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Executive Summary

One of the purposes Marine Protected Areas (MPAs) were declared in Victoria was to protect biodiversity and ecological processes. While it is self-evident that an MPA depends upon the ecological processes occurring within it, the case can be made that ecological processes operating outside an MPA may also be critical to maintaining biodiversity and ecological processes within the MPA’s boundaries.

The Victorian Environmental Assessment Council (VEAC) is required to carry out an investigation into the outcomes of the establishment of Victoria’s existing marine protected areas. VEAC will assess how Victoria’s marine protected areas have performed and how effectively they are being managed, in relation to the purposes for which they were established.

The overall objective of the project presented here is to provide an overview of existing scientific understanding of the scales at which the ecological processes most critical to the biodiversity within Victoria’s IMCRA bioregions and, nested within these regions, within Victoria’s existing marine protected areas (MPAs) operate.

This report presents a summary of the ecological processes thought to be critical to biodiversity in Victorian marine waters, including MPAs. Eight case studies were developed to demonstrate the spatial and temporal scales over which some of the processes operate.

The case studies are:

- Primary production driven by upwelling in Western Victoria
- Recruitment of gastropods on rocky shores, and King George whiting in Port Phillip Bay
- Trophic cascades and other feeding effects- environmental drivers of preferred food for larval snapper in Port Phillip Bay
- Competition and other interspecific interactions between spiny urchin and abalone
- Decomposition and nutrient cycling- denitrification in central Port Phillip Bay
- Bioaccumulation of toxicants in seals
- Invasiveness of Undaria in Victorian waters.

The case studies all describe ecological processes operating at a range of scales mostly or entirely outside MPAs, but with the potential to affect ecosystems within MPAs.

Protection of such processes just within the MPAs would be an ineffective way of maintaining biodiversity across the Victorian marine community. Similarly, protecting one key process may also be ineffective. Recruitment of King George whiting (one of the case studies) depends both on successful spawning in South Australia, and on the presence of suitable habitat for post-larvae in Port Phillip Bay. Efforts to maintain preferred King George whiting habitat (e.g. seagrasses in Port Phillip Bay) will be of little value if spawning in South Australia fails.

Our ability to “manage” the ecological processes described here is limited. Large-scale oceanographic processes such as the Bonney upwelling, and King George whiting transport from SA, are beyond any practical management. On the other hand, while it is still too early to tell if Undaria has been successfully controlled in Apollo Bay, there is some prospect of limiting its impact along the Victorian coast. But a high level of vigilance will be required, since the likely vector for spread (coastal commercial and recreational vessels) is expected to increase in the future. Climate change is also likely to impact most of the processes described here, and the management of climate change impacts, if achievable, will almost certainly be focussed outside MPAs.

Even if some parts of the ecological processes described here occur on scales beyond management, other parts may be manageable. In the example already given, while it is not possible to alter the large-scale oceanic current that transports whiting larvae, Victoria may be able to manage its seagrass beds to improve the chance of successful recruitment of King George whiting. In addition, it may be possible for Victoria to encourage South Australia to do what it can to protect spawning stocks.

For these and other reasons, it is important that processes critical to biodiversity are monitored so that we are able to consider the implications of wider effects that may occur in the future.
Introduction

The coastal and marine environments of Victoria include bays, inlets and estuaries, Bass Strait and the open ocean. Victoria is responsible for about 10,600 km$^2$ of marine waters, including those from the coast to the three nautical mile limit (about 7,000 km$^2$), and a further 3,600 km$^2$ in the coastal bays (Port Phillip, Western Port and Corner Inlet). These waters contain many species of marine flora and fauna found only in southern or south-eastern Australia. The increasing movement of people toward coastal areas inevitably increases pressure on natural resources near the coast. The Environment Conservation Council carried out an investigation of Victoria’s marine, coastal and estuarine areas (ECC 2000), the purpose of which was to make recommendations on the protection of significant environmental values and the sustainable use of the areas. This investigation led to the development of a system of Marine Protected Areas (MPAs). This system included 13 new marine national parks and 11 marine sanctuaries established under the National Parks Act 1975, in addition to six existing marine parks, marine reserves or marine and coastal park areas. The primary objective of the MPAs is to protect biodiversity and to preserve representative examples of natural ecosystems. This system covers nearly 12% of Victoria’s coastal waters (5.3% no-take and 6.4% multiple-use). The system has been in place since 2002, but there has been no formal assessment of whether the MPAs are meeting the purposes for which they were intended.

The Minister for Environment and Climate Change has requested the Victorian Environmental Assessment Council (VEAC) to carry out an investigation into the outcomes of the establishment of Victoria’s existing marine protected areas.

The investigation requires VEAC, an independent council, to assess how Victoria’s marine protected areas have performed and how effectively they are being managed, in relation to the purposes for which they were established – particularly the ecological purposes. VEAC will also identify and assess the threats and challenges the areas may face in the future.

The terms of reference for the investigation are:

Pursuant to section 15 of the Victorian Environmental Assessment Council Act 2001, the Minister for Environment and Climate Change requests the Council to carry out an investigation into the outcomes of the establishment of Victoria’s existing marine protected areas.

The purpose of the marine investigation is to examine and provide assessment of:

(a) the performance and management of existing marine protected areas in meeting the purposes for which they were established, particularly the protection of the natural environment, indigenous flora and fauna and other natural and historic values; and

(b) any ongoing threats or challenges to the effective management of existing marine protected areas, particularly in relation to the biodiversity and ecological outcomes.

In addition to the considerations in section 18 of the Victorian Environmental Assessment Council Act 2001, the Council must take into account the following matters:

(i) all relevant State Government policies and strategies, Ministerial statements and reports by the Victorian Auditor-General;

(ii) all relevant national and international agreements, policies and strategies, including ecosystem-based management approaches; and

(iii) relevant regional programs, strategies and plans.

Three public submission periods are to be held and a discussion paper and a draft proposals paper are to be prepared. The Council must report on the completed investigation by February 2014.

The project reported here will inform VEAC’s assessment for components (a) and (b) of the investigation.
Objectives

The overall objective of this project is to provide an overview of existing scientific understanding of the scales at which the ecological processes most critical to the biodiversity within Victoria’s IMCRA bioregions and, nested within these regions, within Victoria’s existing marine protected areas1 (MPAs) operate.

Its more specific objectives are to:

1. Document, based on current scientific understanding and the judgement of relevant scientific experts:
   
   (i) the ecological processes that are most critical to the biodiversity within each of Victoria’s marine bioregions2;
   
   (ii) the ecological processes most critical to the biodiversity of the existing MPAs (individual or consolidated into sub-groups relevant to this purpose) within each of these bioregions. This includes those ecological processes that operate both within and beyond the MPA boundaries that are critical to MPA biodiversity; and
   
   (iii) the spatial and temporal scales at which these ecological processes operate.

2. Document, on a consistent and agreed template, at least six Victorian case studies describing in more detail, and for a general audience, some well understood examples of critical ecological processes and their spatial scales3.

Purpose of this report

This report presents:

- A summary of the ecological processes thought to be critical to biodiversity in Victorian marine waters, including MPAs
- Case studies of the spatial and temporal scales over which the processes operate.

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1 For the purposes of this project, marine protected areas means the marine component (below high water mark) of the 13 marine national parks, 11 marine sanctuaries, and 6 marine parks, marine reserves or marine and coastal parks established under sections seven, eight and four respectively of the National Parks Act 1975.

2 For the purposes of this project, ‘bioregions’ means the IMCRA bioregions that occur within Victoria’s state marine waters with Port Phillip and Western Port considered separately.

3 The subjects of these case studies should if possible be specifically relevant to the biodiversity of at least one (and ideally more) of the existing MPAs.
Materials and Methods

The ecological processes that are most critical to biodiversity within each of Victoria’s marine bioregions were informed by the collective judgement of key relevant scientific experts through collaborative discussion and review of published information. This drew on, and built on, the workshops that were held to develop the DSE state-wide marine environmental asset map, which describes the locations most important for biodiversity and ecological processes in the multiple use marine waters (i.e. outside the existing MPAs) in each marine bioregion.

The critical ecological processes range, for example, from the nutrient dynamics associated with major upwellings (lifting of cold, nutrient-rich deep waters to the surface) through to the dispersal and recruitment dynamics of an ecologically important species within a particular MPA habitat. Decisions about whether the existing MPAs should be considered individually or consolidated into relevant sub-groups, for the purpose of developing this overview were informed by initial indications about the identity and scale of the relevant ecological processes. These decisions were made in consultation with VEAC.

The case studies were prepared in part by sub-contracting the input of scientists involved in the relevant studies. Candidate case studies were identified by assessing the outputs of the above workshops, associated literature reviews and/or canvassing for advice across the Victorian marine science community.
Results

Review of Marine Assets Map

An ecosystem is a community of living organisms (plants and animals) interacting with the nonliving components of their environment (e.g. water, energy, nutrients). Ecosystems are dynamic, and may respond to disturbance by stabilising about their current state, or by changing to a significantly different ecosystem or state. For example, an intertidal seagrass bed subject to an increase in tidal height may adjust by shifting landward on a muddy or sandy shore. In contrast, a similar tidal increase may lead to the loss of the seagrass bed where a physical barrier (e.g. a rock wall or cliff) prevents shoreward migration. As another example, a modest addition of nutrients to a nutrient-poor system may lead to a modest increase in plant production which is fully consumed in the aquatic food web, whereas a larger nutrient input may lead to explosive plant growth, toxic algal blooms, stagnation, fish kills and other undesirable changes.

Ecosystem stability is thought to increase with increasing biodiversity (Schulze et al. 2005). Biodiversity describes the amount of variation in life forms within an ecosystem. Some Victorian marine ecosystems (including examples of infauna, seaweeds, hydroids, bryozoans and sponges) are highly diverse by national and international standards (Edmunds et al. 2010). Victoria’s marine protected areas (MPAs) are intended to maintain key examples of this biodiversity. The surrounding marine waters are clearly also home to significant biodiversity and ecological processes. Maintaining the key ecological processes that occur in these waters is central to achieving the goal of ecologically sustainable use. Depending on their scale, maintaining these key ecological processes may also be important to achieving the biodiversity goals of the no-take MPAs.

The biodiversity of Victoria’s wider marine environment, beyond the no-take MPAs, and the important ecological functions or processes that take place within this area, are demonstrated by the large number of significant marine environmental assets that have been identified outside the MPA boundaries by Victorian marine scientists, working with natural resource managers. Assets, in this sense, are tangible biophysical elements of the environment that are valuable for the ecosystem services they provide. For example, the seagrass asset in Port Phillip Bay is valuable for its role in nurturing fish stocks. Understanding the assets provides a tool for prioritising the state’s investment in natural resource management.

Workshops of marine scientists held in 2011-2012 identified 122 significant marine assets in Victorian waters (Appendix 1, Maps 1-6). The assets were scored for their relative environmental significance (statewide, bioregional, or local) with respect to criteria relating to biodiversity and ecological function. The workshops identified 51 assets of statewide significance, and 71 assets of local or bioregional significance. Twenty-two of the assets fell within or overlapped MPAs.

Victoria’s marine environment has been divided into five bioregions under a national categorisation scheme, based on biological and physical attributes. The bioregions have differing ecosystems and biodiversity, which reflect the operation of physical processes over hundreds of kilometres (Barton et al. 2012a). The bioregions are Otway, Central Victorian, Victorian Embayments, Flinders and Twofold Shelf (Table 1).

Victorian MPAs lie within the five bioregions. Four lie within the Otway, seven within the Central Victorian, seven within the Victorian Embayments, two within the Flinders, and four within the Twofold Shelf bioregion.

Thirty-four of the significant marine assets lie within the Otway, 22 in the Central Victorian, 43 in the Victorian Embayments, six in the Flinders and 17 in the Twofold Shelf bioregion.

4 The National Strategy for Ecologically Sustainable Development defines ESD as ‘using, conserving and enhancing the community’s resources so that ecological processes, on which life depends, are maintained and the total quality of life, now and in the future, can be increased’.
5 See http://services.land.vic.gov.au/SpatialDatamart/dataSearchViewMetadata.html?anzlicId=ANZV10803004772&extractionProviderId=1
6 The criteria used to identify marine assets in Victorian state waters are comparable to those used by the Australian Government to identify “Key Ecological Features” as part of its marine bioregional planning process.
Further discussion of bioregions and MPAs occurs in Morris and Bathgate (2012).

