of Findings from the SRFME Core Projects

Introduction

The Core Projects in the Strategic Research Fund for the Marine Environment (SRFME) have contributed significantly to our understanding of the marine environment of south-western Australia. Combining physical and biological oceanography with marine chemistry, biology and ecology, this research, and the future studies and publications that arise from it, will better inform decisions in managing, developing and protecting the WA marine environment.

This section provides an overview of the research conducted in the SRFME Core Projects by CSIRO and its collaborators in WA Universities and State government agencies. The detail of this research in each of the three Core Projects has been integrated and is reported on in Volume 2 of the SRFME Final Report.

The Leeuwin Current

In structuring this overview, we start with the physical oceanographic influences on the Western Australian marine ecosystems before moving on to examine the biogeochemical components of the pelagic and benthic parts of the ecosystem, including aspects of their dynamics and ecological interactions. Western Australian marine ecosystems are directly, and measurably, affected by hydrodynamic processes at a wide range of scales, from the circulation in the Pacific and Indian Oceans, down to turbulence from individual waves crossing the reefs. Time-scales range from the seconds associated with breaking waves up to the decades associated with climate change. Research in SRFME has increased our understanding of the oceanography at all of these scales. At decadal to century time-scales, the water temperature at coastal stations in the region has risen by around 0.017 ºC per year over the last 50 years, consistent with the global temperature rise attributed to climate change. At the same time, salinity off the WA coast has also increased. Sea-level at Fremantle is rising at about 1.5 mm per year. There is also a clear suggestion of a lengthening warm season. As in other parts of the world, Western Australia will need to determine how it will respond to a changed climate, and marine studies will be vital to ensure that industry and the community have adequate time and information to adapt. How the Western Australian marine environment will change as a result of climate change remains a great unknown.

The Leeuwin Current is profoundly influential on the marine ecosystems of Western Australia. As one of very few poleward-flowing eastern boundary currents in the world, it has been the subject of much research. SRFME studies have quantified both the annual and ENSO-related interannual variations of the Leeuwin Current, and the relationship between the Fremantle sea level and the strength (volume transport) of the Current. These results justify the usage of the Fremantle sea-level as an index for the Leeuwin Current, that has been widely used in fisheries management in Western Australia, especially for predicting western rock lobster recruitment. The Leeuwin Current is about 40% stronger during a La Nina year than during an El Nino. The Current responds as well to a smaller signal called the Pacific Decadal Oscillation, which can also be monitored by the Fremantle sea-level.

The average flow rate of the Leeuwin Current, estimated from long-term, ship-based measurements, is about 3.4 x 10^6 m^3s^{-1}. An increase in the flow rate of 1 million m^3s^{-1} is reflected by an increased Fremantle sea-level of about 7.5 cm. The strength of the current varies by about a factor of 2 over the year, being strongest in winter and weakest in summer, when it is opposed by southerly winds. These summertime winds may generate northward coastal currents that have been given local names such as the Capes and Abrolhos Currents.

SRFME research has determined that the extent of influence of the Leeuwin Current is much greater than previously envisaged. During the winter, the Leeuwin Current turns east past Cape Leeuwin, and can be tracked, in satellite images of surface temperature and height, all the way to southern Tasmania, a distance of 5500 km from North West Cape, making it the world's longest current. Its name changes to the South Australian Current, and then the Zeehan Current, over this distance.

Eddies form south of the Abrolhos Islands (29ºS) from meanders of the Leeuwin Current. The eddies are studied primarily from satellite altimetry, and are more intense when the Leeuwin Current is strongest, in the winter and in La Nina years. Warm-core eddies drift from the shelf offshore and may persist for months. Approximately six warm-core eddies form each year, carrying a total volume of water roughly equivalent to flushing the southern shelf twice per year. The eddies are believed to carry nutrients and phytoplankton from inshore waters, significantly enhancing offshore primary production, and probably play a significant role in the advection of larvae. Significant advances in the understanding of these eddies and their importance to the southwestern Australian continental shelf ecosystem have resulted from SRFME studies. This work is described in part in both volumes 1 and 2 of the SRFME Final Report and is to be documented in a special issue of the journal *Deep Sea Research*.

