

Chapter 1

Lobsters as Part of Marine Ecosystems – A Review

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Abstract

Lobsters are the focus of valuable fisheries worldwide; they are often regional icons, and mainly because of this are among the most researched animals on earth. As fishery management moves globally from a single-species to an ecosystem-based emphasis, it remains important to understand the role of species functions in marine ecosystems. Despite the wealth of research on lobsters, our understanding of their role in marine ecosystems is patchy. As mid-trophic-level consumers, lobsters function in the transfer of energy and materials from primary producers and primary consumers to apex predators. They are large-bodied and conspicuous, and can comprise a considerable proportion of the collective consumer biomass. Still, the nature and strength of interactions, and the relative importance of top-down and bottom-up effects to their productivity is murky. Australia, the USA, the European Union, Canada and New Zealand are beginning to implement ecosystem-based fishery management. Here, we review two case studies from dramatically contrasting ecosystems: the spiny (rock) lobster *Panulirus cygnus* in subtropical Western Australia, and the American lobster *Homarus americanus* in cool temperate eastern North America. Our analysis identifies knowledge gaps and takes a first step in evaluating the consequences of differing ecosystem-based management approaches to these and other lobster fisheries.

Key Words: lobsters; *Panulirus cygnus*; *Homarus americanus*; ecosystem; fisheries management; large marine ecosystems

1.1 Introduction

Ecosystem-based management (EBM) first developed as a concept in terrestrial systems, using the principles of outcome-based management (Grum-

bine, 1994). Lubchenco (1994) and Sherman & Duda (1999) subsequently laid the foundation for the emergence of the marine EBM movement. Table 1.1 (after Lubchenco 1994) is used as the basis of this chapter. We focus here on 'Individual

Table 1.1 The single-species to ecosystem-based management paradigm shift from Lubchenco (1994).

From	To
Individual species	Ecosystems
Small spatial scale	Multiple scales
Short-term perspective	Long-term perspective
Humans: Independent of ecosystems	Humans: integral parts of ecosystems
Management divorced from research	Adaptive management.
Managing commodities	Sustaining production potential for goods & services

Species to Ecosystems' but comment at times more broadly on the question of ecosystem management in marine systems and lobster fisheries.

Over the last 10 years ecosystem-based fisheries management (EBFM) has emerged as an approach to natural resource management that is more comprehensive than focusing only on a single species. Marine ecosystems are considered to be a dynamic complex of animals, plants and micro-organisms with their associated non-living environment of water, air and sediment, interacting as a functional unit (from Article 2, UN Convention on Biological Diversity). Marine ecosystems may be identifiable and exist across a range of spatial scales, from ocean basin scale, such as the Eastern Tropical Pacific region, to local area scale of a few hundred metres or less, such as an individual estuary or embayment. It is in this context that the EBM of fisheries is conducted. To be effective, EBFM reverses the order of management priorities from starting with objectives for the target species to starting with objectives for the ecosystem, or at least objectives for a species assemblage consisting of multiple trophic levels and the environmental factors related to that assemblage. The movement toward EBM of marine living resources rather than single species management of target stocks further broadens the expectations of EBFM, and is in line with international agreements, most recently as expressed through the Johannesburg and Reykjavik Declarations, and supported by the UN Food and Agricultural Organization through the Code of Conduct for Responsible Fisheries (FAO, 2003).

In the USA, EBM has been mandated by National Ocean Policy (The White House Council on Environmental Quality, 2010). Ecosystem-based research initiatives in the USA include the CAMEO (Comparative Analysis of Marine Ecosystem Organization) programme jointly sponsored by the US National Science Foundation and the National Oceanic and Atmospheric Administration, and the US integrated modelling to service the EBFM approach (Link *et al.*, 2011).

There are many versions of the ecosystem approach to management, including EBM (Ward *et al.*, 2002); EBFM (Brodziak & Link, 2002); ecosystem approaches to fisheries management (EAFM) (Garcia *et al.*, 2003); and integrated oceans management (IOM) (NOO, 2004). Such a large number of terms can be confusing, but it is important to recognize that they are all variations on a theme (Fletcher, 2006). All of these approaches require that in addition to managing the target stocks and the impacts of fishing, the key trophic and habitat interactions, the spatial scale of connectivity among stocks and the other species dependent on the target species, as well as the socio-economic outcomes of fishing activities, are all given consideration within the management system to allow objectives for the broader ecosystems to be met. 'Ecosystem-based fishery management recognizes the physical, biological, economic, and social interactions among the affected components of the ecosystem and attempts to manage fisheries to achieve a stipulated spectrum of social goals, some of which may be in competition.' (Marasco *et al.*, 2007). When implemented effectively, EBFM is a subset of EBM, which for ocean ecosystems where fishing operates encompasses all forms of human activities, some of which will also interact with the fisheries.

We have chosen to focus this review on two contrasting species of lobster: the sub-tropical spiny lobster, *Panulirus cygnus* of Western Australia, and the temperate clawed lobster, *Homarus americanus* of the US Northeast and Atlantic Canada. The shelf waters of the Western Australia and Eastern North America are strikingly contrasting environments. Australia's western rock lobster occupies a geographic range that is subtropical and characterized by a gentle north-south gradient in

Table 1.2 Large marine ecosystems.

	Large Marine Ecosystem 44	Large Marine Ecosystem 7	Large Marine Ecosystem 8	Large Marine Ecosystem 9
Area km ²	543,577	674,862	308,554	303,029
Shelf area km ²	61,032	322,093	238,843	100,016
Inshore fishing area km ²	66,437	137,688	124,784	73,112
Coral Reefs % of world	0.4	0.0	0.0	0.2
Sea Mounts % of world	0.0	0.0	0.0	0.0
Primary production mgCm ⁻² day ⁻¹	476	809	1,536	721

Data from Sea Around Us Project, <http://www.seaaroundus.org/lme/44.aspx>.

sea surface temperature (SST). By contrast, the geographic range of the American lobster in the western North Atlantic has the steepest latitudinal gradient in SST on the planet and large seasonal extremes.