Existing understanding of the ecological characteristics of the significant marine assets and the ecosystems they support will be compiled over time in other projects commissioned by VEAC. However, two features, the Boney upwelling and the Port Phillip Bay sediment basin, were identified during the workshops as major assets of exceptional importance for maintaining ecosystem function within a particular region of Victoria, and they are included in the case studies presented here.

In conclusion, ecosystems with high biodiversity are resilient to disturbance. The biodiversity of Victoria’s wider marine environment and the important ecological processes that take place in Victorian marine waters are demonstrated by the large number of significant marine environmental assets that have been identified outside MPA boundaries. Depending on their scale, maintaining the key ecological processes that support these assets may be important to achieving the biodiversity goals of the no-take MPAs.

Table 1. Locations of Victorian bioregions

<table>
<thead>
<tr>
<th>Bioregion</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otway</td>
<td>SA border to Cape Otway</td>
</tr>
<tr>
<td>Central Victorian</td>
<td>Cape Otway to Cape Liptrap</td>
</tr>
<tr>
<td>Victorian Embayments</td>
<td>Port Phillip Bay, Western Port and Corner Inlet</td>
</tr>
<tr>
<td>Flinders</td>
<td>Cape Liptrap to Port Albert</td>
</tr>
<tr>
<td>Twofold Shelf</td>
<td>Port Albert to NSW border</td>
</tr>
</tbody>
</table>

Review of key ecological processes

Ecologists study the interactions between organisms and the environment in which they live (collectively termed an ecosystem). Ecosystems are sustained by physical, chemical and biological processes. Collectively, these processes use energy to generate organic matter by photosynthesis, transfer carbon and nutrients through food webs and through decomposition and enable the reproduction of organisms (USEPA 2008). The existence and continued functioning of each of the ecological assets described above depends on the interaction of a range of ecological processes. In general, a diverse ecosystem relies on the interaction of a network of ecological processes, rather than any single process. Ecological processes operate in Victorian marine waters on scales from millimetres to hundreds of kilometres, and may operate continually, or on tidal, seasonal, decadal or event-driven time scales. They can be grouped into four fundamental ecological processes: the water cycle, nutrient cycling, energy flow and community dynamics, i.e. how the composition and structure of an ecosystem changes following a disturbance (succession).

Physical drivers of ecosystem processes include:
- Those based on water movement (e.g. larval transport, catchment runoff, dispersion of pollutants, upwelling)
- Temperature changes
- Changes in water depth (tidal, storm surge, longer term)
- Meteorological processes affecting all the above
- Underwater light climate.

Chemical drivers of ecosystem processes include:
- Photosynthesis
- Acidification
- Nutrient uptake
Bioaccumulation of toxicants.

Biological processes include:

- Plant growth
- Cycling of organic matter (microbial decomposition)
- Competition/predation.

Edmunds et al. (2010) identified 23 ecosystem processes that they believed were critical to the Victorian coastal environment (Table 2). Some of these processes overlap (e.g. “all biological processes”), others are more complex than listed (e.g. benthic nutrient cycling is influenced by physical, chemical and biological factors), and some may not necessarily apply in or be relevant to MPAs. Fairweather (2012) listed seven processes as important to MPAs (which could be viewed as a super-set of Edmunds et al. 2010):

- Primary production
- Recruitment
- Trophic cascades and other feeding effects
- Competition and other interspecific interactions
- Decomposition and nutrient cycling
- Bioaccumulation
- Invasiveness.

Eight case studies are described here to illustrate these ecological processes. Though the examples as presented are area-specific, some apply more widely to most if not all of the bioregions. They illustrate all of the processes identified by Fairweather (2012) and many of those identified by Edmunds et al. (2010) (Table 2). The case studies include:

- Primary production as a result of upwelling in Western Victoria
- Recruitment of gastropods on rocky shores, and King George whiting in Port Phillip Bay
- Trophic cascades and other feeding effects - environmental drivers of preferred food for larval snapper in Port Phillip Bay
- Competition and other interspecific interactions between spiny urchin and abalone
- Decomposition and nutrient cycling - denitrification in central Port Phillip Bay
- Bioaccumulation of toxicants in seals
- Invasiveness of Undaria in Victorian waters.

A summary of the IMCRA bioregions, MPAs and Victorian marine assets potentially influenced by each of the test case ecological processes is listed in Table 3.
Table 2. Ecological processes critical to the Victorian coastal environment (adapted from Edmunds et al. 2010).

<table>
<thead>
<tr>
<th>Ecological process</th>
<th>Type of process</th>
<th>Victorian examples (those presented here shown in bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwater light climate</td>
<td>Physical</td>
<td>Light limiting the extent of seagrass beds</td>
</tr>
<tr>
<td>Long-term changes in water temperature</td>
<td>Physical</td>
<td>Migration southward of NSW species</td>
</tr>
<tr>
<td>Sea level</td>
<td>Physical</td>
<td>Distribution of seagrass beds</td>
</tr>
<tr>
<td>Tides</td>
<td>Physical</td>
<td>Daily submersion of intertidal species</td>
</tr>
<tr>
<td>Storm frequency</td>
<td>Physical</td>
<td>Temporary loss of beaches by erosion (wind, waves, current)</td>
</tr>
<tr>
<td>Large-scale oceanography</td>
<td>Physical</td>
<td><strong>King George whiting recruitment; intertidal gastropod recruitment</strong> (large- and small-scale oceanography)</td>
</tr>
<tr>
<td>Localised oceanographic fronts</td>
<td>Physical</td>
<td><strong>Bonney upwelling</strong></td>
</tr>
<tr>
<td>Upwelling</td>
<td>Physical</td>
<td>Far west and far east coasts (<strong>Bonney Upwelling</strong> and Bass Canyon Upwelling)</td>
</tr>
<tr>
<td>Geomorphology</td>
<td>Physical</td>
<td>Accretion/erosion of the Sands in Port Phillip Bay</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>Physical</td>
<td>Creation of the central muddy zone in Port Phillip Bay (<strong>denitrification</strong>)</td>
</tr>
<tr>
<td>Seasonal changes in water temperature</td>
<td>Physical</td>
<td>Control on phytoplankton growth</td>
</tr>
<tr>
<td>Dissolved CO₂ concentration</td>
<td>Chemical</td>
<td>Increased concentrations may increase seagrass growth</td>
</tr>
<tr>
<td>Catchment processes</td>
<td>Chemical</td>
<td>Silicate from catchment erosion stimulates diatom growth in bays and estuaries.</td>
</tr>
<tr>
<td>Geochemistry</td>
<td>Chemical</td>
<td>Nutrient cycling (<strong>denitrification</strong>)</td>
</tr>
<tr>
<td>All biological processes</td>
<td>Biological</td>
<td><strong>Bioaccumulation of toxicants in seals</strong></td>
</tr>
<tr>
<td>Trophic interactions</td>
<td>Biological</td>
<td><strong>Snapper recruitment</strong></td>
</tr>
<tr>
<td>Benthic nutrient cycling</td>
<td>Biological</td>
<td><strong>Port Phillip Bay denitrification</strong></td>
</tr>
<tr>
<td>Primary and secondary production “hotspots”</td>
<td>Biological</td>
<td><strong>Bonney Upwelling</strong></td>
</tr>
<tr>
<td>Ecological succession</td>
<td>Biological</td>
<td>As mangroves advance seaward, they are replaced by saltmarsh on the landward side.</td>
</tr>
<tr>
<td>Biogenic habitat</td>
<td>Biological</td>
<td>Saltmarshes provide habitat for rare birds</td>
</tr>
<tr>
<td>Competitive interactions</td>
<td>Biological</td>
<td><strong>Spiny urchin and abalone</strong></td>
</tr>
<tr>
<td>Community composition</td>
<td>Biological</td>
<td>Algal blooms in the Gippsland Lakes</td>
</tr>
<tr>
<td>Primary production</td>
<td>Biological</td>
<td><strong>Bonney upwelling</strong></td>
</tr>
</tbody>
</table>
Table 3. Summary of the IMCRA bioregions, MPAs and marine assets currently potentially affected by the case study ecological processes.

<table>
<thead>
<tr>
<th>Ecological process</th>
<th>IMCRA bioregion</th>
<th>MPAs potentially affected</th>
<th>Marine asset nos. currently affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upwelling/primary production</td>
<td>Otway; Twofold</td>
<td>Discovery Bay, Merri, The Arches, Marengo, 12 Apostles; Beware Reefs, Cape Howe, Point Hicks</td>
<td>1-34; 128-138</td>
</tr>
<tr>
<td>Recruitment of gastropods</td>
<td>Embayments; Central</td>
<td>Eagle Rocks, Marengo Reefs, Point Danger, Barwon Bluff, Port Phillip Heads, Point Cooke, Jawbone, Ricketts Point, Wilsons Promontory</td>
<td>1, 3, 5-8, 12, 17, 20, 25, 26, 34, 37, 47, 49, 65...</td>
</tr>
<tr>
<td>Recruitment of King George whiting</td>
<td>Embayments</td>
<td>Port Phillip Heads, Yaringa, French island, Churchill Island, Corner Inlet, Nooramunga, Shallow Inlet</td>
<td>49, 53, 55-61, 64</td>
</tr>
<tr>
<td>Feeding effects -snapper</td>
<td>Embayments, Central, Otway</td>
<td>Port Phillip Heads, Point Cooke, Jawbone, Ricketts Point</td>
<td>56, 58, 62-69</td>
</tr>
<tr>
<td>Competition-urchin</td>
<td>Twofold</td>
<td>Beware Reefs, Cape Howe, Point Hicks</td>
<td>126-138</td>
</tr>
<tr>
<td>Decomposition-nutrient cycling</td>
<td>Embayments</td>
<td>Port Phillip Heads, Point Cooke, Jawbone, Ricketts Point</td>
<td>49-73</td>
</tr>
<tr>
<td>Bioaccumulation</td>
<td>Otway</td>
<td>Discovery Bay, Merri, The Arches, Marengo Reefs, 12 Apostles</td>
<td>10, 32, 36</td>
</tr>
<tr>
<td>Invasiveness</td>
<td>Embayments, Central</td>
<td>Port Phillip Heads, Point Cooke, Jawbone, Ricketts Point</td>
<td>45-50, 55-73</td>
</tr>
</tbody>
</table>

*Marine assets are shown in maps 1-6, appendix 1*
Case Study 1: Primary production: Bonney upwelling

Easterly winds in November to March lift nutrient-rich deep water to the surface on the far west coast of Victoria. The nutrients initiate a food web that supports a wide range of species, including penguins, squid and blue whales. The increased productivity affects a wide area of the otherwise nutrient-poor Bass Strait, from South Australia to Cape Otway, including Discovery Bay and The Arches MPAs.

What is the ecological process?
Primary production driven by upwelling. Upwelling is the transport of nutrient-rich water from the deep to the surface, where light and nutrients combine to increase primary production. Primary production is the growth of plants. These may be:

- microscopic drifting plants (phytoplankton)
- large seaweeds (macroalgae) that attach to rocks and other hard substrates
- seagrass that lives in shallow marine waters
- epiphytes (plants growing on other plants).

The plants use sunlight, carbon dioxide, nutrients and water to build sugar, starch and cellulose (carbohydrates). The plants then become food for animals.

Primary production is important because it is the basis of most food webs in the ocean. Areas with high primary production can support more plant and animal life than areas of low production.

Where does it operate (spatial and temporal scales)?
Upwelling operates on the western coast, west of Portland, and on the eastern coast east of Lakes Entrance. In this case study, the effects of upwelling are experienced west of Cape Otway. Upwelling is greatest in summer, and primary production peaks in late summer-autumn, but the effects of upwelling-enhanced summer primary production are most likely experienced at higher trophic levels (e.g. seabirds, seals and whales) throughout the year.

What MPAs does it affect?
The Bonney upwelling described here affects MPAs west of Cape Otway (Discovery Bay and The Arches).

What influences the process?