The Leeuwin Current is apparent in images of both sea-surface temperature and sea-surface height. As part of SRFME, an accurate numerical (hydrodynamic) model of the Leeuwin Current has been developed, at 10 km horizontal resolution, by forcing it with the surface observations, and using the model equations to calculate the 3-dimensional current and density fields. The model has been validated against ship-based observations of eddies, and inshore moorings.

Three moorings were deployed across the shelf from Two Rocks in water depths of 20 m, 40 m and 100 m, and maintained for a year, primarily recording currents and water temperature. At the innermost mooring (approx. 5 km offshore), the currents follow the wind direction, principally north in the summer and south in the winter, with the current speed close to 3% of the wind speed. At the 100 m mooring, about 50 km offshore, surface waters tend to follow the wind direction, while waters below 50 m flow south under the influence of the Leeuwin Current. The water is warmer and saltier inshore during the summer, but during the winter the Leeuwin Current keeps the offshore water warmer. In summer, the surface water in 100 m is about 2 ºC warmer than the bottom, but the water is well-mixed during the winter.

Biogeochemistry

Two Rocks was also the base for a major SRFME measurement program along a transect from nearshore to the outer continental shelf (100 m water depth). The transect was occupied monthly from 2002 – 2004, with a quarterly extension to offshore waters (1000 m depth). Cruise sampling was combined with satellite observations of sea-surface temperature (SST), ocean colour and altimetry, and subsurface measurements of currents and temperature from the moorings to provide both a cross-sectional description of the physics and productivity, and verification data for the modelling.

The Two Rocks transect data reveal that summer conditions on the shelf and offshore were oligotrophic, characterised by a shallow upper mixed layer, with a strong thermocline and well stratified water column. Surface waters were nitrate-depleted and generally contained low phytoplankton biomass levels (< 0.2 mg m^{-3}), overlying a deep chlorophyll maximum (DCM) layer located between the 0.1% and 1.0% light levels. The DCM was frequently associated with a deep nitracline (between 100 and 150 m water depth). By contrast, in late autumn and winter, the upper mixed layer deepened and stratification weakened, leading to shoaling of the nitracline and DCM. Except within the lagoon, where no clear seasonal cycle was observed, phytoplankton biomass integrated through the water column was generally twice as high from April – September as in the spring and summer (October – February).

Satellite data reveal the spatial extent of the dynamics observed at the transect. Near-surface chlorophyll-*a*, an indicator of phytoplankton biomass, can be inferred from ocean-colour sensors mounted on satellites. Over the continental shelf, phytoplankton production appears to peak during the late autumn and early winter, corresponding to the onset of winter storms and the seasonal strengthening of the Leeuwin Current and its eddy field. Further offshore, the phytoplankton biomass peaks in late winter, assisted by the eddies' transport of both nutrients and phytoplankton from the shelf. Deeper mixing during winter is also likely to enhance nutrient levels. The offshore flux of phytoplankton biomass by the warm-core eddies is estimated as equivalent to about 4×10^5 tonnes of carbon per year.

A relatively simple, one-dimensional, biophysical model has been developed during SRFME to demonstrate the importance of spinup over the shelf for warm-core eddies. The model represents an eddy as a trapped body of water and follows it as it detaches from the Leeuwin current and moves offshore. Given appropriate density and nutrient properties during eddy formation, the model successfully distinguishes between the productivity of the warm and cold-core eddies as they evolve. Cold-core eddies tend to spin up on the low-nutrient, seaward side of the Leeuwin Current.

High-nutrient water below the nutricline is not considered to contribute directly to the shelf, because the Leeuwin Current inhibits upwelling. However, vertical mixing, associated both with storms and the increased intensity of the Leeuwin Current, is thought to bring nutrients locally towards the surface, into the photic zone, during autumn and winter.