These two species of lobsters are currently demonstrating opposite trends in catch – the annual catch of *H. americanus* is increasing in its most productive areas while that of *P. cygnus* is declining. Both species have been the subject of extensive research and both species are the basis for fisheries that have received Marine Stewardship Council (MSC) certification, at least for sections of, if not the entire fishery. This also means that extensive and current reviews of the literature pertaining to these species are available.

We refer to the large marine ecosystems (LMEs) relevant to the lobster species in question as described by Sherman & Duda (1999) and accepted by the US National Oceanic and Atmospheric Administration (NOAA) and endorsed by the White House Council on Environmental Quality (2010). The world-wide classification of LME is available at <http://www.lme.noaa.gov>. *Panulirus cygnus* predominantly occurs in the West-Central Australia LME 44 in Western Australia. The geographic range of *Homarus americanus* spans the Northeast US Continental Shelf LME 7, the Scotian Shelf LME 8, and the Newfoundland–Labrador Shelf LME 9. While *H. americanus* occupies a smaller geographic range than that of *P. cygnus*, it traverses a much steeper latitudinal gradient in SST and range of environmental conditions. The basic details of the LMEs used in this study are shown

in Table 1.2. The data are from Sea around Us project: <http://www.seaaroundus.org/lme/44.aspx>.

Plate 1.1 presents a general overview of some of the main ocean activities in lobster fisheries which need to be considered in ecosystem management. In this chapter we have attempted to examine the material that is available on lobsters in these ecosystems over the last 30 years.

1.2 Species overviews

1.2.1 Western rock (spiny) lobster *Panulirus cygnus*

Life history, geographic range, depth, habitat and fishery

The western rock lobster occurs only in the Indian Ocean on the western seaboard of Australia and is found in commercial quantities from Augusta in the south to Shark Bay in the north, along approximately 1000 km of coast (Plate 1.2A). The distribution of the population is greater than LME 44, but the majority of the fishery for this species falls within this LME. The offshore movement of the phyllosoma larvae takes them well beyond LME 44, and this large spatial scale of the distribution of the small lobsters makes EBM of the fishery difficult.

A full review of the species is provided in Chapter 10 and earlier data is available in Phillips (2006). After hatching, the Stage I phyllosoma larvae rises to the surface and they are rapidly dispersed offshore in a wind-driven surface layer of

the Indian Ocean. As they are transported offshore in the plankton they develop through a series of moults, increasing in size. Nine to 11 phyllosoma stages have been defined.

Much of the larval life of the lobster is spent in the open ocean and by May/June each year most have grown to Stages VI–VIII. By this time most of the phyllosoma are more than 200 km from the coast. They become widely distributed in the south-eastern Indian Ocean and have been found at least as far as 1500 km offshore at 99°E and between 13°S and 34°S, which is the limit of sampling that has been conducted. The area in the Indian Ocean where the larvae are found is an area of low plankton density characterized as a marine desert (Tranter, 1962). The highest abundances occurred between 26°S and 32°S, west of the centre of the adult population along the coast. After developing through the early and middle stages offshore, late-stage phyllosoma are returned towards the continental shelf by the deeper circulation. There is a geostrophic inflow from the ocean towards Western Australia in the upper 2 or 3 m as a result of a strong alongshore pressure (Clarke & Li, 2004). By September/October/November each year there are large numbers of late Stages VIII and IX phyllosoma (which are about 35 mm total in length) near, but offshore from, the continental shelf. The late stage phyllosoma (Stages VI–IX) tend to occur lower in the water column than early and mid-stage larvae and are found at 0–60 m at night and descend to 60–140 m during the day (Phillips & Pearce, 1997).

The final Stage IX phyllosoma metamorphoses into the puerulus stage (the post-larva) in the slope region beyond the shelf break (Phillips *et al.*, 1978; McWilliam & Phillips, 1997, 2007; Phillips & McWilliam, 2009). The puerulus is a transitional stage short (3–4 weeks) which bridges the planktonic and benthic phases of the life cycle and swims 40–60 km across the continental shelf toward shore, where it settles in holes and crevices in the shallow coastal reefs.

When the puerulus settles, it moults after a few days into a benthic juvenile stage, which has the form and structure of the adult lobster. These post-puteruli are usually found in shallow coastal reefs where they remain for 3–5 years. Larger juveniles

migrate offshore in November to January each year. It is in these depths of 30–150 m that they reach maturity, mating takes place and the life cycle is completed.

Rocky reefs are an important habitat type in the near-shore coastal waters of LME 44, supporting a diverse assemblage of benthic macroalgae and associated fish and invertebrates. The rocky reef communities are a key component of coastal productivity, provide habitat and food for marine fauna, contribute to biogeochemical cycles, and can exert influence over nearby habitats such as seagrass meadows. In many places, these reefal habitats are offshore, and they protect the shallower inshore waters from wave energy, creating more protected inshore lagoon habitats and providing a wide variety of soft and hard substrata for a diverse marine fauna and flora.

Early juvenile spiny lobsters tend to be solitary in the small holes or dens that they choose, but as they grow they become gregarious. For example Fitzpatrick *et al.* (1990) showed that in *P. cygnus* over 95% of newly settled pueruli and post-puteruli (6–10 mm carapace length (CL)) were solitary, but less than 20% of animals that had been settled for about a year (i.e. 20–25 mm CL) were solitary. Their gregarious behaviour is considered an effective anti-predator strategy (Butler *et al.*, 1999). Nonetheless, natural mortality rates of lobsters, and particularly those of juvenile animals, are extremely high. Herrnkind & Butler (1994) estimated mortality of *P. argus* to be 96–99% in the first year after settlement, while Phillips *et al.* (2003) found similarly high rates of natural mortality (80–96%) for *P. cygnus* juveniles at the end of their first year after settlement. In the case of *P. cygnus*, as few as 3% of settling pueruli are estimated to survive to recruit into the fishery, 3.5 years after they first settled as pueruli (Phillips *et al.*, 2003).