**Wind:** Primary production is influenced by a range of physical, chemical and biological factors, key of which is the supply of nutrients. Upwelling provides the nutrients, and upwelling is driven by winds, ocean currents and topography.

Victorian surface waters, including Bass Strait, are considered to be nutrient-poor (Gibbs et al. 1986; Nieblas et al. 2009), with some exceptions. This case study is one of those exceptions.

In summer a belt of high air pressure (the sub-tropical ridge) lies south of the Australian mainland and directs a series of weather systems eastward to the south of Victoria. Because the winds in high pressure systems rotate anti-clockwise, they generate a south-easterly wind along the western Victorian coast.

On the southern coast of Australia, wind blowing to the west along the coast drives surface water offshore at right angles to the wind direction. Since there is land to the right of the wind, replacement water can only come from depth. Deeper waters on the Australian continental shelf off the Bonney coast are generally nutrient-rich in summer (Nieblas et al. 2009). In winter, the sub-tropical ridge moves northward over the continent, and the wind on the western Victorian coast becomes predominantly westerly.

The interaction of persistent easterly winds and coastal topography result in upwelling on the Bonney coast (Figs 1-2), which brings cold (11-12 °C), nutrient-rich water to the surface in the period November-March.

Over the period 1998-2006, 48% of winds in November-April were in a direction favouring upwelling, compared to 17% in the rest of the year (Nieblas et al. 2009). On average about 10 upwelling events were observed each year between November and April, which lasted an average of nine days each. The area directly affected by upwelling (as indicated by anomalously low surface water temperature) peaked at 5,000 to 14,000 km² and averaged 3,000 km² over the upwelling period (Nieblas et al. 2009).

**Currents and topography:** In addition to wind direction, upwelling is also affected by currents and topography. There are two main currents affecting this area- Leeuwin and Flinders-which vary seasonally in strength and direction. The Leeuwin current originates in Western Australia, and moves across the Great Australian Bight, becoming weaker in summer. The Flinders current flows north to the west of Tasmania, turning west at the continental shelf break. The
Flinders current is stronger in summer, and may enhance upwelling by lifting cold water closer to the surface on the continental shelf (Nieblas et al. 2009).

**Responses to upwelling:** The biological response to upwelling-favourable wind events depends on the timing, persistence, direction, and strength of the wind. It also depends on environmental conditions such as light levels, turbulence in the water column and water temperature.

The injection of nutrients into surface waters, particularly in summer when light and temperature are high, accelerates primary and secondary productivity which supports the higher trophic levels and fisheries productivity. Some of the world’s largest fisheries depend on upwelling (e.g. the anchovy fishery off Chile; Escribano et al. 2004).

**Primary production:** Periods of upwelling-favourable winds on the Bonney coast are usually followed by calm periods long enough (5-10 days) to promote plankton growth (Nieblas et al. 2009). The upwelling leads to an increase in phytoplankton abundance, clearly visible in satellite images (ref). Primary production peaks in February–March about three months after the onset of upwelling (Nieblas et al. 2009).

**Secondary production:** Abundant phytoplankton leads to swarms of krill, a crustacean which is food for many species, including Blue Whales. Coastal krill (*Nyctiphanes australis*) is the principal species of euphausiids in southeast Australian and New Zealand shelf waters, including the Bonney upwelling area. It is observed in surface swarms, related to the upwelling event on the Bonney Coast (Butler et al. 2002).

**Higher production:** Gill (2002) recorded 261 Blue Whale sightings from a range of sources in the Bonney Upwelling between 1998 and 2001. Whales were observed between December and May, associated with surface swarms of coastal krill in 48% of sightings, and feeding on krill in 36% of sightings (Gill 2002).

*N. australis* is also a vital part of the trophic system for a range of fish and seabird species, including jack mackerel, tiger flathead and short-tailed shearwater (Johannes and Young 1999).

Impacts of the upwelling on rock lobster (Linnane et al. 2008) include reduced growth rate because of reduced temperature. In Discovery Bay, CPUE decreases as upwelling increases. The marine park at this location would clearly be impacted by this process.

The high productivity of the Bonney Upwelling also favours predators such as little penguins (Collins et al. 1999) and Australian fur seals (Phillip Island Research Centre 2002) feeding on baitfish. It also favours New Zealand fur seals feeding on arrow squid (Bayliss et al. 2008). The Bonney Coast is a highly productive region for arrow squid (Jackson et al. 2005), but annual abundance fluctuates greatly from year to year.

A simple regression model using wind speed in the previous August and November reliably predicts trawl CPUE – an indicator of squid abundance (Coutin 2008). August is the peak hatching period and November marks the beginning of the upwelling season. The ecological processes underlying this relationship are poorly understood. They may be related to food availability, dispersal of larvae, or the size of larvae.

In assessing conservation values in Commonwealth waters, Butler et al. (2002) considered that the upwelling event is the pivotal conservation value of the Bonney coast. The upwelling is also likely to be a key influence in near-shore coastal areas, including the MPAs on the Victorian coast west of Cape Otway.

**Future climate:** Nieblas et al. (2009) found a linear relationship between wind stress and primary productivity. Predictions of wind changes that may arise from climate change indicate the likelihood of stronger and more frequent SE wind leading to increased upwelling and greater marine productivity on the Bonney coast. During years of El Niño, there is also likely to be more intensive upwelling of cold nutrient rich waters in summer (Middleton et al. 2007).
Figure 1. Areas of upwelling on the southern Australian coast as identified by sea surface temperature. The Bonney upwelling appears as a dark blue (colder) area off the west Victorian coast. Image from Butler et al. (2002).

Figure 2. A simplified view of the upwelling process in western Victoria.
Case Study 2: Recruitment (1- Intertidal gastropods)

Water movement (currents) and coastal structure (headlands, bays) affect the dispersal and recruitment of intertidal and shallow subtidal gastropods to rocky reefs. The spatial scale of recruitment varies between species and location, from a few metres for abalone to tens of kilometres for long-lived larvae. Recruitment from outside an MPA may be crucial for replenishment of gastropods within the MPA. Recruitment peaks in the warmer months for many species. Many MPAs are affected, including all of those with rocky reefs.

What is the ecological process?

Larval dispersal and recruitment of gastropods (marine snails and limpets) inhabiting intertidal and shallow subtidal reefs. Many intertidal gastropods produce planktonic larvae, and larval dispersal is a critical mechanism connecting populations. Recruitment involves the settlement and survival of larvae onto the reef/adult habitat and is an equally important process in sustaining populations.

Where does it operate (spatial and temporal scales)?

On and amongst all intertidal reefs where gastropods are present – particularly along the open coast and in Port Phillip Bay and Western Port where areas of reef are more extensive. Intertidal reefs are absent from Ninety-Mile Beach on the east coast but there is evidence that populations of some gastropod species are connected across this dispersal barrier (Hidas et al. 2007, Ayre et al. 2009). Dispersal potential varies according to species biology, and is influenced by hydrodynamics and coastal topography.

What MPAs does it affect?

All Victorian MPAs that contain intertidal and shallow subtidal reefs on the open coast and embayments (see Barton et al. 2012a-e). These include Marine National Parks and marine Sanctuaries.

The extent to which populations inside MPAs are self-recruiting or acting as larval sources or sinks will affect the extent to which their ecological performance is dependent on conditions beyond their boundaries ie: occurring in the surrounding marine environment. It will also affect the extent to which MPAs affect the abundance, dynamics and conservation of species beyond their boundaries, although this was not the aim of establishing Victoria’s MPAs. Studies have shown that where MPAs enhance the number and size of animals within their boundaries, this can - have flow on effects and can significantly increase the abundance of gastropod recruits on nearby unprotected reefs (Branch and Odendaal 2003).

Protection and conservation of ecological processes such as recruitment was one of the objectives in establishing Victorian MPAs. Recruitment of common intertidal reef gastropods in MPA and non-MPA sites has been investigated outside the Heads and in Port Phillip Bay to determine the effect of protection on recruitment in two regions with different hydrodynamic conditions (Bathgate 2010). In this same study, reproductive output of spawning gastropods was also investigated, because larval supply can be an important determinant of recruitment success and population replenishment.

Coupled hydrodynamic and particle dispersal models have been used to identify the destination of larvae of Cellana tramoserica (the variegated limpet) originating from MPAs in the Central Victoria Bioregion and Port Phillip Bay (from Eagle Rock Marine Sanctuary, eastwards to Point Nepean (Port Phillip Heads Marine National Park) as well as from marine sanctuaries in Port Phillip Bay). This approach shows whether existing MPAs are acting as sources of larvae for other reefs (Bathgate 2010). Keough and Quinn (unpublished) have undertaken a long-term investigation 1988-1997) of gastropod recruitment on intertidal reefs in and adjacent to the Point Nepean MPA in order to examine long-term effects of protection on intertidal gastropod populations – including size and abundance of adults, and number of recruits. More recent field surveys by the same researchers have added to the long-term data set.

What influences the process?

Larval dispersal:

- Species biology – larval duration and behaviour
- Hydrodynamics – e.g. currents, eddies and fronts, waves
- Coastal topography – e.g. headlands, inlets, beaches
- Physical factors influencing timing of reproduction and larval development, e.g. temperature, salinity, pH

Recruitment:

- Larval supply –density, abundance and size of adults in the source population, larval mortality in the plankton
- Availability of suitable settlement habitat
- Post-settlement mortality, e.g. from dessication, predation etc.
Larval dispersal: Gastropod larvae of species occurring in Victorian MPAs have a wide range of dispersal potentials ranging from centimetres to hundreds of kilometres. *Dicathais orbita*, *Lepsiella vinosa* and *Cominella lineolata* all lay egg masses from which well-developed juveniles emerge and these remain on or near the maternal reef. Broadcast spawning limpets (e.g. *Cellana tramoserica*) periwinkles (*Austrocochlea* spp.) and turban shells (*Turbo* spp.) have restricted dispersal as they have a short non-feeding larval phase (lecithotrophic larvae) with most larvae settling within metres to kilometres of spawning sites. *Bembicium nanum* and *Nerita atramentosa* lay egg masses from which long-term planktotrophic (feeding) larvae hatch and these spend weeks (*B. nanum*) to months (*N. atramentosa*) in the water column before recruiting back to reef habitat.

Although small, gastropod larvae are able to exert some behavioural control over their position in the water column, thereby reducing the likelihood of being transported away from the natal reef. Larvae of abalone *Haliotis rubra* are negatively buoyant and sink to the bottom soon after fertilisation to shelter in crevices and depressions where currents are slower and chances of being swept away are minimised (Prince et al. 1987, McShane et al. 1988). Sub-populations of *H. rubra* on individual reefs in southern Australia have been found to be largely self-seeding with larvae recruiting within 50 m of their parents (McShane et al. 1988).

Recruitment: The timing of larval production and recruitment is species-specific and can vary between sites, however many Victorian gastropods are thought to have a peak in recruitment over the warmer months (Underwood 1974, Parry 1977, Quinn 1988, Przeslawski and Davis 2007). Larval duration influences not only the distance larvae are transported but also the relationship between adult-recruit densities and the timing of recruitment. For example, long-term monitoring by Keough and Quinn (unpublished) at Point Nepean (Port Phillip Heads MNP) shows there is a strong correlation between the number of *C. tramoserica* adults and recruits (Bathgate 2010). Local production is tightly linked to local recruitment in this species which has a short larval duration. *C. tramoserica* has a brief spawning period over summer with recruitment occurring over the same period (Parry 1977).

In contrast *B. nanum* spawns over several months and larvae develop in egg capsules for two weeks before spending several weeks in the plankton (Underwood 1974, Przeslawski 2008). Long-term recruitment monitoring at Point Nepean showed no correlation between the number of adults and recruit abundance for *B. nanum*.

Larvae that spend more time in the water column are more likely to be transported away from their reef of origin, decoupling the stock-recruitment relationship (Keough and Quinn unpublished, Bathgate 2010). It should be noted that the relationship between the number of adults and recruitment is not always straightforward, as existing adults can have an inhibitory effect on the number of larvae recruiting – either through occupation of suitable habitat (i.e. leaving no space for new recruits), competition for food and refuges, or by bulldozing newly settled individuals (Underwood et al. 1983, Connell 1985, Raimondi 1990).