The role of vertical mixing on the biogeochemistry was also tested with a simplified one-dimensional biogeochemical model. The model was set up to simulate the upper 200 m at station E, the outermost station on the transect, 85 km offshore and in 1000 m of water, for the year 2003. Vertical mixing due to atmospheric conditions and the Leeuwin Current was simulated by forcing ("relaxing") the vertical temperature and salinity profiles to synTS (a technique which, given the surface height and temperature, derives T and S profiles from historical data sets).

There were only 5 transects to Station E during 2003, providing limited data for comparison. The model appears to predict well (given only 5 comparison points) the measured seasonal cycle of temperature. It predicts the stable summertime nutrient profile with a deep (100 m) chlorophyll maximum, and the transition to a surface bloom in autumn. It failed to predict the deep chlorophyll maximum observed in late winter. The winter observation corresponded to an exceptional cold event (2 °C cooler at 100 m depth), relative to synTS predictions, and may have been associated with an eastward migration of the Leeuwin Current, obviously beyond the scope of a 1-d model.

Thus, the late-autumn and early-winter bloom appears to be at least partially explained by enhanced vertical mixing, and the transport, by eddies, of nutrient-rich water from the shelf. It is also possible that the intensified Leeuwin may entrain nutrients in the north, where the nutricline is shallower, and advect them southward.

One of the main roles of the SRFME hydrodynamic model was to provide the ocean-forcing for a fully 3-dimensional biogeochemical model. The biogeochemical model simulates the cycling of carbon, nitrogen and oxygen through the water column and sediments. Its primary output is phytoplankton biomass, and its key initial challenge is to represent the seasonal cycle of phytoplankton productivity as observed from satellites and measurements from the Two Rocks transect. The model appears to simulate the large-scale variability, with low productivity in the summer and blooms in the late autumn and winter. However, it does not reproduce the high inshore productivity visible in satellite images for autumn and winter.

Nutrient sources remain a significant unknown for the coastal and shelf biogeochemistry. The inshore productivity is assumed to be due to onshore or nearshore sources that are not sufficiently identified or quantified to be included in the model. Nutrients will also be stored in coastal and shelf sediments, and presumably released during high wave and swell conditions. Sensitivity tests with the model indicate the likely importance of nutrient storage in the sediments, but the magnitude of the store is unquantified. Further, the large-scale nutrient distribution, required for both initialising the model, and for its open boundary conditions, is not well established. The hydrodynamic model currently uses temperature and salinity fields predicted from synTS. The model can also access CSIRO's global BLUElink model for initial and open boundary conditions. Equivalent fields for nutrients do not yet exist.

Plankton Ecology

Measurements along the Two Rocks transect indicate that phytoplankton biomass and production integrated through the water column were generally several-fold higher offshore, although maximum volumetric chlorophyll concentrations were observed inshore. Depth-integrated chlorophyll concentrations on the shelf and offshore generally ranged from 20 – 40 mg chl *a* m^{-2}, compared to 5 – 15 mg chl *a* m^{-2} inshore. This difference was considerably reduced in spring and summer, because the seasonal cycle was less pronounced in the lagoon environment. Annual phytoplankton production over the study period was 46 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ inshore and about 115 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ on the shelf and offshore—relatively oligotrophic for a coastal environment. Not unexpectedly, given the nutrient depleted conditions generally observed in the euphotic zone, biomass and production were far greater in the small phytoplankton size fraction (< 5 μm): the median percentage of biomass and primary productivity in the small size fraction was 5 and 12%, respectively. Based on analysis of HPLC pigments, the outer shelf and offshore stations were characterised by high prochlorophyte and unicellular cyanobacteria populations. Small flagellates were most prevalent on the shelf, and periodic blooms of larger diatoms dominated inshore waters. Small haptophytes were ubiquitous.

Zooplankton biomass was also generally greatest in late autumn and winter. The assemblages differed significantly in nearshore and shelf/offshore waters and between winter and other seasons, following patterns among species groups observed elsewhere in coastal waters.