Waddington (2008) and Waddington *et al.* (2010) used stable isotope analysis and gut content analysis to determine the diet and trophic position of western rock lobsters from mid-shelf coastal ecosystems (35–60 m depth) at three locations. Lobsters were primarily carnivorous, and no consistent differences in diet were detected with varying lobster size, sex or among locations. The main components of the diet were bait (from the fishery) and

small crustaceans – crabs and amphipods/isopods. Foliose red algae, bivalves/gastropods and sponges were minor contributors to diet. The diet of lobsters in these mid-depth coastal ecosystems differed from the results of other studies of diets of lobsters from shallow coastal ecosystems (MacArthur *et al.*, 2011). In particular, coralline algae and molluscs – important prey in studies of lobsters from shallow coastal ecosystems – were found to be minor components of the diet. These differences are likely to reflect differences in food availability between these systems and, potentially, differences in choice of prey by lobsters that inhabit deeper water. Given the high contribution of bait to lobster diet in both shallow and deep waters, bait is likely to be subsidizing lobster production in deep coastal ecosystems during the fishing season (Waddington & Meeuwig, 2009; MacArthur *et al.*, 2011).

Bellchambers *et al.* (2010) and Bellchambers (2010) examined the relationship between abundance and size of western rock lobster and benthic habitats in deep water (35–60 m) based on the annual independent breeding stock survey and benthic towed video transects conducted near Dongara, Jurien Bay and Lancelin in Western Australia between 2005 and 2007. Abundance of western rock lobster was found in these studies to be partly related to benthic habitat, with high abundances associated with high cover of mixed assemblage and the macroalga *Ecklonia* sp. Lobster size was more strongly associated with habitat, with larger lobsters found in mixed assemblages with sponges, and smaller lobsters associated with mixed assemblages with *Ecklonia* sp.

The spatial complexity and quality of habitats where the lobsters live is also likely to have an influence on their nutrition and possibly their growth rates. Coralline algae were recorded as the major component of lobster guts sampled from reefs across the central area of LME 44, indicating an important trophic role for these algae and their habitats in lobster productivity. However, animal prey may provide more nutrition when it is available (MacArthur *et al.*, 2011). This infers that these lobsters may benefit significantly by choosing habitat that has a broad range of structures and supports a diverse array of flora and fauna prey items.

Fisheries in the LME 44

This LME has a very narrow continental shelf, and primary and secondary production is limited by low levels of nutrient-rich upwelling. As a result, fish stocks in the West-Central Australia LME are limited. Many of the targeted species are endemic to Australia or Western Australia. There are small but locally important commercial fisheries for rock lobster, abalone, pink snapper, shark, crabs, pilchards, prawns and scallops. Constantly changing ocean conditions affect the abundance and distribution of all species in the marine food chain, including both targeted and non-targeted species.

There have been a number of dramatic changes in the lobster fishery in recent years. These changes are described in detail by Phillips *et al.* (2010) including the new management arrangements, the status of the stocks and the current economic and social situation of the fishery. Here, we summarize the major changes in the fishery and discuss aspects relevant to this study of the ecosystem. For earlier details on fishery see Phillips *et al.* (2007) and Phillips *et al.* (2010).

The EBFM study by Fletcher *et al.* (2010) reported that that this fishery is currently facing a number of significant issues, including recent persistent reductions in recruitment levels, and major reductions in the allowable catch have been designed to prevent breeding stock levels from being adversely affected. In addition, the income levels for fishers are being affected by relatively low prices due to overseas market conditions and high currency exchange rates, which are exacerbating the impacts of increased costs associated with fuel and labour. This combination is generating significant social issues for the catching and processing sectors, and there are flow-on economic impacts to the dependent human communities and service groups.

Annual commercial catches of *P. cygnus* since the mid-1980s have fluctuated between about 8000 and 14,400 t, but on average have yielded around 11,000 t. Catches from 1945–6 to 2009–10 for *P. cygnus* are shown in Chapter 10 (Fig. 10.3). After almost a decade of good to average levels of puerulus settlement, below average and very low pueruli settlements of this species have been observed since the 2006–7 fishing year, including the latest

available data (2011–12). There is a close relationship between pueruli settlement levels and recruitment into the fishery 3 and 4 years later (Phillips, 1986; Caputi *et al.*, 1995a,b). This relationship and the low levels of settlement provides the driver for concern for the stock, and is expressed in the reduction in catch levels enforced in the fishery from 2008–9 to 2011–12.

There are two major research and management issues associated with the series of low puerulus settlements. First, understanding the causes that have led to the low puerulus settlement, and second, devising management measures that are required to deal with the effects of the low settlement. These low settlement years commencing 2006–7 will have had a major impact on recruitment into the fishable stock, commencing with the 2009–10 fishing season. Without management actions being taken to significantly reduce exploitation on the rock lobster stock, the recent years of low puerulus settlement would also have the potential to result in much lower breeding stock levels 4–6 years after settlement, and then possibly have major ongoing consequences for the fishery.

Catches since the mid-1980s, and increasingly in the last 5 years, have been constrained by management measures which have been introduced to limit effort in the fishery. The 2008–09 fishing season, for example, was predicted to catch 9200 t, but through a range of management measures taken to reduce fishing pressure, the actual catch was reduced to 7600 t (Fig. 1.1A). The fishery was then constrained in the 2009–10 season to a target catch of 5500 t and this target level has been applied for the following 3 years. In 2008/09, the 7600 t fishery was estimated to be worth A\$191 million and the 5500 t catch in 2009/10 was worth about A\$156 million.