Long-term monitoring over nine years at Point Nepean showed significant spatial and temporal variation in recruit abundances but no difference in recruitment between MPA and non-MPA sites (Keough and Quinn unpublished, Bathgate 2010). Short-term monitoring of these plus additional mollusc species in MPA sites at the Heads and in Port Phillip Bay showed that recruitment was greater on the open coast. This is likely a consequence of increased intertidal wave action (Black et al. 1993, Jenkins and Black 1994, Bathgate 2010). Larval transport, and thus population connectivity, is strongly influenced by oceano graphical features such as currents and eddies, and by shoreline configuration (Archambault and Bouget 1999).

Currents: Larval dispersal distances are greater from MPAs on the open coast. The Central Victorian bioregion has a relatively high energy coastline where stronger coastal currents of (10s of cm s$^{-1}$) operate, compared to Port Phillip Bay where weak wind-driven currents around marine sanctuaries are typically 0.05 to 0.1 m s$^{-1}$ and there is low-negligible wave action (Black et al. 1993, Jenkins and Black 1994, Bathgate 2010). Larval transport, and thus population connectivity, is strongly influenced by oceanographic features such as currents and eddies, and by shoreline configuration (Archambault and Bouget 1999).

Currents tend to accelerate as they move past rocky headlands in MPAs such as Point Addis MNP, Barwon Bluff MS and Eagle Rock MS. Currents slow in the lee of headlands, and other obstructions such as islands, often forming retentive eddies where larvae are entrained. This build-up of larvae may lead to enhanced recruitment (Harlan et al. 2002, Shanks 2005). For example, recruitment of green lip abalone, *Haliotis laevigata*, which occurs in Victorian MPAs, has been found to be greatest in places where eddies and stagnation zones would be expected to concentrate larvae (Shepherd et al. 1992).

At the same time, larvae produced on the tips of headlands are likely to be dispersed more rapidly than populations located on straight sections of the coast, thus headland populations may potentially experience greater larval loss but also serve as larval sources for more distant sites (Stephens et al. 2006). Even less prominent ‘headlands’ at sites in the bay such as Point Cooke show accelerated currents (Bathgate 2010).

On the open coast, the coastal boundary layer – a nearshore region of weak current – is an important determinant of dispersal, as short-term lecithotrophic larvae are unlikely to move beyond it to the strong along-shore flows further offshore (Larger 2003). Longer-lived planktotrophic larvae may take several days to move through this “sticky water” as...
they move offshore and back again to settle on reefs, spending only a brief period in the stronger currents that move larvae greater distances downshore (Largier 2003).

Modelling of larval dispersal for the intertidal limpet, Cellana tramoserica, from MPAs in the Central Victoria Bioregion (Figs 3-5) showed that most larvae disperse in the direction of the prevailing eastward flowing current. Larvae originating from Eagle Rock MS, Point Addis MNP and Barwon Bluff MS disperse several kilometres and are sources of recruits for intertidal reefs downstream – ensuring coastal populations are well connected (Bathgate 2010). In contrast, larvae from marine sanctuaries in Port Phillip Bay showed limited dispersal and while capable of seeding neighbouring reefs, were isolated from reefs in other MPAs and those on the open coast (Bathgate 2010). Levels of gastropod recruitment were found to be greater on the open coast – a likely consequence of increased intertidal reef habitat on the coast supporting greater numbers of reproductive adults and stronger currents transporting larvae between populations (Figure 6).

C. tramoserica was chosen as a model species because it has reproductive and larval characteristics – broadcast spawning, short planktonic period of a few days - shared by other gastropods including the common periwinkle Austrocochlea spp., turban shells, Turbo spp., and abalone Haliotis rubra. For these species, existing MPAs in the bay and central coast have high levels of self-recruitment, but populations in the bay are more demographically isolated and therefore more vulnerable to extinction.

In another recent study of oceanography and larval dispersal in Victorian MPAs, Lindsay (2013) investigated oceanic influences on recruitment of barnacles and mussels in Wilsons Promontory Marine National Park. Lindsay (2013) found that a large proportion of the locally-produced larvae are likely to disperse out of the protected area with population persistence within the MPA dependent on larvae originating upstream.

Post-settlement mortality: Recruitment patterns are influenced by mortality occurring after settlement and metamorphosis (e.g. through desiccation or predation) and on numbers of larvae arriving on the reef. Whether self-recruiting or dependent on larvae from outside populations, the size, age and density of individuals within adult source populations can be a strong determinant of the numbers of recruits settling inside MPAs.

Human harvesting of gastropods on the reef platform can decrease the density and size of reproductive adults, diminishing the number of gametes produced and lowering fertilisation success (Levitan 1991, Dunmore and Schiel 2000). While rocky reef gastropods in Victorian MPAs show a wide range of reproductive modes (e.g. egg laying species with internal fertilisation or external mixing of gametes), a decline in density is most critical for species that broadcast spawn – including limpets, abalone, turban shells and periwinkles, as they depend on high gamete concentration for successful fertilisation (Hockey and Branch 1994, Shepherd and Brown 1993). Even species of gastropods with internal fertilisation such as nerites, whelks and many littorinids, require a critical density of conspecifics for successful mating and production of offspring and some will not mate or lay eggs below certain population densities (Stoner and Ray-Culp 2000, Tewfik and Béné 2003).

For MPAs that rely on outside sources or larvae for population replenishment, human compliance with, and enforcement of, regulations prohibiting shellfish collection along the entire coast may be crucial for species population persistence inside protected areas.

Other physical drivers: Temperature can have a significant influence on the timing and magnitude of gametogenesis and on animal health and condition (Giese 1959, Lloret and Planes 2003). Many species have optimal temperatures for gonad production where the rate or magnitude of gamete development is enhanced (Giese 1959, Choi et al. 1994). Reproductive output (as measured by gonad indices GI) of Cellana tramoserica and Turbo undulatus has been shown to be significantly higher in Port Phillip Bay compared to the open coast (Bathgate 2010). This is a possible result of higher average water temperatures in the bay (average 11°C in winter and 21°C in summer (Harris et al. 1996)) compared to the coast (13.5 °C in winter to 17.5 °C in summer (Plummer et al. 2003)). Wave exposure and surge height may also be factors underlying bay and coastal differences in GI as gastropods at coastal sites have to expend more energy adhering to rock to avoid dislodgment and have less time to graze, therefore having less energy to invest in growth and reproduction.

Future climate: Climate change is the focus of a separate report (Morris and Bathgate 2013), but impacts related to gastropod recruitment are summarised here. Climate change may impact both larval dispersal and recruitment through increased sea surface temperature, increased salinity, increased dissolved CO2, reduced rainfall and reduced runoff. Larval dispersal is also likely to be impacted by changes to current direction and speed while recruitment will further be impacted by increased air temperatures and rising sea levels. The spatial and temporal variability shown in recruitment in Victorian MPAs may increase (Bathgate 2010). Dispersal in Port Phillip Bay is likely to change as salinity influences bay circulation. A decline in freshwater input combined with increased evaporation will substantially elevate salinities and shift the bay from a hyposaline to hypersaline system (Lee et al. 2012). One result already observed under drought conditions is greater flushing at the bay entrance. Modelling shows that gastropod larvae originating from Point Lonsdale and Point Nepean (Port Phillip Heads Marine National Park) will be dispersed further out to sea and conversely deeper into the bay.
than under normal hyposaline conditions (Lee et al. 2012). In both instances larvae will be dispersed beyond suitable reef settlement substrate.

The likely impacts of climate change in all MPAs on recruitment and species range expansion, are further discussed in Morris and Bathgate (2013).

Figure 3. Point Cooke MS, Jawbone MS, Ricketts Point MS larval releases. Port Phillip Bay. Concentration of larvae ‘settled’ at the end of a 2-month spawning period Nov-Dec 2004. 2D dispersal model (Model POL3DD, ASR).
Figure 4. Eagle Rock MS and Point Addis larval releases. Concentration of larvae ‘settled’ at the end of a 2-month spawning period Nov-Dec 2004. 2D dispersal model (Model POL3DD, ASR).
Figure 5. Barwon Bluff MS, Point Lonsdale and Point Nepean (PPHeads MNP) larval releases. Concentration of larvae ‘settled’ at the end of a 2-month spawning period Nov-Dec 2004. 2D dispersal model (Model POL3DD, ASR).

Figure 6. The effect of variable water movement on gastropod recruitment.
Case Study 3: Recruitment (2- King George whiting)

The recruitment of King George whiting to Port Phillip Bay depends on successful spawning in South Australian waters, survival of the larvae while they drift eastward through Bass Strait for several months, and abundant seagrass beds in which to settle once the larvae are carried through the Heads. The prevailing current and westerly winds in winter enhance the transport of larvae. Spawning to recruitment takes 4-5 months, and the distance between spawning and recruitment is about 800 km. The MPAs affected include those in Port Phillip Bay and Western Port.

What is the ecological process?
Recruitment of King George whiting in Victoria, resulting from transport of larval fish from the spawning area to Victorian bays and inlets.

Where does it operate (spatial and temporal scales)?
From the SA border to Western Port (more than 800 km) from autumn through to spring (April-November).

What MPAs does it affect?
Those MPAs in which King George whiting has been observed (Barton et al. 2012a-e) include Port Phillip Heads, Bunurong, Yaringa, Churchill Island, French Island and Corner Inlet Marine National Parks, and Point Cooke, Jawbone and Ricketts Point Marine Sanctuaries. This case study focuses on Port Phillip Bay.

What influences the process?
Zonal westerly winds; ENSO; ocean currents; sea surface temperature.

Successful recruitment of King George whiting depends on three key phases:

- Successful spawning
- Factors affecting mortality during transport of larvae to Port Phillip Bay (including feeding and predation)
- Presence of suitable habitat on entering Port Phillip Bay.

King George whiting (Sillaginodes punctatus) is an important commercial and recreational fish in Victorian bays and inlets. Though the fish may live to 20 years (Fowler et al. 2011), the fishery in Victoria comprises 2-4 year old fish. The closest known spawning area for King George whiting is in South Australian waters near Kangaroo Island (Fowler et al. 2000). King George whiting eggs are buoyant, and hatch after a few days into larvae, which drift with ocean currents. Larvae are thought to drift eastward for 4-5 months before they enter Port Phillip Bay and Western Port, where they settle during September-November as post-larvae in seagrass beds (Figure 7; Jenkins et al. 2012).

They remain in these habitats until 2-4 years old, when they are thought to migrate back to South Australia to spawn. The Victorian fishery therefore depends on sub-adult fish, the number of which may depend on the success of larval transport hundreds of kilometres from South Australia.

King George whiting is one of the best-studied fish in Victoria. Jenkins and May (1994) examined recently–settled post-larvae (16-20 mm long) in Swan Bay, and determined that they were 100-170 days old. This implied spawning occurred in April-July. The spacing of daily rings in ear bones indicated growth slowed after 45-75 days. Settlement in Swan Bay occurred in pulses 7-14 days apart, which Jenkins and Black (1994) linked to the passage of weather fronts in Bass Strait that influence the net flow of water from Bass Strait into Port Phillip Bay.

Settlement habitat: In addition to larval supply, King George whiting relies on seagrass as a key component of its life cycle. In the first year, there is little evidence of migration within Port Phillip Bay. Juvenile whiting up to a year old are found in or near the shallow seagrass habitats where they first settled (e.g. in Swan Bay and the Geelong Arm), and maintenance of seagrass cover in these shallow regions is thought to be critical to successful recruitment of King George whiting in Port Phillip Bay (Jenkins et al. 2012).

Jenkins and Wheatley (1998) found King George whiting in a range of habitats in Port Phillip Bay, including seagrass, reef/algae and to a lesser extent, bare sand. They concluded that the presence of structure was important, but so was the level of food present in each area. King George whiting appeared to switch to algal/reef habitat a couple of months after initial settlement on seagrass.