Microzooplankton biomass peaked in winter, consistent with the winter peak in chlorophyll. Species richness was significantly higher on the shelf and offshore than nearshore, which was ascribed to the generally less stable inshore environment. Dilution experiments indicated that the microzooplankton consumed, on average, 60% of primary production. Growth of the picoplankton was particularly closely coupled with microzooplankton grazing.

The impact of grazing of mesozooplankton on the phytoplankton was generally low, but the impact on the microzooplankton increased with distance offshore. Incubation experiments showed that increased densities of mesozooplankton grazed down an increased proportion of the microzooplankton, which led to a decrease in grazing on phytoplankton.

Particularly clear trends in onshore-offshore and seasonal assemblages were seen in the ichthyoplankton. These trends were related to water mass structure and the seasonal characteristics of spawning in the region. The inshore region was characterized by reef fishes, such as gobies, clinids, blennies and tripterygiids, whereas pelagic fishes, such as clupeids and carangids, dominated over the shelf. Oceanic fishes, such as myctophids, phosichthyids and gonostomatids dominated the ichthyoplankton at the shelf break and over the slope. However the changing seasonal dynamics of the Leeuwin and Capes Currents were clearly reflected in the ichthyofauna assemblages.

Benthic Ecology

Towards the coastline, the seabed falls within the photic layer, and macrophyte productivity begins to dominate phytoplankton productivity. SRFME made significant advances in our knowledge of the patterns found in the benthic components of Western Australia's marine ecosystems and the underlying processes and dynamics that give rise to these patterns and the variability exhibited in benthic communities. Western Australia is unusual in possessing high-biomass, high-productivity benthic ecosystems despite the relatively low-nutrient levels that result from the low-rainfall climate and the influence of the Leeuwin Current.

SRFME focused on improving understanding of one major habitat type – coastal rocky reefs – that had previously received relatively little attention. Rocky reefs are an important habitat type in nearshore coastal waters, supporting a diverse assemblage of benthic macroalgae and associated fish and invertebrates. The rocky reef communities are a key component of coastal productivity, provide habitat and food for marine fauna, contribute to biogeochemical cycles, and can exert influence over nearby habitats such as seagrass meadows. Despite their recognised importance, comparatively little is known of the ecology of rocky reef habitats along the lower west coast of Western Australia.

SRFME research incorporated the first quantitative, broad-scale investigations of several key ecological processes on the reef benthos of south-western Australia. Major findings were that spatial gradients in wave exposure were significantly correlated with spatial patterns in the species richness and composition of macroalgae, that the rates of some ecological processes (e.g. algal productivity) and the abundances of both mobile and sessile fauna vary significantly between inshore and offshore reefs, and that consumers (including humans) exert a significant influence on some reef-associated biota. The understanding of both pattern and process is essential to achieving the ultimate goal of modelling the coastal ecosystem and gaining the ability to predict ecosystem behaviour.

The benthic field sites were categorized into 3 “regions” – Jurien, Perth and Geographe Bay – within each of which there were two “locations” – Green Head and Jurien Bay, Two Rocks and Marmion, and Bunbury and Cape Naturaliste, respectively. Each location had two measurement “sites”, within which quadrats were sampled.

There is a strong seasonal signal in algal biomass in all regions, but processes underlying this pattern varied for different locations, or for particular sites within locations depending on the dominant algal habitat type. Most locations (e.g. Jurien Bay, Marmion, Two Rocks and Bunbury) showed lowest biomass in winter. The proximal factors that drive these variations also differ among locations. Erosion of biomass is most likely to be driving changes in *Ecklonia*-dominated sites (Marmion, Two Rocks, Perth) while light-limitation is likely to be a major factor at Bunbury. Here, seasonal resuspension of particulate matter and sediment by winter and spring storms and swell appears to affect the entire algal community, which is largely made up of foliose red and brown algae. At sites where *Sargassum* dominates (Green Head), there is a summer minimum in biomass because of the algal phenology. In contrast to the pattern for biomass, algal community structure showed no seasonal trend.