The management measures introduced to constrain the fishery are extensive and complex, and have been applied at the same time as the fishery prepares to move from a mainly input set of controls to a hybrid system of management controls that are based on catch quotas. As a result of the management measures, the number of boats declined in 2009–10 by about 20%. In the northern zone (zone B) of the fishery, for example, in December 2008 there were 89 boats authorized to

fish, but in 2009/10 there were 71 authorized vessels. Rules about how the pots can be used in the fishery have also changed. The number of ‘licensed pots’ has not changed, but fishers will only be able to fish with 40% of the pots they own, only on weekdays, and only on 4 days of the week. The numbers of days of closure will be adjusted to ensure that the target catch is achieved, pending the introduction of a system of specific catch quotas. Recreational fishers, although they only take a small proportion of the overall catch, will also be constrained to fishing only within specified seasons, and by pot limits, pot requirements, lobster minimum size limits and other constraints, possession limits, and a range of locally closed areas. All of these controls are designed to limit effort and catch in the fishery to thereby ensure that the breeding stock level is not further depleted. The controls are also intended to smooth the catch in the commercial fishery and reduce the economic impact of the low puerulus settlement years.

A workshop (Brown, 2009) which focused on examining the ‘likelihood’ of factors that could have caused the recent decline in puerulus settlement concluded that the decline could have been caused by either changes in environmental conditions and productivity in the eastern Indian Ocean, by overfishing causing a decline in the abundance of the rock lobster breeding stock, particularly in the northern region of the fishery, or by a combination of these two factors. The uncertainty regarding the cause of the low puerulus settlements represents a high risk to the fishery.

Environmental factors such as the Leeuwin Current (influenced by the El Niño–Southern Oscillation (ENSO) cycle, represented by the Southern Oscillation Index – SOI) and westerly winds in late winter–spring significantly affect the inshore puerulus settlement *P. cygnus*. A major concern regarding the recent low puerulus settlements was that the longstanding numerical relationship between puerulus recruitment and these environmental conditions, which had previously provided a good explanation of the variations in settlement (Caputi *et al.*, 2001), no longer provided an adequate explanation of the recent settlement patterns, particularly the very poor settlement of 2008/09 (Fig. 1.1B). The relationship between the strength of the SOI,

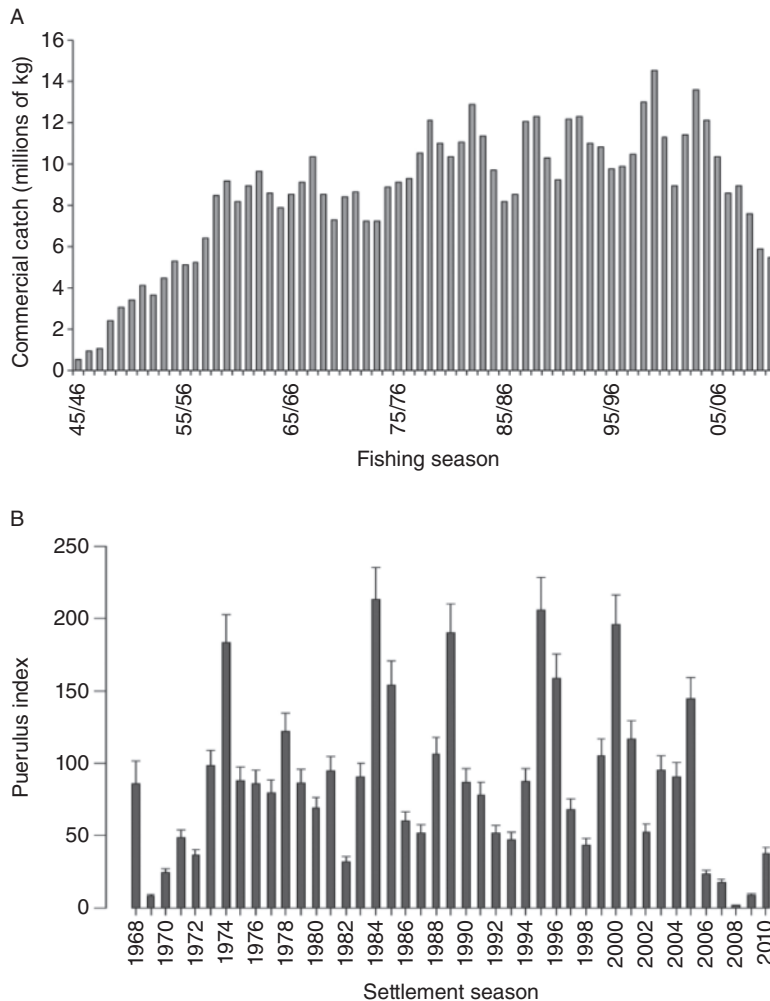


Fig. 1.1 (A) Seasonal catches in the commercial western rock lobster fishery for *Panulirus cygnus* from post war years to 2009/10, and (B) puerulus settlement index in the central region of the western rock lobster fishery for *Panulirus cygnus* (Dongara and Jurien) from 1968 to 2008/09. (From Phillips *et al.*, 2010, with permission from the Journal Marine Biological Association of India).

the Leeuwin Current and the levels of puerulus settlement appears to have been eroded over the last few years (Fig. 1.2).

The main cause for the decline in puerulus settlement is still unclear, but changes in the ecosystem are affecting the pelagic part of the *P. cygnus* life cycle, and overfishing of the breeding stock is still a possible contributing factor. A small increase in the puerulus settlement level in 2011/12 has been taken as a good sign for the fishery. However, it remains to be seen if this new level of settlement is sustained and if it carries through into increased adult abundances in future years. This situation emphasizes the need for knowledge of ecosystem scale changes

in the environment and the ecological interactions in sub-legal stages of the lobster to understand what is influencing the decline in puerulus settlement and provide for a more robust ecosystem-based approach to management of this fishery.