This study, and a related study using artificial seagrass (Jenkins et al. 1998) concluded that variation in hydrodynamics is probably more important for whiting recruitment than variation in habitat. Recruitment at some sites in Port Phillip Bay appeared to be influenced more by post-settlement factors (e.g. wave and current disturbance) than by larval supply. Jenkins et al. (1998) hypothesised that whiting prefer seagrass because it generally contains a greater abundance and diversity of prey species, but Hindell et al. (2002) believed the seagrass provided a refuge from predation; predators on King George whiting appeared to avoid seagrass. Smith et al. (2012) found that whiting prefer the edges of shallow (<1.5 m) seagrass beds until they reach about 200 mm length, when they may be found in the centre of the beds.
Westerly winds: Because the larval stage is long (5-6 months) and the spawning area is remote from the settlement area (hundreds of kilometres), Jenkins (2005) believed climate factors could play a key role in successful recruitment. Jenkins (2005) found that catches in Port Phillip Bay and Western Port were highly correlated, implying a large-scale environmental influence on abundance. Cyclic variability in catches in Port Phillip Bay correlated with Zonal Westerly Wind (a measure of the number of days of westerly winds in a year), with a lag of five years. Catches also correlated strongly with the El Nino Southern Oscillation Index, with no lag. A time series of post-larval abundance (1993-2003) also correlated with Zonal Westerly Winds, with no lag. Strong westerly winds between spawning and settlement led to higher recruitment, and then increased catches 3-5 years later.

Other physical factors may also influence the success of larval survival during transport.

Water temperature: Examination of growth rings in earbones of post-larval fish (Jenkins and King 2006) indicated that increased water temperature near Portland in Western Victoria led an increase in larval growth, and subsequent increased recruitment of King George Whiting in Port Phillip Bay. This was reconciled with the earlier finding of stronger recruitment in years of stronger westerly winds by noting that the prevailing current (the Leeuwin Current) is a warm water current. Increased winds would most likely increase the transport of warmer water into western Bass Strait.

Effects of future climate: Sea surface temperature has been increasing in south-eastern Australia for the last 60 years, and is predicted to continue to increase. On the other hand, the Leeuwin Current has been declining since the 1970s and may continue to decline (Feng et al. 2009), and in the future strong westerly winds may not be accompanied by higher sea surface temperature. The ultimate impact of future climate variability on the survival of larval King George whiting remains unclear. The increased primary production created by the Bonney upwelling (case study 1) may affect the area through which the King George whiting larvae are transported, but the upwelling probably occurs too early in the year to assist larval growth. Since upwelling is associated with reduced temperature, the finding cited above of increased recruitment with increased water temperature also indicates little association between upwelling and successful recruitment.

Figure 7. King George whiting larval recruitment in Port Phillip Bay.
**Case Study 4: Trophic cascades and other feeding effects- snapper recruitment**

All snapper in Victoria west of Wilsons Promontory are spawned in Port Phillip Bay. Spawning occurs in November-January, and recruitment occurs 20-30 days later, but is highly variable between years. The variability is related to the availability of selected zooplankton (calanoid copepods), which is related to rainfall and the growth of a high-food-quality family of phytoplankton (diatoms). Best recruitment occurs with a moderate river flow in October (not too low and not too high). MPAs affected include all those from the South Australian border to Wilsons Promontory.

**Trophic cascades** occur when predators in a food web suppress the abundance or otherwise affect their prey, releasing the next lower trophic level from predation. The case presented here relates to feeding effects, in which physical processes determine the presence or absence of preferred food for recruitment of a fish.

While this does not directly impact on any MPA, the case shows that changes to a food web in one area may impact organisms over a much greater area (most of Victorian coastal waters west of Wilsons Promontory). Also, because they are so abundant in Port Phillip Bay, snapper almost certainly play a role in predation in a number of MPAs.

**What is the ecological process?**

Freshwater flows in spring affect zooplankton species abundance, influencing spawning and recruitment of snapper in Port Phillip Bay.

**Where does it operate (spatial and temporal scales)?**

In the north-east of Port Phillip Bay, in summer (late November-early January).

**What MPAs does it affect?**

Those MPAs in which snapper has been observed (Barton *et al.* 2012a-e) include: The Arches Marine Sanctuary, Ricketts Point Marine Sanctuary, Point Cooke Marine Sanctuary, Jawbone Marine Sanctuary, Eagle Rock Marine Sanctuary, French Island MNP, Bunurong Marine National Park and Ninety Mile Beach Marine National Park.

**What influences the process?**

River flow stimulating primary production and influencing the abundance of the dominant copepod, preferred food for snapper larvae (Figure 8).

Snapper, *Chrysophrys auratus*, is a member of a world-wide family, and is related to species in Japan, Africa and the Mediterranean. It is found throughout the southern half of Australia and in New Zealand. In Victoria, there are two stocks, one to the east, and the major one to the west of Wilsons Promontory (Hamer and Jenkins 2004). Snapper is one of the most popular recreational fish, with 90% of catches in Victorian waters from Port Phillip Bay and Western Port.

Hamer *et al.* (2003) identified natural chemical tags in the ear bones of juvenile snapper. The tags showed that almost all of the fish caught west of Wilsons Promontory spawned in Port Phillip Bay (Hamer *et al.* 2005; 2011), identifying it as an area critical for the survival of the fishery.

Fish spawn in Port Phillip Bay in late November-early January, and remain in the bay for up to two-three years, when they migrate into coastal waters. Adult fish (>4-5 years) return to the bay in October of each year to spawn, when they are heavily targeted by fishers (Hamer *et al.* 2011).

Recruitment in Port Phillip Bay varied 10-fold between 2000 and 2003 (Hamer and Jenkins 2004). Abundances of recently hatched larvae correlated with 0+ snapper abundance 3 months later, indicating recruitment variation may originate in the pre-settlement stage (Murphy *et al.* 2011).

Recruitment of some fish depends on an overlap in the spatial and temporal availability of food with the location of larvae from spawning to settlement. If the food supply is limiting, larvae may starve or grow more slowly, increasing the length of developmental phases and making them more prone to predation.

Snapper larvae are most abundant in the eastern part of Port Phillip Bay from Mordialloc to Frankston, which is thought to be the spawning area (Hamer *et al.* 2010). Hydrodynamic modelling (Hamer, unpublished) indicates this relates to the dispersion of the Yarra River plume.

Snapper larvae from years of high abundance in Port Phillip Bay fed selectively on calanoid nauplii (mostly *Paracalanus* spp.), while those from years of low abundance were generalist feeders (Murphy *et al.* 2011). Densities of calanoid nauplii varied by as much as 5-fold between years of higher and lower larval snapper abundance.

In contrast to low-abundance years, prey quality increased with larval size in high-abundance years, indicating that selective feeding allowed snapper to maximise their energy intake.

Snapper larvae are visual feeders, and fed only during the day, when they aggregated at 4 m, where the density of some (but not all) preferred prey was also most abundant (Murphy *et al.* 2011).

**River flow and preferred diet:** Snapper larval survival and juvenile recruitment strength is linked to changes in larval diet that relate to prey abundance and composition (Murphy *et al.* 2012). Recent research has indicated that snapper
recruitment in Port Phillip Bay appears to be most successful in years of moderate rainfall. Jenkins (2010) found a strong relationship (R=0.6) between Yarra River flow in October and the recruitment of 0+ snapper each year from 2000 to 2010. However, recruitment fell at higher flows observed in 2011 and 2012.

Calanoid nauplii abundance in Port Phillip Bay is reduced at both low and high river flow rates (Paul Hamer, pers. comm.). Low abundance at low flow is thought to be a reflection of low primary productivity. Low abundance at high flow rates may be a consequence of the lack of tolerance for low salinity by Paracalanus, or some other freshwater-related effect. Cervetto et al. (1999) demonstrated that Acartia tonsa, a typically estuarine zooplankton, preferred salinities well below that of full seawater.

In contrast, a zooplankton thought to be marine, such as Paracalanus, could be expected to prefer salinities close to seawater. Uriarte and Villate (2005) found that Paracalanus declined with declining salinity in Spanish estuaries because of increasing pollution, rather than from intolerance for lowered salinity. Pollutant indicators included hypoxia and turbidity.

Hypoxia is unlikely to be an issue in Port Phillip Bay (Longmore and Nicholson 2012). The Yarra plume may be turbid at high flow, but this would not be expected to extend to the snapper spawning area (EPA 2012). Unless Paracalanus breeds in the northern part of the bay, and is then carried to the snapper spawning area by the currents, it is difficult to see how pollution may impact on this species in Port Phillip Bay. However, food quality and quantity may also vary with river flow.

**Phytoplankton (food quality):** In a highly productive upwelling system off the Oregon coast, Gomez-Gutierrez and Peterson (1999) showed that phytoplankton biomass rarely fell below 2 µg chlorophyll a/L, above which level zooplankton produce eggs at a maximum rate in the laboratory.

Vargas et al. (2009) found that marine copepods thrived best on diatoms, possibly because of higher food “quality” (fatty acid content) than dinoflagellate and ciliate phytoplankton. Turner et al. (2002) found that copepod growth and egg production declined when the phytoplankton was dominated by Phaeocystis, a haploid alga.

Chlorophyll a concentrations have been measured in Port Phillip Bay for more than 35 years, and phytoplankton community composition measured intensively for two periods, 1990-95 (Arnott et al. 1997) and 2008-11 (EPA 2012). In both periods, diatoms dominated the phytoplankton population. In 1990-95, diatoms comprised more than 60% of the total cell count, and were most abundant along the eastern shoreline of Port Phillip Bay. The 2008-11 study found a similar pattern: diatoms dominant in the north of the Bay, with peaks in biomass and abundance more likely to occur in spring or summer. In contrast, in the centre and south of the Bay species composition was more diverse, and peaks in biomass occurred more often in winter (Figure 9, EPA 2012).

Over the period 2008-2011, cell numbers exceeded 1 million cells L⁻¹ on 76 observations, and 66 of these were dominated by diatoms. Six were dominated by “other flagellates” - in the Yarra River or Hobsons Bay - and were dominated by the common cryptophytes (Plagioselmis prolunga and Hemiselmis spp) during periods of low flow from the Yarra River. EPA (2012) concluded that these species dominate in the north of the bay opportunistically when conditions are moderate in terms of salinity and nutrients, but are out competed by diatoms when nutrient concentrations (including silicate) increase with increased river flow.

Baywide, chlorophyll a concentration averages less than 2 µg L⁻¹ (central bay 0.6, Hobsons Bay 1.8 µg L⁻¹; Longmore and Nicholson 2012). In the period leading up to spawning (Sep-Dec), over 2003-2011, central bay averaged 0.66 and Hobsons Bay 2.35 µg L⁻¹. Modelling (Paul Hamer, pers comm.) has identified the snapper spawning area in eastern Port Phillip Bay as an area of elevated primary production in spring/summer, which is not well-represented by either Hobsons Bay or central bay. EPA (2012) presented ship-board instrumental measurements of chlorophyll a close to the spawning area from 2009 to 2012. These data indicated chlorophyll a concentrations exceeding 2 µg L⁻¹ were observed in March 2009, May 2009, December 2010, January, March and July 2011. It appears that copepod egg production, at least in the area of snapper spawning, is unlikely to be close to a maximum rate.
Figure 8. Snapper spawning in Port Phillip Bay.

Figure 9. Monthly sampling of phytoplankton species and chlorophyll a in central Port Phillip Bay. From EPA (2012).
Case Study 5: Competition and other interspecific interactions- urchins and abalone

Abalone habitat on eastern Victorian reefs may be under threat from the spiny sea urchin. The urchin has spread from NSW as far west as Wilsons Promontory, possibly assisted by the southward extension of the East Australian Current over the past 50 years. The urchin eats macroalgae preferred by abalone, creating barren areas which can no longer support abalone. Elsewhere, overfishing of a key urchin predator, rock lobster, has aided urchin expansion. MPAs currently affected include Wilsons Promontory, Point Hicks and Cape Howe Marine National Parks and Beware Reef Marine Sanctuary.

What is the ecological process?
Urchins competing for habitat with abalone

Where does it operate (spatial and temporal scales)?
On reefs in eastern Victoria from Cape Conran to Gabo Island, at the reef scale or less (though the East Australian Current extension that is responsible for larval dispersion is on the scale of hundreds of kilometres).

What MPAs does it affect?
*Centrostephanus rodgersii* has been observed (Barton *et al.* 2012a-e) in Wilsons Promontory, Point Hicks and Cape Howe Marine National Parks and Beware Reef Marine Sanctuary.