Among the study regions, the overall number of algal species recorded was similar. In all the regions, by far the largest contribution to overall species diversity was made by the red algae. While variations in species richness were not large, more species were recorded at the lower latitude sites, and fewer recorded in the Perth region. This may be explained by variation in the relative dominance of large brown algae in the different regions, since there is an inverse relationship between *Ecklonia* biomass and that of red algae. The highest densities of *Ecklonia* were found at reefs in the Perth region.

Macroalgal community structure varied at all the spatial scales we examined, but was strongest at the site level. In fact, at the site level, the differences between sites, even within locations, was greater than the differences between sites at the most widely separated regions. This strongly suggests that, for algal community structure, processes operating or varying across relatively small scales may be responsible for much of the observed variation observed. Assemblages not dominated by *Ecklonia* or other canopy species were most often composed of a diverse mixture of medium to small sized foliose algae, mainly red and brown, although green algae were occasionally dominant. Our study has shown that these habitats can on average form almost 50% of all algal communities, and are likely to be of greater importance than previously assumed in WA.

Since the nature of this variation was often associated with clear qualitative differences in community structure, for example, the presence or absence of a canopy, we developed a method to classify algal communities based on a semi-quantitative mix of structural and taxonomic attributes. The system was accurate in 75% of cases and offers a means of classifying algal assemblages for use in higher-level analysis of patterns at the landscape scale, and as a rapid system for visual quantification of habitats for mapping and ground-truthing (for example, in hyperspectral mapping).

A statistical model relating algal-assemblage structure to physical environmental variables in the Jurien region showed that the two factors most strongly associated with community structure were seabed roughness at the 1 m and 10 m scales, and modelled seabed orbital velocity. Wave-generated water movement across the seabed and small-scale seabed topography interact very strongly, further reinforcing the conclusion that small scale variations in ecological processes are likely to be of prime importance in determining the structure of benthic reef assemblages. Processes controlled by interactions of topography and water motion include physical disturbance (dislodgement), diffusive processes (gas and nutrient exchange) and sediment transport (scour and burial). It is important for us to understand this small scale variation in algal assemblages, as a basis for future work and for scaling up results to larger areas.

For invertebrates, weaker patterns in community structure were present, particularly for the algal-associated epifauna. Some pattern was present in the larger sessile and solitary fauna, but levels of similarity/dissimilarity did not vary markedly across scales. The lack of pattern suggests that the spatial scales encompassed in the sampling (regions, locations, sites), which was designed primarily to quantify algal assemblages, did not adequately capturing variation in the invertebrate assemblages.

However, informative patterns did emerge at different spatial scales. Species number varied according to the algal habitat type with epifaunal invertebrate species richness (at the scale of 0.25 m^2 quadrats) higher for turf habitats, followed by *Caulerpa*, *Ecklonia* forest, *Sargassum*, low algae, red foliose and mixed brown habitats. A higher number of solitary and sessile invertebrates (1 m^2 quadrat) were found to be associated with low algae and red foliose habitats, followed by mixed brown, turf, *Sargassum*, *Ecklonia* forest and *Caulerpa* habitats. As for the algae, the highest number of invertebrate species was recorded at Jurien, and Perth had the lowest numbers of species although numbers were only marginally greater at Geographe Bay. While the magnitude of the differences is relatively small, it is once again interesting that the region with the most *Ecklonia*-dominated sites had the lowest number of species.

For larger sessile invertebrates, belt transects revealed strong trends for coral and sponge abundance, within low algae and red foliose algal habitat types. Brown algal dominated habitats totalled 53% of habitats covered by transects at Marmion, yet within these transects only 22% of sponges and 7% of corals were recorded. These patterns essentially reflect algal habitat structure and coverage, and its patchiness or variability, not just at the site level but within sites. Interestingly a coral species (*Plesiastrea*) was one of the taxa most responsible for dissimilarity among sessile and solitary invertebrate assemblages at the site level. Sessile invertebrates such as corals and sponges may achieve a higher larval settlement rate, and/or higher subsequent survival and growth, in habitat that is lower and more sparsely covered by algae, in contrast to the typically dense, canopy forming brown algae species.