1.2.2 The American lobster *Homarus americanus*

Life history, geographic range, depth, habitat and fishery

The American lobster *H. americanus* occurs in the coastal waters from Labrador, Canada, to New

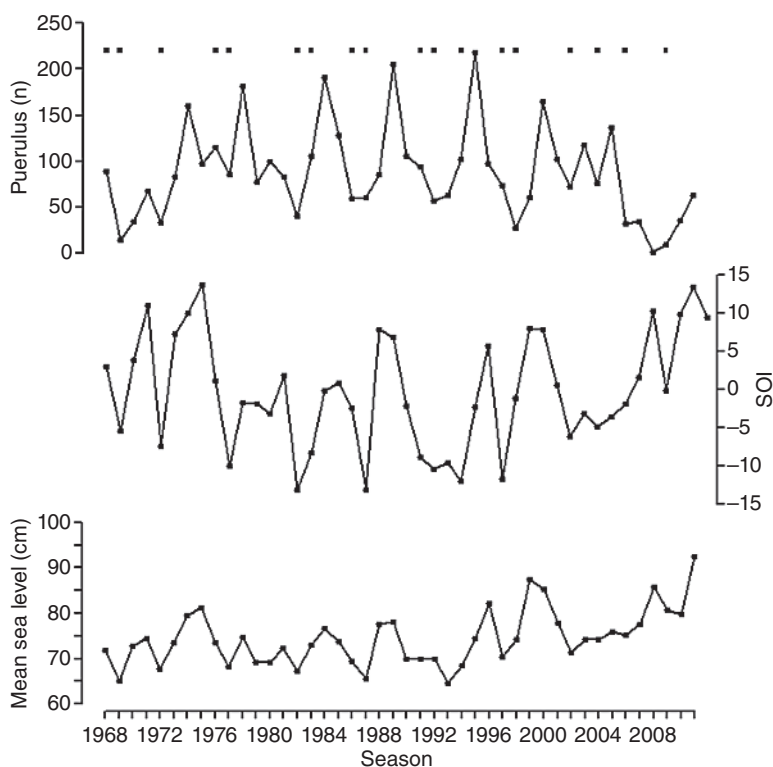


Fig. 1.2 Diagram illustrating the relationship between the Southern Oscillation Index (SOI; denoted by ~), Fremantle sea level (mm) (which is an indicator of the strength of the Leeuwin Current; denoted by ■), and the puerulus settlement at Dongara in Large Marine Ecosystem 44. (Updated from Pearce and Phillips 1988). ENSO Events are shown along the top of the diagram.

Jersey, USA, although the southern extent of its range departs from shallow coastal waters and extends into deeper shelf waters as far south as North Carolina on the US continental shelf. The life history, ecology and fishery of *H. americanus* are reviewed in detail elsewhere (Factor, 1995; Phillips, 2006; Chapter 8 of this volume). The range of *H. americanus* in the western North Atlantic spans the greatest latitudinal gradient in SSTs of any oceans (Plate 1.3 and Plate 1.4). Over the distance of a few hundred kilometres summer maximum temperatures range from the mid-20s centigrade in coastal southern New England, USA, to just over 10°C in the Bay of Fundy, Canada. At the northern limit of the *H. americanus* range in Atlantic Canada, the lobster is largely restricted to waters less than 50 m deep. In the middle of its range *H. americanus* is more broadly distributed from the coast to deep-water canyons on the continental shelf break. The southern limit of the species' coastal distribution is Long Island Sound and the northern Mid-Atlantic

Bight, USA, but even further south it becomes increasingly restricted to deeper, cooler water out to the edge of the continental shelf off Virginia and North Carolina. Consequently the commercial fishery transitions from predominantly near-shore in the north to predominantly offshore in the south.

The shelf waters of the Northwest Atlantic have been warming rapidly in recent decades (Steneck *et al.*, 2011). As the climate warms, the coastal environments at the southern end of the *H. americanus* range are becoming increasingly physiologically stressful during the summer, whereas those in historically cooler regions may be becoming more favourable (see Chapters 4 and 8). The thermal gradient is associated with a biogeographic shift in the diversity and composition of associated marine fauna, and this may have implications for the nature of trophic interactions across the lobster's geographic range (Frank *et al.*, 2007; Wahle *et al.*, in press). Essential elements of the American lobster's life history and fishery are provided here, and a full

review of the species is provided in Chapter 8. *Homarus americanus* has three planktonic larval instars and one post-larval instar that is the transition from a pelagic to benthic existence. The first three larval stages distribute over a range of depths, but the post-larva is neustonic and therefore more prone to wind-driven transport. The post-larva is also a capable swimmer and swimming behaviour plays an important role in vertical and horizontal movements. About half-way through the post-larval stage they become competent to settle and begin diving to select appropriate shelter-providing habitat, typically in relatively shallow zones above the summer thermocline. Following settlement, early juveniles are cryptic and remain strongly associated with rocky shelter. As they grow they undergo an ontogenetic shift in behaviour and habitat use and they range increasing distances from shelter and become seasonally migratory between inshore and outer coastal waters (Wahle & Steneck, 1991; Lawton & Lavalli, 1995). Unlike spiny lobsters, clawed lobsters are not social – shelters are typically used by a single individual except during mating. Sexual maturity comes sooner and at a smaller size for males than females, but males larger than the female tend to have greater mating success (Atema & Voight, 1995). Maturation size and age varies regionally, most probably with thermal regime – females in the warmer southern New England, for example, mature in 4–5 years, whereas those in the colder Bay of Fundy mature at 8 or 9 years.

There are fisheries for *H. americanus* in both US and Canadian waters, and together they extend through most of the *H. americanus* geographic range. The US fishery is mostly near-shore (<100 m) within the Gulf of Maine (Area 1), and offshore (>50 m) in the south, including Georges Bank (Area 2), the southern New England shelf and Mid-Atlantic Bight (Area 3). In the USA, the lobster fishery within 3 nautical miles of shore is managed by the respective state marine resource agency. From 3 to 200 nautical miles offshore (the boundary of the Exclusive Economic Zone) the fishery is managed by the federal National Marine Fisheries Service (NMFS) and the Atlantic States Marine Fisheries Commission, a consortium of all lobster-producing states.

The Canadian lobster fishery is managed by the Department of Fisheries and Oceans and is divided into 41 Lobster Fishing Areas (LFA). In Canada, there is no division between provincial and federal waters as there is in the USA. To date only Canada's LFA 41 lobster fishery is certified by the Marine Stewardship Council (see also Chapter 6).