What influences the process?
East Australian Current extension (global warming).

Abalone habitat: The black-lip abalone (*Haliotis rubra*) is found throughout southern Australia, and forms one of the most valuable fisheries in Victoria. Living for up to 20 years, they inhabit crevices, caves and rocky surfaces on reefs from 5-40 m depth. Juvenile blacklip abalone feed on biofilms and coralline algae (Jenkins 2004). Adult abalone feed on drift algae, particularly kelp, which accumulates in gutters and crevices on reefs. Abalone grow fastest on a diet high in algal protein. Adults are sedentary, moving within a range of tens of metres, and larval dispersal is localised, rather than widespread (McShane *et al.* 1988; Gorfine 2002).

Sea urchin habitat: Sea urchins play an important role in near-shore rocky habitats worldwide (Pederson and Johnson 2006). They are the principal herbivore in temperate coastal areas. *Centrostephanus rodgersii* – the spiny sea urchin – plays a key role in controlling the abundance of benthic macroalgae in NSW (Hill *et al.* 2003). It lives on intertidal rocky shores and coastal reefs to 35 m, where it uses its spines to wedge itself into crevices. It is currently found in NSW, Victoria and Tasmania, but is thought to have spread from NSW since the 1960s-1970s (Johnson *et al.* 2005). Johnson *et al.* (2005) proposed that the urchins first spread as larvae from NSW, carried by the East Australian Current. The East Australian Current has grown in volume over the past 60 years, and warmer, saltier water has moved 350 km southward from the southern NSW coast to the south-east of Tasmania (Ridgway and Hill 2009). A small scale fishery for urchin roe has operated in eastern Victoria since 1998.

Competition: Adult abalone and sea urchins in SE Australia compete directly for food, and grazing by sea urchins can greatly reduce algal cover, creating barrens which are unsuitable for abalone (Hobday *et al.* 2008). The urchins themselves are able to continue to use and maintain the barrens, as they also feed on microalgae and drift algae (Johnson *et al.* 2005).

Barrens may make up 50% of the near-shore rocky reef habitat in NSW as large continuous tracts (Andrew and O’Neil 2000). In Tasmania they are mostly smaller discrete areas.

Strain and Johnson (2009) carried out enclosure experiments in intact algal beds (not urchin barrens) which indicated that the urchin was a superior competitor to abalone in Tasmania. Changing abalone densities had no effect on urchin, but changing urchin density affected abalone condition. This was because abalone was a specialist feeder, whereas urchin was a generalist feeder (including preferred abalone feed).

*Centrostephanus rodgersii* hides in crevices during the day, coming out to graze at night. The size of barrens therefore relates to how far an urchin can travel overnight, and return to (or find another) crevice. Once invaded, habitats with low numbers of crevices would not be likely to change to extensive barren habitat (but it is equally true that such areas would not be favoured abalone habitat either).

Barrens and macroalgal-dominated habitats have quite different plant and animal communities, with barrens typically lower in diversity (Edgar *et al.* 2004).

A change from kelp dominated to barren-dominated habitat means loss of macroalgae, loss of a major primary producer, and subsequent decline in secondary production (Pederson and Johnson 2008). Loss of kelp may also mean loss of protection for some species.

Over a five-week period, abalone recruited at higher densities in barrens than in adjacent algal communities (Aguirre and McNaught 2011). However, recruits on deep algal habitats were larger and more survived than on barrens.
Removal of macroalgae by urchins may also mitigate against further abalone settlement. Huggett et al. (2005) demonstrated that macroalgae play a role in encouraging abalone settlement by a surface-related (physical) cue.

**Effect of urchin predators:** There is evidence elsewhere that urchin abundance has increased because of the loss of an urchin predator, and the flow-on effects of loss of kelps may be extensive (Figure 10).

Stewart and Konar (2012) described the change in balance in the Aleutian Islands (Alaska) when a decline in sea otter numbers in the 1990s led to an increase in urchin numbers (preferred otter prey) and subsequent formation of urchin barrens. With sea otters present, urchins are maintained at a low population, and kelps may flourish. In the Aleutian Islands, kelp removal by sea urchins had negative effects on bald eagle, glaucous-winged gull, benthic feeding sea duck, harbor seal and fish abundance (Stewart and Konar 2012). Even the urchins in the barrens were smaller than those in kelp forests.

Johnson et al. (2004, 2005) found that once recruited, overfishing of rock lobster on the Tasmanian east coast reduced predation on urchins, which then created barrens and reduced abalone habitat.

A similar mechanism has been invoked in New Zealand, where the creation of an MPA led (over 20 years) to a 25-fold increase in lobster biomass, and a reduction in urchin barren cover from 40% to 14% (Shears et al. 2006).

Edmunds et al. (2010) proposed replacement of rock lobster in east Victorian MPAs, on the basis that “loss of kelps from the creation of urchin barrens may be prevented or mitigated through increased density and predation by large adult rock lobsters, which are presently fished down to very low densities”.

In some countries, urchins and abalone may not be competitors. Mayfield and Branch (2000) studied the interaction between rock lobsters, sea urchins and juvenile abalone in South Africa.

**Not always competitors:** In the converse of the Tasmanian experience, abalone in South Africa were found to shelter under sea urchins. An increase in rock lobster numbers led to a decline in urchins, a decline in abalone, and a dramatic increase in foliar algal abundance. Day and Branch (2002) removed sea urchins in the field in South Africa, and observed a decline in juvenile abalone abundance to zero after 5 months. In this case, sea urchins trapped drift algae, rather than grazed, and so urchin removal did not lead to an increase in algal abundance.

**Mitigation:** A range of potential solutions to urchin invasion have been proposed, including reintroduction of rock lobster (above) and re-seeding of abalone.

Goodsell et al. (2006) assessed the survival of black abalone when seeded into abalone habitat at natural abundances. They also attempted to see if C. rodgersii could act as a shelter from predators. Little evidence was found of this, and survival of juvenile abalone was very low after four months.

**Larval transport and future climate:** Johnson et al. (2004, 2005) hypothesised that C. rodgersii larvae was able to spread to Tasmania because of an extended larval phase (~100 days), increased water temperature, and East Australian Current southward extension to carry the larvae southward. Further southward extension of the East Australian Current is predicted under climate change (Ridgway and Hill 2009). If the extension is able to move westward into Bass Strait, then further westward expansion of C. rodgersii may be possible.
Figure 10. Competition between abalone and spiny sea urchin.
Case Study 6: Decomposition and nutrient cycling - denitrification

Transformations carried out by microbes in the muddy sediments of Port Phillip Bay (nitrification and denitrification) convert nitrogen from forms that could otherwise promote algal blooms and other undesirable outcomes into a harmless gas that is lost to the atmosphere. The processes occur year-round, and are most efficient in winter. MPAs affected are all those within Port Phillip Bay. This is an example of a process that is of key importance in specific areas critical to the well-being of MPAs, but not necessarily occurring to any extent within the MPAs themselves.

What is the ecological process?
A combination of physical, chemical and biological processes responsible for denitrification - the recycling of nitrogen from detritus into a gas that is lost to the atmosphere, thus minimising the occurrence of algal blooms.

Where does it operate (spatial and temporal scales)?
Port Phillip Baywide all year round, but most effectively in the deeper muddy areas of Port Phillip Bay in winter.

This is an example of a process that is of key importance in specific areas critical to the well-being of MPAs, but not necessarily occurring to any extent within the MPAs themselves.

What MPAs does it affect?
All those within Port Phillip Bay: Port Phillip Heads Marine National Park, Point Cooke Marine Sanctuary, Jawbone Marine Sanctuary and Ricketts Point Marine sanctuary.

What influences the process?
Key factors with the potential to affect denitrification include:
- Those that influence plant growth (nutrient supply and physical conditions - light, temperature, salinity)
- The oxygen regime at the sediment surface
- Mechanisms (e.g. bio-irrigation by infauna) that affect nutrient transport through the sediment.

Primary production: The food supply of all animals in Port Phillip Bay ultimately depends on the production of plants. Plant growth is affected by nutrient supply (see also Case Study 1 above). Too little nutrient may lead to reduced growth rates or starvation, while too much nutrient may lead to the explosive growth of one or more plants. This may lead to a number of undesirable outcomes, including impacts on aesthetics, the ecosystem and human health.

Phytoplankton accounts for more than half of net primary production in PPB (Beardall et al. 1997). Phytoplankton growth in PPB is thought to be limited by the nitrogen supply, and seasonally by light and/or temperature (Harris et al. 1996). Phytoplankton biomass in PPB is generally low compared to similar estuaries and bays within Australia and internationally (Harris et al. 1996). Beattie et al. (1997) concluded that phytoplankton biomass within PPB is maintained at low levels by zooplankton grazing, which rapidly transfers products of photosynthesis into the food chain.

N cycling mechanism: Of the 6,000-8,000 tonnes of nitrogen discharged to the Bay each year, little (~700 t) is exported to Bass Strait, or buried in the sediments (~1,200 t). There is no long-term build up of nutrients because most of the input is eventually lost from the system as N₂ gas (Harris et al. 1996). The process leading to this loss takes place in the sediment, and arises from the coupling of two microbial processes, called nitrification and denitrification. These processes are important because they result in the conversion of nitrogen from forms (ammonium and nitrate) readily available for plant growth, to a gaseous form (N₂) that is lost to the atmosphere (Berelson et al. 1998). Nitrification involves the conversion of organic nitrogen in organic matter settled on the sediment surface (principally phytoplankton) to nitrate, in the presence of oxygen. It can therefore only occur in areas of the sediment which are oxygenated. Denitrification involves the conversion of nitrate to N₂ gas, and occurs in different areas of sediment which have no oxygen. Port Phillip Bay is thought to be efficient at denitrifying N inputs because of the bioturbation and bioirrigation carried out by infauna, which transports chemicals between oxygen-rich and oxygen-poor zones in the sediment.

Symptoms of change: Port Phillip Bay appears to be unusually efficient at denitrification and a substantial drop in denitrification efficiency, even at current inputs, would lead to large increases in plankton production, and in the extreme cause a shift to a highly enriched state (Harris et al. 1996). Symptoms of eutrophication may include blooms of nuisance or toxic algae, or excessive growth of epiphytes and fouling organisms on plants. Such changes would have major impacts on Bay ecology, recreation and tourism. Protection of the denitrification capacity of the bay is therefore critical to the maintenance of water quality in the bay and its MPAs.

The conceptual model of nutrient cycling in PPB (Harris et al. 1996; Berelson et al. 1998; Longmore 2005; 2006) (Figure 10) is based on the following principles and observations:
- Nutrient inputs stimulate plankton growth
- Plankton growth in PPB is limited by the availability of nutrients, particularly nitrogen
- A significant proportion of the plankton settle to the seabed where they are consumed by microbes
- The microbial activity consumes oxygen and releases nutrients into the sediment and water column.
- A range of processes transport regenerated nitrogen between oxygen-rich and oxygen-poor zones in the sediment to facilitate sequential nitrification and denitrification.
- Denitrification is the key process limiting nitrogen availability and associated plant growth in PPB, because it leads to the net loss of nitrogen from the system.

Figure 11. Conceptual model of nutrient cycling in Port Phillip Bay under low and high nutrient loadings (from Longmore 2006).
Case Study 7: Bioaccumulation in seals

The Australian fur seal is a top-level predator in southern Australia. Adult seals forage over large distances (up to 350 km) from their breeding sites well offshore, while juvenile seals feed closer to home. Female juvenile seals from Lady Julia Percy Island, the largest seal colony in Victoria, are losing hair. This is thought to be due to the accumulation of toxins (trace metals and organic compounds), but the source of the toxins is unknown, as is the reason why females are affected more than males. How long the toxins have been affecting seals is also unknown. Many MPAs act as seal haul-out sites, including Discovery Bay and The Arches.

What is the ecological process?
Bioaccumulation is the accumulation over time of chemicals in the tissues of organisms to concentrations higher than they exist in the surrounding environment. They accumulate because they are taken up, via respiration, ingestion or absorption through the skin, at a higher rate than the organism can eliminate them either by breaking them down or excretion.