At the scale of individual quadrats, there were significant patterns in the overall abundance of mobile invertebrates, particularly molluscs and crustaceans. Most of these animals are relatively small and likely to be key contributors to secondary production in the reef ecosystem. This pattern resulted from a significant negative correlation between invertebrate abundance and the biomass of *Ecklonia radiata*, that has a key indirect influence on invertebrate assemblages.

Fish assemblages showed a contrasting pattern to those of algae and invertebrates, with a high level of variation among assemblages at the regional level and virtually none at the location level. However, at the site level there was once again significant variation in fish assemblages. We attribute this consistent variation at the site level to the association of fish assemblages with definable algal habitat types that tend to dominate at particular sites. While large brown algal assemblages dominated at just over half the sites, nearly as many sites were instead characterized by a diverse assemblage of foliose and filamentous red and brown algae.

At small scales across all three major groups we have studied, algae, invertebrates and fish, we see the importance, even dominance, of processes operating at distances of metres to tens of metres for structuring variation in benthic assemblages. This variation has important implications for understanding which ecological processes structure these communities. As noted, analysis of algal community structure strongly suggests that some aspect of wave action, coupled with the nature of the substratum, interact to determine the characteristics of the algal community. The characteristics of the algal community in turn appear to strongly determine the nature of invertebrate assemblages. For fish, these aspects of habitat also appear to be important, although in their case there may also be stronger large-scale biogeographic factors influencing distribution across the west coast region.

At the regional level, some locations have physical characteristics that mean larger-scale processes play a more important role. Variation in water quality in eastern Geographe Bay creates conditions that result in a seasonal change in algal biomass, quite distinct from other parts of the west coast. The implications of this unusual pattern merit further exploration. It is possible that elevated nitrogen levels in Perth metropolitan waters are linked in some way to the abundance of *Ecklonia*-dominated habitats at Marmion. For most of the coast, smaller-scale studies focused on the impact of environmental factors at the site, or even quadrat, scale are likely to lead to a broader general understanding of key ecological processes across the coastal ecosystem as a whole. The role of such small-scale processes, and of nutrients in coastal reef systems, remains an important area of research yet to be fully explored.

In December 2005, 4 acoustic doppler velocimeters, capable of measuring wave orbital velocities, were deployed across the Marmion reef to measure the cross-shore change in wave signature. The amplitude diminished by up to 1/3 as the waves travelled 1500 m across the reef. This behaviour was reproduced by a standard wave model (SWAN), but with enhanced bottom friction attributed to the reef roughness.

In these shallower waters, the water movement tends to be dominated by the effect of surface waves. The 20-m mooring on the Two Rocks transect included a pressure sensor to measure waves, and an acoustic doppler current profiler, which could be used to infer the sediment suspended from the seabed by the waves. The data were used to calibrate a sediment-transport model. They show that, at this inshore location, the waves are sufficiently energetic to keep medium-sized sand mobile most of the time.

South and north of Perth, the sediment mobility was examined by nesting a local wave model (SWAN) inside a global model (WAVEWATCH 3). The modelling suggests high levels of sand mobility (>60% of the time) in Geographe Bay throughout the year, with an increase (to 80%) in the winter. There is a small area in the lee of Cape Naturaliste where the mobility is much reduced. Mobility rates are also similar off Geraldton.

Exposure to waves affects the distribution of macroalgal species on the reefs. For Jurien Bay, the wave model was used to estimate exposure to large wave events at the 26 sites sampled during the benthic field program. The species diversity at the sites was positively correlated with wave disturbance; that is, the more exposed the site to large wave events, the higher the diversity. Presumably, the breakage and removal of plants by big waves increases opportunities for new species to establish. There is a suggestion that, at the highest exposure, diversity begins to diminish again, presumably because only the hardiest species survive under the most extreme conditions. This increase, and subsequent decrease in species diversity with increasing disturbance rate is a well-documented phenomenon, generally known as the *intermediate disturbance hypothesis.*

Accumulated wave exposure over an 8 year period provided a significantly better explanation of species richness patterns than wave-energy over a single year. This suggests that species richness of macroalgae might be the result of integration of processes occurring over years, rather than the result of short-term responses to disturbance.