Lobster fishing is characteristically a near-shore coastal fishery in Atlantic Canada and the Gulf of Maine, where it does not extend much beyond 100 m depth. In southern New England and the mid-Atlantic states of the USA, it becomes more of an offshore, deeper water fishery, especially targeting the banks and canyons along the edge of the continental shelf. Harvesting is almost exclusively conducted by trap, although some lobster by-catch is permitted in trawl fisheries that operate in these areas.

Over the past three decades landings of the American lobster have increased dramatically, but not uniformly across the various areas. In the Gulf of Maine and maritime Canada lobster grounds, for example, lobster landings are experiencing historic highs, while the lobster fishery in southern New England is near historic lows. These changes are of great concern to the industry and managers alike. For the first time in history, fishery managers have been considering a moratorium on lobster harvesting in southern New England. The scientific consensus to date suggests that these dramatic changes in catch reflect changes in abundance that have less to do with changes in fishing effort and more to do with a widespread alteration of the physical and biotic environment, as we discuss below.

The total fishery catches from LMEs 7, 8 and 9, while collectively about 10-fold higher than those from LME 44, have been severely depleted of fin-fish. This has been followed by an increase in lobster and other crustacean landings (Fig. 1.3) especially in northern sectors (Worm & Myer, 2003; Frank *et al.*, 2006, 2007; FAO 2003).

LME 7

Much has been published on Northeast U.S. Shelf LME fisheries, including resource population assessments (Sherman *et al.*, 1996; Kenney *et al.*, 1996; Mavor & Bisagni, 2001) and the status of living marine resources in 'Our Living Oceans'

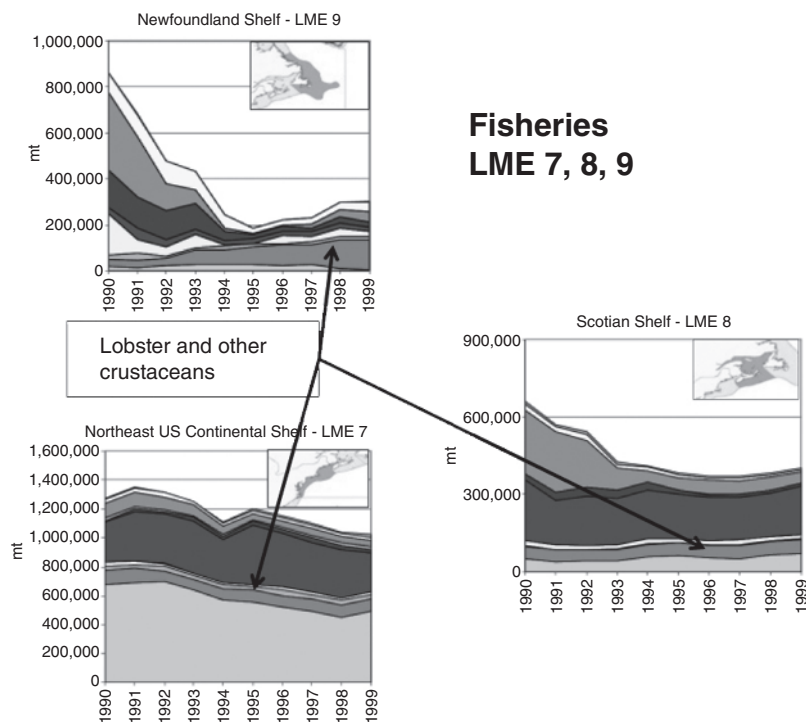


Fig. 1.3 *Homarus americanus* and other crustaceans caught in Large Marine ecosystems 7, 8, and 9. Data from FAO (2011).

(NMFS, 1996) and in the NEFSC Status of Stocks reports. The catch composition of this LME is diverse, and comprises demersal fish (groundfish) dominated by Atlantic cod, haddock, hakes, pollock, flounders, monkfish, dogfish, skates and black sea bass, pelagic fish (mackerel, herring, bluefish and butterfish), anadromous species (herrings, shad, striped bass and salmon) and invertebrates (lobster, sea scallops, surfclams, quahogs, northern shrimp, squid and red crab). In the late 1960s and early 1970s there was intense foreign fishing within the US Northeast Continental Shelf LME.

The precipitous decline in biomass of fish stocks during this period was the result of excessive fishing mortality (Murawski *et al.*, 2000). Total reported landings declined from more than 1.6 million t in 1973 to less than 500 000 t in 1999, before increasing to just less than 800 000 t in 2004. The value of the reported landings reached US\$1.8 billion (expressed as 2000 US dollars) in 1973 and in 1979, and has maintained a level above US\$1

billion except for the 3-year period between 1998 and 2000. Among the most valuable species are lobster, sea scallops, monkfish and summer flounder (Sherman & Hempel, 2009).

LME 8

Commercially exploited species in LME 8 include cod, haddock, pollock, silver hake, halibut, white hake, and turbot. Pelagic species include the Atlantic herring and the Atlantic mackerel. Invertebrates include snow crab, northern shrimp and short fin squid. Both snow crab and northern shrimp prefer cold water and the increased landings for both those species coincide with the cooling of the eastern shelf (Zwanenburg, 2003). Systematic fishery surveys of the shelf made between the 1960s and the present are the most consistent source of information available concerning this LME.

Total reported landings recorded a peak of 889 000 t in 1970 and declined to less than a quarter of this level or 213 000 t in 2004. Major changes

include a dramatic decline in landings of cod, silver hake and redfish. However, the value of the reported landings reached its peak of US\$1.2 billion (in 2000 US dollars) in 2000, as a result of high value commanded by its landings of crustaceans.