Bioaccumulation is a natural process, by which an organism accumulates rare but essential chemicals it requires for growth (e.g. vitamins). It becomes a concern when chemicals are introduced in the environment at higher than natural concentrations, and then accumulate in organisms to levels where they become toxic to the organism (or to the next consumer of the organism).

The example given here is accumulation of toxins in seals.

Where does it operate (spatial and temporal scales)?
Western Victoria; the full spatial extent is unknown, as is the period over which toxic levels have existed in seal tissue

What MPAs does it affect?
Discovery Bay and The Arches

What influences the process?
Proximity to pollutant sources; trophic level of prey; age of seal, duration of exposure, mode of uptake (Figure 11).

Bioaccumulation process: Many organisms bioaccumulate toxins; pollutants ingested in food may be stored in the organism to concentrations orders of magnitude higher than in the prey. A very early example of occupational toxicity was the use of mercury to treat felt in hats in the 17th and 18th centuries. The mercury was absorbed through the skin and selectively accumulated into the brains of hat-makers, leading to mental disorder (Lee 1968). A 20th century example is the impact on bird breeding of DDT in the US, which accumulated in adult birds and led to the formation of weak egg shells (Carson 1962).

Sedentary organisms (e.g. mussels) have been used to identify sources of toxins in the environment, by examining how the level of toxins varies with location of the organism (Tripp et al. 1992; Kimbrough et al. 2008). Similarly, mussels produced for human consumption have the potential to accumulate toxins from algal blooms to levels harmful to humans, leading to toxic shellfish poisoning (DPI 2008).

Where the organism is highly mobile, or where the toxin is transported atmospherically, identifying the source of the toxin is more difficult.

Duration of exposure: The longer the prey is consumed (e.g. the older the consumer), the more toxin is accumulated. Toxin concentrations also typically increase with increasing trophic level of the prey, as each successive trophic level accumulates toxins to concentrations higher than they were in the prey. Australian fur seals are benthic (seabed) feeders, consuming a variety of bony fish species, squid, octopus and rock lobster and are apex predators in southern Australian waters (Arnould 2004).

Chemicals that bioaccumulate to toxic levels typically bind to key areas in an organism (e.g. in fat, liver or kidney), from which they are difficult to excrete.

Large, fat, long-lived individuals may therefore accumulate toxins to higher concentrations than smaller, short-lived individuals. Seals are large, long-lived, and contain fat layers below the skin to maintain warmth. The seal is also a top predator. For all of these reasons, the seal is a top candidate to accumulate toxins, if they are found in the ecosystem the seal depends on.

Duinker et al. (1979) observed higher trace metal and organic contaminant concentrations in dead seals from a declining population off the Dutch coast, compared to a stable population off the German coast. Female harbour seals fed in captivity for two years on fish from contaminated (Dutch Wadden Sea) or clean (Atlantic Ocean) waters accumulated more polychlorinated-biphenyls (PCBs) from the contaminated fish (Boon et al. 1987).

Persistent contaminants have been found in seals from the remotest parts of the earth’s oceans, including the Arctic and Antarctic, far from any known point sources (Trumble et al. 2012). Blais (2005) described the various routes that could
account for the accumulation of persistent pollutants in seals in pristine areas. The most likely route was atmospheric transport.

**Local example:** Lady Julia Percy Island is a marine asset of state significance on the Department of Environment and Primary Industries map of significant marine environmental assets\(^7\). It is about 5 km off the coast at Port Fairy. The island lies between two MPAs, Discovery Bay Marine National Park about 60 km to the west, and the Arches Marine Sanctuary, about 140 km to the east.

The Australian fur seal, *Arctocephalus pusillus doriferus*, is the largest of all the fur seals and has a relatively restricted distribution around the islands of Bass Strait, parts of Tasmania and southern Victoria. Lady Julia Percy Island is home to one of the largest Australian fur seal colonies (about 30,000 individuals), accounting for about 25% of the total Australian population. Up to 50% of juvenile female seals at Lady Julia Percy Island are affected by alopecia (patchy hair loss), compared to less than 3% in other Australian fur seal colonies (Lynch *et al.* 2012).

**Elimination of other causes:** From paired sampling of 59 alopecic and 58 control animals, no evidence of viral, bacterial, fungal, or parasite infection was found. Microscopic examination indicated that the hair loss was due to fracture of the hair shaft above the skin, rather than hair loss from the follicle. Histological examination of skin biopsies revealed no pathological variation between case and control seals.

Affected animals had statistically significant lower tyrosine (amino acid) and zinc concentrations in hair than unaffected seals. This may increase hair brittleness and, therefore, increase the likelihood of its fracture. Seals with alopecia also had higher levels of heavy metals and persistent organic pollutants than those without alopecia. Satellite tracking indicated juveniles foraged closer to the coast than adults, and juvenile females stayed closer to the colony than juvenile males. Though several of the Victorian MPAs include areas for seal haulout, feeding areas are not usually within the MPAs, and the toxins were almost certainly ingested while foraging outside the MPAs.

**Foraging areas:** Female Australian fur seals give birth in summer, and continue to nurse their pups for 10-11 months. The foraging range is therefore restricted through autumn and winter, but may increase significantly in spring, when the pup is weaned. Arnauld (2004) observed female fur seals making trips of 3-4 days duration during autumn, from Lady Julia Percy island east to Cape Otway, south-east to King Island, and directly south to the edge of the continental shelf (200 m depth). In spring, journeys became longer in time (up to 18 days) and distance travelled (up to 1,200 km) to the south-east, south and the north-west as far as Kangaroo Island, but still within the continental shelf. Seals showed considerable differences in foraging locations between individuals, but most trips were within 200 km of Lady Julia Percy Island, in waters 60-200 m deep, up to 120 km from the coast. There is up to 100,000 km\(^2\) of potential habitat in this area, almost all of it outside Victorian jurisdiction (Arnauld and Kirkwood 2008). No particular preference was shown for foraging in the area of the Bonney upwelling (Kirkwood and Arnauld 2012).

Metals occur naturally in the environment, but industrialization (mining, burning coal, agriculture, industrial processing and manufacture) has led to much greater discharge of metals into the environment. World-wide, zinc is the fourth-most widely used metal, principally for galvanizing steel (Kimbrough *et al.* 2008). It is also an essential element for humans. In contrast, all of the chlorinated organics found in alopecic seals are man-made.

**Source of toxins:** The source of the toxins is unknown. Trace metal and organic toxicants are usually found at highest concentration near urban and industrial areas (Kimbrough *et al.* 2008). Pollutants on the Victorian coast are most likely associated with runoff. The western Victorian coast is only lightly industrialised, apart from the cities of Portland and Warrnambool, and the closest river discharges to the seal colony are the Moyne River, 22 km distant in Port Fairy, the Surry River 26 km away at Portland, and the Hopkins River, 44 km away at Warrnambool.

The toxins could be transferred to the young seal across the placenta, from its mother’s milk, or from contaminated food (Kakuschke *et al.* 2008). The difference in foraging habitats of juvenile females and males, but presumably similar exposure to transfer from mother, suggests that the source is more likely to be habitat-related (Lynch *et al.* 2012).

Juvenile males foraged closer to the coast, and had higher zinc concentrations than juvenile females. Since the males were less affected by alopecia than the females, this suggests the females may have been suffering from a zinc deficiency. However the differences in concentrations were small, and alopecic females had a higher overall burden of toxins than the males or other non-alopecic females.

Bioaccumulation of heavy metals has been observed in seals from a wide range of environments, including those thought to be pristine (Dehn *et al.* 2005). These authors found seals that foraged on benthos and invertebrates accumulated more zinc than those that fed on fish and other pelagic prey. Spatial differences in cadmium and mercury concentrations in ringed seal muscle between the eastern and western Arctic were attributed to differing underlying geology (Wagemann *et al.* 1995).

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\(^7\) See Appendix 1, Maps 1-6, and also [http://services.land.vic.gov.au/SpatialDatamart/dataSearchViewMetadata.html?anzlicId=ANZV08030004772&extractionProviderId=1](http://services.land.vic.gov.au/SpatialDatamart/dataSearchViewMetadata.html?anzlicId=ANZV08030004772&extractionProviderId=1)
Figure 12. Bioaccumulation of a toxicant through the food chain. At each level, the concentration of toxicant in the animal increases.
Case Study 8: Invasive species- Undaria

Since European settlement, Port Phillip Bay has become host to more than 200 species of plants and animals introduced from elsewhere. A green seaweed (Undaria pinnatifida) grown for centuries for human consumption in Japan has been spread by shipping to many sites across the world, including Port Phillip Bay in 1996. An infestation was also found in Apollo Bay in 2012. Undaria competes with native plants for light and substrate. In Port Phillip Bay, plants are generally found attached to rock, consolidated sediments, abalone and bivalve shells. Undaria may have a competitive advantage over native macroalgae in winter and spring, when N concentrations in western Port Phillip Bay are high, but native macroalgae may re-establish in summer, when Undaria dies back and the native species become more efficient at taking up N at the lower concentrations that persist in summer.

Undaria is currently found in Point Cooke, Jawbone and Ricketts Point Marine Sanctuaries, but also has the potential to spread along the Victorian coast. Recruitment now occurs year-round in Port Phillip Bay.

What is the ecological process?
Establishment and subsequent expansion of exotic flora or fauna at the expense of native flora or fauna. The example given here is the invasion by Undaria pinnatifida of Victorian waters.

Where does it operate (spatial and temporal scales)?
Port Phillip Bay since 1996 and Apollo Bay since 2012. New recruits have now been observed in Port Phillip Bay year-round (Paul Carnell, pers. comm.)

What MPAs does it affect?
Undaria is now found at numerous sites in Port Phillip Bay, and recent discovery at Apollo Bay suggests it has the potential to spread along the Victorian coast. MPAs potentially affected include all those in Port Phillip Bay with suitable substrate, and it has already been found in Point Cooke Marine Sanctuary, Jawbone Marine Sanctuary and Ricketts Point Marine sanctuary.

What influences the process?
Invasion may be influenced by a large number of factors, including movements of ships, boats or other vectors, presence of other macroalgae, presence of suitable substrate (especially turfing coralline algae), nutrient supply and oceanic currents.

Shipping: Australians are well aware of the damage to the environment brought about by the introduction of terrestrial pests, such as rabbits and cane toads. They are much less aware of the impact of introduced marine pests. Since European settlement of Victoria began, a large number of species new to the area has been introduced to Victorian marine waters, both deliberately and inadvertently. Many arrived on the hulls or in the bilges or ballast water of ships. Almost 200 now inhabit Port Phillip Bay, with an estimated 2-3 new species introduced each year (Hewitt et al. 1999).

Introduction of exotic species may pose a threat to human health (e.g. via toxic algae), to the economy (e.g. through overgrowth on aquaculture species) and to society (e.g. through loss of recreational access to intertidal shellfish which are out-competed by introduced shellfish).

Undaria life cycle: Undaria pinnatifida is a large brown alga native to cool temperate waters of Japan and nearby countries. It has been grown for human consumption (wakame) in Japan for more than 1300 years. Typical of most kelps, Undaria and continuea has two distinct life phases: the large macroscopic sporophyte phase, and the microscopic sexual gametophyte stage. The sporophyte stage displays an annual life cycle, but its peak growth and reproduction appears to vary between locations and from year to year. In Port Phillip Bay, the initial recruitment peak is in winter and continues through spring. Die-back in summer is accompanied by the release of tens to hundreds of millions of spores. The spores germinate within a few hours of settling out. Sexual differentiation occurs within a few days; fertilization occurs about nine days later, and at this point the plant may remain dormant for up to 2.5 years (Hewitt et al. 2005). When re-activated, the mature plant develops over the rest of the year. The Undaria sporophyte is mature at 400 mm, but ultimately grows to 1-2 m long (Figure 13; Talman et al. 1999).

Invasion timelines: Undaria pinnatifida has invaded Europe (France, UK, Holland and Belgium), South America, New Zealand and Australia (Talman et al. 1999), and more recently the USA and Mexico (Meretta et al. 2012).