The consequences of wave action for an individual alga include detachment from the substrate on which it grows. Our research showed that, once detached, kelps may drift for many kilometres. Substantial accumulations of detached reef algae occurred at an inshore reef, coinciding with high densities of sea urchins, which eat mainly detached fragments of algae. Analyses of the morphology of individual kelps at this location indicate that a large proportion originate from reefs several kilometres further offshore. These results demonstrate large-scale trophic linkages across the lagoon that are a result of wave action.

Trophic linkages such as these are likely to have profound implications for the function of WA's coastal ecosystems at broad scales. For example, differences between inshore and offshore reefs were observed for densities of sea urchins (higher densities inshore) and grazing on drift kelp by sea urchins (higher inshore), as well as for algal productivity and diversity. This overall trend might be a result of the gradient in wave action, and gradients in ecological processes that occur due to physical disturbance by waves, such as detachment and export of reef algae. Our measurements of rates of recruitment to collectors indicated that while rates were higher inshore, they were also highly variable. This suggests that densities of adult urchins inshore were not due to higher recruitment, but to the higher availability of food (drifting fragments of algae).

Primary productivity of *Ecklonia* was greater at Jurien than in the Perth Region. In addition, productivity was higher offshore at Jurien, but not in the Perth Region. These results suggest that nitrogen *per se* might not be limiting for growth of macroalgae on this coast since these productivity patterns are directly opposite to the C:N trends found in *Ecklonia* plants from these sites. The C:N values were far lower at Perth, than at Jurien — yet production was higher at Jurien. There is potential for anthropogenic nitrogen sources in the Perth region to enhance the growth of macroalgae which is worthy of further investigation. Nutrient levels offshore from Perth seem to be elevated and to carry a high level of $\delta^{15}N$, a sign of terrestrial effluent origins for this nitrogen. In addition, C:N ratios of kelps from both regions were lower inshore than offshore — yet production tended to be higher offshore, at least at Jurien. The most common paradigm for marine algae of all types is that their growth is nitrogen limited, yet our data contradict this assumption. The suggestion that availability of nitrogen might not be limiting growth of *Ecklonia* on the WA coast requires investigation through controlled experiments. Other potential influences on the rate of N uptake, such as light availability, and the role of wave-driven turbulence, must also be investigated.

Little of the *Ecklonia* primary productivity was directly consumed. The only direct grazing was by herbivorous fish. However, densities of herbivorous fish, and rates of grazing by herbivorous fishes, varied from reef to reef, and showed no broad trends. The highest rates of consumption of tethered kelps were on drifting fragments, and mainly by sea urchins. Similar observations have also been made in seagrass and intertidal habitats in the region. It is clear that detached macroalgae are ubiquitously important in sustaining coastal food webs on the Western Australian coast.

Humans can exert a strong influence on the structure of communities through harvesting of key species. For example, in several parts of the world, hunting and fishing has reduced predators of sea urchins to ecologically trivial abundances, resulting in increases in sea urchin density and landscape-scale decreases in canopy-forming primary producers due to grazing. Similar processes are possible in WA, and are a potential explanation for variation in the structure of assemblages of reef algae. SRFME research included the first assessment of the effects of a 16-year fishing closure (the Kingston Sanctuary at Rottnest Island) on assemblages of fish and invertebrates.
The overall abundance of fish, abundance of predatory fish and western rock lobster (*Panulirus cygnus*) was higher inside the Kingston Sanctuary than at adjacent fished

reefs. For fish, two popular angling species and four by-catch species were more abundant inside the sanctuary, while some bycatch species showed opposite patterns.