LME 9

Commercially exploited fish species in LME 9 include cod, haddock, salmon, American plaice, redfish, yellowtail and halibut. Also harvested are lobster, shrimp and crab. Historic records of catches of Atlantic cod can be reconstructed back to 1677 (see Forsey & Lear, 1987). Total reported landings, dominated by cod until the 1990s, exceeded 1 million t from 1967 to 1970, but declined to 525 000 t by 2004.

1.3 How far have we come in thinking about lobsters as part of the ecosystem?

1.3.1 *Panulirus cygnus*

Ecosystem structure and foodweb

The shelf waters of Western Australia and the east coast of North America are strikingly contrasting environments. Australia's western rock lobster occupies a geographic range that is subtropical to temperate and characterized by a gentle, although sometimes complex, north–south gradient in SSTs and ambient temperature. The West-Central Australia LME 44 extends from Cape Leeuwin (about 34.5°S), at Australia's south-west edge, to North West Cape (22°S). The LME owes its unity to the West Australia Current, a north-flowing current coming from the circulation pattern of the counter-clockwise Indian Ocean Gyre and West Wind Drift. But it also has a southward-bound band of warm water close to the continental margin known as the Leeuwin Current, which delivers warm waters to the coast in the Austral winter, permitting tropical and sub-tropical reefs systems to flourish in the shallow coastal waters at 29°S, the most southerly occurrences of hard coral reefs in the Indian Ocean. Biodiversity of the two regions is also very different (Plate 1.5).

The LME has an extremely narrow shelf, and much of the environment comprises cool, temperate waters with complex, diverse and abundant reefal, seagrass and algal communities, much of which is in good condition (DSEWPAC, 2011). The region is an important nursery area for the Antarctic-feeding humpback whale, and home to many species of other mammals (such as dolphins and sea lions) sharks, including the whale shark, and seabirds associated with the coastal islands and reefs. As with the targeted species, many species of flora and fauna are endemic to Western Australia, and the ecological values of these ecosystems are consequently high. Some elements of this biodiversity, such as the seagrass and algal assemblages, are of global significance, because of their substantial abundance, rich species diversity and extensive endemism. For example, Shark Bay and Ningaloo Reef, which are at the northern end of LME 44, are both World Heritage listed for the outstanding universal significance of their natural marine ecosystems (DSEWPAC, 2011).

The region has a Mediterranean climate, with mild wet winters and hot dry summers. There are only few major rivers delivering land-based nutrients, and nutrient-rich upwellings from the deep ocean waters are mainly limited to small shelf-edge canyons, which are the focus for significant local production, and attract large mammals and pelagic fish. The dominant feature of the shallow water ecosystems is the gradation between tropical and temperate flora and fauna, from the north to the south of the region, the low nutrient status waters, and the extensive system of barrier reefs running south to north that establish the inshore lagoonal ecosystem along much of the length of LME 44.

Ecosystem modelling

The trend in number of primary publications dealing with ecosystem approaches to fisheries and developing or applying ecosystem modelling for fisheries management was evaluated by Christensen & Walters (2011). They included results for the 20-year period from 1999 to 2009, and found 2785 ecosystem and multispecies modelling publications, of which 391 were publications developing, applying or reviewing ecosystem modelling

approaches. The results indicate an approximately 19% growth per year in the annual number of model publication since 1995.

Ecopath/EcoSim modelling (Christensen *et al.*, 2000) is a mass-balanced energetic modelling approach of ecosystem function that has gained increasing application. We are aware of Ecopath models applied to both the *P. cygnus* and *H. americanus* ecosystems. There have been two Ecopath studies in sections of the LME 44 and another modelling study attempted to identify indicators for the effects of fishing using a range of alternative models. None of these models were for the whole ecosystem, and they do not answer all the questions which might be asked, but they do provide a useful synthesis of some aspects of the problem, and some of the relevant data.

Jurien Bay Marine Park

Loneragan *et al.* (2010) and Lozano-Montes *et al.* (2011) used an Ecopath model to characterize the structure and function of the Jurien Bay marine ecosystem in temperate Western Australia ($\sim 30^\circ\text{S}$) and to explore the ecosystem impacts of fishing in the Jurien Bay Marine Park (area 823 km^2), a protected area with several levels of management zoning, including no-take areas. Jurien Bay Marine Park is not a protected area for the western rock lobster, and fishing, both commercial and recreational, is permitted in most areas of the park. Estimated total catches of all species in the marine park by the commercial sector (340 t in 2006) and recreational fisheries (56 t), were dominated by western rock lobster (*P. cygnus*) ($\sim 70\%$ of total catches).

A mass-balance Ecopath model was developed by Lozano-Montes *et al.* (2011) to quantify the interaction of prey, predators and the rock lobster fishery in Jurien Bay Marine Park. The model contained 250 species that were aggregated into 80 functional groups based on similar functional ecosystem roles or significance to fishing. A set of model parameters including biomass, consumption rates (Q/B), production per unit of biomass (P/B) and diet composition were used in the analysis.

The functional species groups covered more than four trophic levels (TLs). Sharks occupied the highest trophic level of the ecosystem, whereas

primary producers, detritus and other non-living groups (e.g. detached algae and bait) represented the lowest level (TL1). Owing to the nature of the adult rock lobster dietary characteristics (generalist feeders that feed on a range of plants and animals) the TL of adult lobsters was taken to be 2.7. Jurien Bay Marine Park was found to be dominated by the lowest trophic levels (TL1 and TL2) as the majority of functional species groups had a trophic level lower than 3.5 and comprised 80% of the total biomass ($1229\text{ t km}^{-2}\text{ year}^{-1}$).