Undaria was first found in western Port Phillip Bay near Point Wilson in 1996 (Campbell and Burridge 1998) at densities of up to 150 plants m⁻², and had spread to Station Pier and St Kilda Pier by 1998 (Talman et al. 1999). In 2008/09, plants were found in nine of 21 marinas in Port Phillip Bay: at Geelong, Werribee, Altona, Williamstown, Brighton, Sandringham, Half Moon Bay, Blairgowrie and Portarlington (Primo et al. 2010).

A small number of immature sporophytes were found on discarded abalone shells near Flinders Pier in 2000 (Jenkins 2004). All these plants were removed and no further sporophytes were found during subsequent surveys in 2008/09 (Primo et al. 2010). An immature sporophyte of U. pinnatifida was found in July 2009 in Apollo Bay (Primo et al. 2010).
The population had grown to such an extent that divers removed five tonnes wet weight in December 2012 in an attempt to eliminate it.

The rate of spread is different in different areas, from 800 km in New Zealand in 21 years; 150 km in Tasmania in 20 years; 500 km in Argentina in 16 years; and 200 km in Port Phillip Bay in 12 years (Russell et al. 2008; Primo et al. 2010). The recent discovery in Apollo Bay extends the spread in Victoria to 300 km in 17 years. The spread may depend as much on commercial or recreational fishing vessels introducing new material as on expansion from the site of original infestation. Schiel and Thompson (2012) found that while Undaria in New Zealand was prolific, producing up to 700 million spores per plant, under calm conditions, spores settled less than 20 cm from the plant.

Primo et al. (2010) believed the spread around Port Phillip Bay was more likely due to shipping movements than water circulation. Spore dispersal is localised to within 100 m in its native habitat (Forrest et al. 2000). The spread to Apollo Bay is even more likely to have been via shipping, since the direction of spread is against the prevailing current.

**Currents:** In contrast, the spread along open coasts in New Zealand has been attributed to drifting mature sporophytes (Russell et al. 2008). Russell et al. (2008) rejected the perception that Undaria could not invade open rocky wave-affected shores, by showing it has established in a broad range of wave-exposed habitats in New Zealand, from rockpools to the intertidal and subtidal, in addition to the sheltered areas it is most often found in elsewhere. Few are found on fine silt, where there is no obvious attachment surface (Russell et al. 2008). In some harbours in New Zealand, Undaria has not spread more than a kilometre in 20 years, presumably because of lack of suitable habitat.

Valentine and Johnson (2004) showed that removal of canopies of native kelp and fucoids allowed Undaria to invade patches, but that Undaria declined in the following year as the native canopy recovered. They found no evidence of displacement of native species and concluded that it was competition for light that prevented Undaria from gaining growing beneath canopies. Russell et al. (2008) found that invasion in New Zealand was independent of disturbance.

**Limiting factors:** Undaria can release spores and grow under a wide range of temperature (Campbell and Burridge 1998), and it is likely that temperature on the Victorian coast is not a limiting factor for its expansion. Its spread may be facilitated by its annual life cycle and therefore quick turnover of populations, wide temperature tolerance, rapid growth and high reproductive output (Schiel and Thompson 2012).

Undaria competes with native plants for light and substrate, and may also be favoured by relatively high fecundity and a lack of consumers compared to native seaweeds (Casas et al. 2004; Primo et al. 2010). It has an ability to attach and grow on many natural and man-made surfaces (Russell et al. 2008). In Port Phillip Bay, Campbell and Burridge (1998) found plants generally restricted to hard or at least semi-consolidated bottom. They were found attached to rock, consolidated sediments, abalone and bivalve shells, encrusting algae and, in the case of very small plants, to seagrass blades and unconsolidated large-grain sediments.

Schiel and Thompson (2012) found no evidence of competition with native seaweeds in New Zealand. Rather, Undaria took advantage of batches bare of seaweeds, particularly those covered by short turfing coralline algae (a habitat unsuited to native seaweeds). They saw no evidence of Undaria overgrowing or shading native seaweeds. They found no evidence of grazing by native fauna, in part because Undaria colonises turfing algae which is difficult to graze.

On the other hand, Undaria has been shown to alter native algal communities. Examples include a 64% decrease in species richness and diversity in native seaweeds in Patagonia (Casas et al. 2004) and a decline in the associated benthic animals (Irigoyen et al. 2011). Undaria pinnatifida has also invaded New Zealand coastal areas and dramatically reduced local biodiversity (Battershill et al. 1998). In Port Phillip Bay, Undaria has replaced native species that provide habitat for abalone (Talman et al. 1999).

Thompson and Schiel (2012) found that where the native fucoid canopy was removed, U. pinnatifida recruited into gaps of all sizes, but the smallest gaps (5 x 5 cm) recovered their native canopy within several months (after the Undaria sporophytes died off in summer). Coralline turfing algae greatly facilitated Undaria success, but not other turfs, shell surfaces or encrusting coralline algae.

**Nutrient uptake:** There is some evidence that Undaria could out-compete native algae, at least on the nutrient-enriched western side of Port Phillip Bay, because of its high capacity to take up nitrogen. Campbell (1999) found that Undaria in Port Phillip Bay has a high uptake rate for ammonium, while Dean and Hurd (2007) in New Zealand found that Undaria assimilates nitrate rapidly, and responds to increase in supply. Campbell (1999) proposed that Undaria may have a competitive advantage over native macroalgae in winter and spring, when N concentrations in western Port Phillip Bay may be high, but that the native macroalgae may re-establish in summer, when Undaria dies back and the native species become more efficient at taking up N at the lower concentrations that persist in summer. Experimental studies are underway (Carnell and Keough, University of Melbourne) to examine this process at Beaumaris on the eastern coast of Port Phillip Bay.

**Eliminating infestations:** Treatment has only been possible in a few restricted infestations. It is too early to tell whether the removal program in Apollo Bay has been successful, but manual removal every month for 2.5 years failed to
eliminate Undaria from an 800 m² area within a Tasmanian Marine reserve (Hewitt et al. 2005). Manual removal appears to have been effective at Flinders in Western Port (Parry and Cohen 2001), presumably because the plants found were immature, and had not released spores. Treatment is difficult because part of the life cycle of Undaria is microscopic (not visible by eye). Undaria spores were destroyed on a trawler hull in New Zealand by heat treatment (Wotton et al. 2004), but such a treatment would not be possible for an infestation on natural substrates.

Figure 13. Life cycle of Undaria pinnatifida.
Discussion

One of the key purposes for which Victoria’s MPAs were declared was to protect biodiversity and ecological processes. While it is self-evident that an MPA would be affected by the ecological processes occurring within it, the case studies presented here make it clear that ecological processes operating outside an MPA may also be critical to achieving this purpose (e.g. the import of larvae or plant propagules). The case studies described here cover a range of spatial and temporal scales. The common feature of all the case studies is that they describe ecological processes operating mostly or entirely outside MPAs, but with the potential to affect ecosystems within MPAs.

In the case studies described here, the key ecological processes operate over spatial scales ranging from millimetres vertically (benthic nutrient cycling) to hundreds of kilometres horizontally (King George whiting recruitment). Table 3 summarises the spatial and temporal scales relevant to the case studies.

Most of the processes fluctuate over time (e.g. the amount of nutrient cycling varies with organic supply to the sediment, probably on a diurnal basis, and certainly seasonally). Others are queued to annual events (e.g. the Bonney upwelling, snapper spawning). Some are also event-driven (e.g. the success of snapper recruitment may depend on the right river flow at the right time; denitrification may respond to a flood event).

As indicated here, many important ecological processes operate outside the MPAs, and protection of such processes within the MPAs alone would be an ineffective way of managing towards the MPAs establishment purpose. Similarly, protecting one key process relevant to a biodiversity value may also be ineffective; for example, protecting fish populations by catch restrictions will be of little benefit if other ecological processes are altering fish habitat. The King George whiting case study here is another example: efforts to maintain preferred habitat (seagrasses in Port Phillip Bay and Western Port) will be of little value if spawning in South Australia fails. Maintaining ecological processes operating outside the MPAs is of course also important in its own right, beyond its implications to the MPAs, in working towards ecologically sustainable development of Victoria’s wider marine environment.

Our ability to “manage” the ecological processes described here is limited. Large-scale oceanographic processes such as the Bonney upwelling, and King George whiting transport from SA, are beyond any practical management. On the other hand, while it is still too early to tell if Undaria has been successfully controlled in Apollo Bay, there is some prospect of limiting its impact along the Victorian coast. But a high level of vigilance will be required, since the likely vector for spread (coastal commercial and recreational vessels) will only increase in the future. And this is a management activity which will be required outside MPAs. Climate change is also likely to impact most of the processes described here, and the management of climate change impacts, if achievable, will almost certainly be focussed outside MPAs.

Even if some parts of the ecological processes described here are beyond management, other parts may be manageable. For example, Victoria may be able to manage its seagrass beds to improve the chance of successful recruitment of King George whiting. In addition, if it is confirmed that the Victorian King George whiting population is limited by spawning success in South Australia, it may be possible for Victoria to encourage South Australia to do what it can to protect spawning stocks. So while there is no possibility of managing large-scale oceanographic processes like currents, we may be able to carry out other activities that maximise the opportunity for successful spawning, settlement and growth. For these and other reasons, it is important that the physical, chemical and biological processes critical to biodiversity in Victorian marine waters are monitored so that we are able to consider the implications of wider effects that may occur in the future.
### Table 4. Key spatial and temporal scales for each ecological process.

<table>
<thead>
<tr>
<th>Ecological process</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upwelling-driven primary production (Bonney coast)</td>
<td>Up to 14,000 km$^2$, but varying significantly between years</td>
<td>Annual, summer-autumn</td>
</tr>
<tr>
<td>Gastropod recruitment on rocky intertidal and shallow subtidal</td>
<td>Centimetres to hundreds of kilometres</td>
<td>Larval stages from days to months, with peak settlement over summer</td>
</tr>
<tr>
<td>King George whiting recruitment in Port Phillip Bay</td>
<td>About 800 km</td>
<td>Annual, autumn-spring</td>
</tr>
<tr>
<td>Snapper recruitment in Port Phillip Bay</td>
<td>Eastern Port Phillip Bay, about 200 km$^2$</td>
<td>Annual (November-January)</td>
</tr>
<tr>
<td>Competition (abalone and sea urchins)</td>
<td>Metres (reef-scale) to hundreds of kilometres (Eastern Australian Current)</td>
<td>Year-round, most likely increasing over time.</td>
</tr>
<tr>
<td>Nutrient cycling (denitrification) in Port Phillip Bay</td>
<td>Millimetres (vertically in the sediment) to about 1,000 km$^2$ (muddy central bay)</td>
<td>Diurnal, seasonal and event-driven</td>
</tr>
<tr>
<td>Bioaccumulation of toxicants in seals</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Invasive species (Undaria)</td>
<td>Expanded to about 300 km since 1996</td>
<td>Annual spawning with a strong seasonal pattern</td>
</tr>
</tbody>
</table>
Acknowledgements

Dr Rachael Bathgate provided Case Study 2 (gastropod recruitment). Paul Carnell made helpful additions to Case Study 8 (Undaria). Dr Liz Morris provided information on several of the case studies.

The staff at the Victorian Environmental Assessment Council, and most particularly Dr Jo Klemke, are thanked for the guidance and information they provided for this report.

Dr Leanne Gunthorpe at Fisheries Victoria is thanked for her role in contractual negotiations between DPI, VEAC and Melbourne University.
References


Appendix 1 – Marine Assets
Spatial and temporal scales of key ecological processes in MPAs

VEAC Marine Investigation

Marine National Park/Sanctuary

Spatial and temporal scales of key ecological processes in MPAs

VEAC Marine Investigation
Marine Assets (Statewide significant assets have underlined numbers. Other assets are local/bioregional significance).

126. Cape Conran
127. Beware Reef
128. Bemm River region reef upwelling communities
129. Sydenham Inlet
130. Point Hicks Reefs
131. Croajingolong Reefs
132. Skerries offshore islands
133. Star Bank inside state limit
134. Secret Beach intertidal reef
135. Bastion Point intertidal reef
136. Mallacoota Inlet
137. Gabo Island
138. Cape Howe and Iron Prince

Map Produced by Fisheries Management and Science Section, October 2012

Eastern Victoria
Map 6 of 6
Department of Sustainability and Environment

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