The differences in abundance of predatory fishes and lobsters were reflected by experimental predation rates on small and medium size invertebrates. The intensity of predation on tethered sea urchins was higher in the sanctuary. However, there were no simple trends in the abundance of prey: the abundance of one species of sea urchin (*Heliocidaris erythrogramma*) was lower in the area protected from fishing, consistent with the pattern predicted if predation was a strong influence, but the abundance of a second species (*Centrostephanus tenuispinus*) was higher. There was also no evidence of trophic-cascade effects outside the protected area as a result of lower abundance of predators, with no difference in assemblages of macroalgae between the sanctuary and fished areas.

The correlation between wave energy and both algal diversity, and community structure, plus the patchy nature of macroalgal assemblages, suggests that physical disturbance may have much more pervasive and important influences on benthic communities of WA coastal reefs than do top-down effects resulting from variations in predation. Curiously, bottom-up effects (supply of nutrients) also appear to have less influence on the structure of benthic assemblages than might be predicted in what has been assumed to be a nutrient-limited coastal ecosystem. The dynamics of patches and the influence of varying nutrient availability require more detailed investigation before we can be certain of their impact on the dynamics of WA coastal ecosystems.

Data Storage and Access

As a by-product of its research, SRFME has set high standards in the archiving and documentation of data collected and has developed innovative tools for the visualisation and analysis of data and model outputs.

The SRFME field and model data have been stored in standard formats (mostly NetCDF and ASCII column-files) in a data repository that is accessible for visualisation by the software DIVE (Data Interrogation and Visualisation Environment). DIVE enables data from different sources (such as models, vessels, moorings and diving), to be overlaid and compared in up to 4 dimensions. The DIVE software has been supplied to State Agencies to give them direct access to the SRFME data set.

DIVE is supplemented by other software tools developed during SRFME. WebOLIVE is a web-based visualisation program for regularly gridded data such as model output and climatology. WebOLIVE is installed on the SRFME website. Aus-Connie (The Australian Connectivity Interface, *http://www.per.marine.csiro.au/aus-connie*) allows users to investigate large-scale patterns of spatial connectivity around Australia. It provides estimates of the probability that any two regions are connected by ocean circulation. Meanwhile, the Argo website (*http://www.per.marine.csiro.au/argo*) provides an interactive data explorer to display tracks and vertical profiles from over 100 Argo vertical profiling floats which have been deployed in the Indian and Southern Oceans.

SRFME also constructed high-resolution climatology for temperature, salinity, nitrate, phosphate, oxygen and silicate off the Western Australian coast. The SRFME-CSIRO Atlas for Regional Seas (CARS) covers the domain 110E-130E, 40S-10S at one-eighth-degree resolution, with data at 56 standard depths. SRFME CARS is available at *http://www.per.marine.csiro.au/SRFME-modelling/olive_atlas.html*

Conclusion

While SRFME has made very significant advances in our understanding of many aspects of Western Australian marine ecosystems, much remains to be done. The area is known for its unique oceanography, productive benthic ecosystems and as a biodiversity “hotspot” worthy of significant conservation measures. However, the area is also one that creates great wealth for Australia through the exploitation of its natural resources and, increasingly, nature-based tourism. Achieving the right balance of these activities and ensuring their sustainability is a major challenge, particularly as the population of Western Australia's coastal regions is growing rapidly. As the coastal population grows, so too will pressures on the coastal region. The range of often competing uses and cumulative impacts has the potential to degrade Western Australia's unique marine environment, if the coasts are not managed with care.

Continued high-quality strategic research like that conducted over the five years of SRFME can ensure that decision-making in the marine environment is based on continually improving knowledge of these marine systems. Thus, while this report closes a successful chapter in marine science in Western Australia, the need for strategic marine science remains as great today as when SRFME began. The chapters in this report outline where SRFME has advanced our knowledge of Western Australian marine ecosystems. In addition, the chapters set out a path for future strategic research to further understanding of these systems. In many cases, the new research needs to test hypotheses that have arisen in SRFME. It should also target our need to describe key processes in the marine environment, to enable us to better predict the response to future anthropogenic change.