The mixed trophic impact (MTI) analysis showed that several of the ecosystem functional groups ($>60\%$) were influenced by changes in the biomass of benthic groups (e.g. *Ecklonia*, seagrasses, macroalgae, phytoplankton and benthic invertebrates). When the biomass of *Ecklonia* increased, the biomass and trophic flows for groups such as post-puerulus rock lobster, juvenile rock lobster and crabs also increased. The overall relative change in MTI (biomass and energy flow) of post-puerulus, juvenile and adult rock lobsters was 0.22, a change almost double the magnitude of change in *Ecklonia* production. A possible explanation for this strong response by lobsters to changes in biomass of *Ecklonia* could be attributed to the food substrata and shelter the seaweed provides for lobsters. The MTI analysis also investigated the trophic role of adult rock lobsters and showed that even a small simulated increase in the MTI of adult lobsters resulted in a theoretical increase in lobster catch (18%) and a small decline of biomass and trophic flows of lobster prey (e.g. coralline algae, small gastropods, epifauna, crabs and small grazers) as well as a decrease in biomass and trophic flow to juvenile lobsters. The increase in adult lobsters also resulted in a small theoretical increase in biomass and trophic flow of lobster predators such as small sharks, rays, octopus and sea lions.

The results of these studies indicate that Jurien Bay Marine Park in its present condition is a dynamic ecosystem (Primary Production: Biomass ratio = 1.68) showing low recycling rates and is dominated by benthic functional groups (biomass of benthic: pelagic groups = 1.27). This domination by benthic communities suggests a greater importance of bottom-up processes than top-down interactions, driven primarily by *Ecklonia*, seagrasses

and macroalgal communities that are the main habitat and food source for many invertebrates and fish species in the marine park. This study did not simulate the ecosystem structure that may have existed in the absence of fishing, and so it is unclear how the natural (unfished) ecosystem would have been structured or have functioned in the presence of natural abundances of the various age classes of lobsters that would exist within the marine park (puerulus of *P. cygnus* settle in high abundances in this region, and in suitable habitat in this marine park). Also, the study did not consider in detail the potential effects of input of settling lobsters originating outside the study area. The relative importance of the benthic processes, the ecological function of the lobsters and the high-level predators may be somewhat different in the natural condition from that reported in these Ecopath studies for this ecosystem.

Lobster structuring of benthic communities

Moore & Hynes (2011) reported that although there has been over 30 years of research into the biology, ecology and behaviour of *P. cygnus*, there was still little quantitative information on potential flow-on trophic effects on the structure and functioning of benthic marine assemblages resulting from the removal of *P. cygnus* by this fishery. They undertook a project to quantify the impact, if any, of the western rock lobster fishery on trophodynamics within shallow-water assemblages.

The results demonstrate that *P. cygnus* may influence the abundance of the numerically dominant gastropod grazer *Cantharidus* spp. However, they showed no evidence of flow-on effects through the food web or any evidence that *P. cygnus* plays a role in structuring benthic assemblages as a whole and they could find no evidence that *P. cygnus* plays a 'keystone' role anywhere in its biogeographic range. Based on these investigations of the role of *P. cygnus* density, diet and behaviour in influencing assemblage structure, it was concluded to be unlikely that the western rock lobster fishery has a significant structuring impact on shallow-water benthic assemblages, or is a bottleneck through which large amounts of shallow water biomass and energy passes. However, this conclu-

sion has been challenged by MacArthur *et al.* (2007), who consider that there is little evidence to determine if the western rock lobster is or is not playing a major ecological role in community structuring. They point to the better studied examples of lobsters in other parts of the world where such ecological structuring roles are more evident (e.g. *P. interruptus*: Robles, 1987, 1997; Robles & Robb, 1993; Lafferty, 2004; *Jasus edwardsii*: Babcock *et al.*, 1999; Babcock, 2003; *J. lalandii*: Barkai & McQuaid, 1988) and conclude that the hypothesis for western rock lobster remains to be tested in any convincing manner. MacArthur *et al.* (2007) also further conclude that while the western rock lobsters may not be demonstrated to be keystone species, they are likely to be important components of the energy cycling in both shallow- and deep-water areas, and hence represent important grazers and predators, respectively, and provide an important prey source for many species of coastal fish, sharks and other large invertebrates such as octopus. This conclusion about the likely important role of the lobsters in energy cycling and trophic structure of shallow water ecosystems has been further reinforced by subsequent studies of the diet and nutrition in shallow waters near patch reefs in the region (MacArthur *et al.*, 2011).

Larval advection modelling

Caputi *et al.* (2010) have developed a model to assess the relative contribution of larval production from different areas of the breeding stock to the abundance and spatial distribution of puerulus settlement using a larval advection model. It is hoped that this model will assist in developing an understanding of the space and time factors influencing the advection of puerulus, and contribute to a better understanding of the causes of the low puerulus settlements in recent years.

Effects of fishing

The identification of indicators of the indirect effects of fishing is often an issue for fisheries management, particularly if only commercial catch data (i.e. direct effects of fishing) are available. Complex, intermediate and simplified qualitative models,

including aspects of uncertainty and aggregation error, were produced for two fishery case studies off Western Australia to identify potential indicators of change caused by fisheries extraction and bait input (Metcalf *et al.*, 2011). The two sites studied were in the West Coast Bioregion (WCB) between 20 and 250 m depth. High levels of both recreational and commercial effort in the WCB, particularly in the metropolitan zone near Perth, have been identified to be responsible for a decline in the abundance of several species of fin-fish, including dhufish and pink snapper (Fletcher & Santoro, 2010). Commercial and recreational rock lobster fishing also occurs in this bioregion. The study also explored the indirect ecological impacts of lobster fishing (*P. cygnus*) and focused on a smaller study area within the coastal zone (40–

60 m) of the WCB, off Jurien Bay. This region was selected as it is located towards the centre of the lobster fishery's distribution and has been demonstrated to be representative of the wider fishery in terms of habitats, fishing effort and lobster catch (Bellchambers, 2010).

Models of intermediate complexity (Fig. 1.4) were used to identify indicators as they produced the lowest aggregation error (9% and 25%) and structural uncertainty was considered through the use of a series of structurally different intermediate models. Small fish without significant economic value, including old wife (*Enoplosus armatus*), footballer sweep (*Neatypus obliquus*), king wrasse (*Coris auricularis*) and bullseyes (*Pempheridae* spp.) were identified as potential indicators of the impacts of extraction of other demersal fish due to

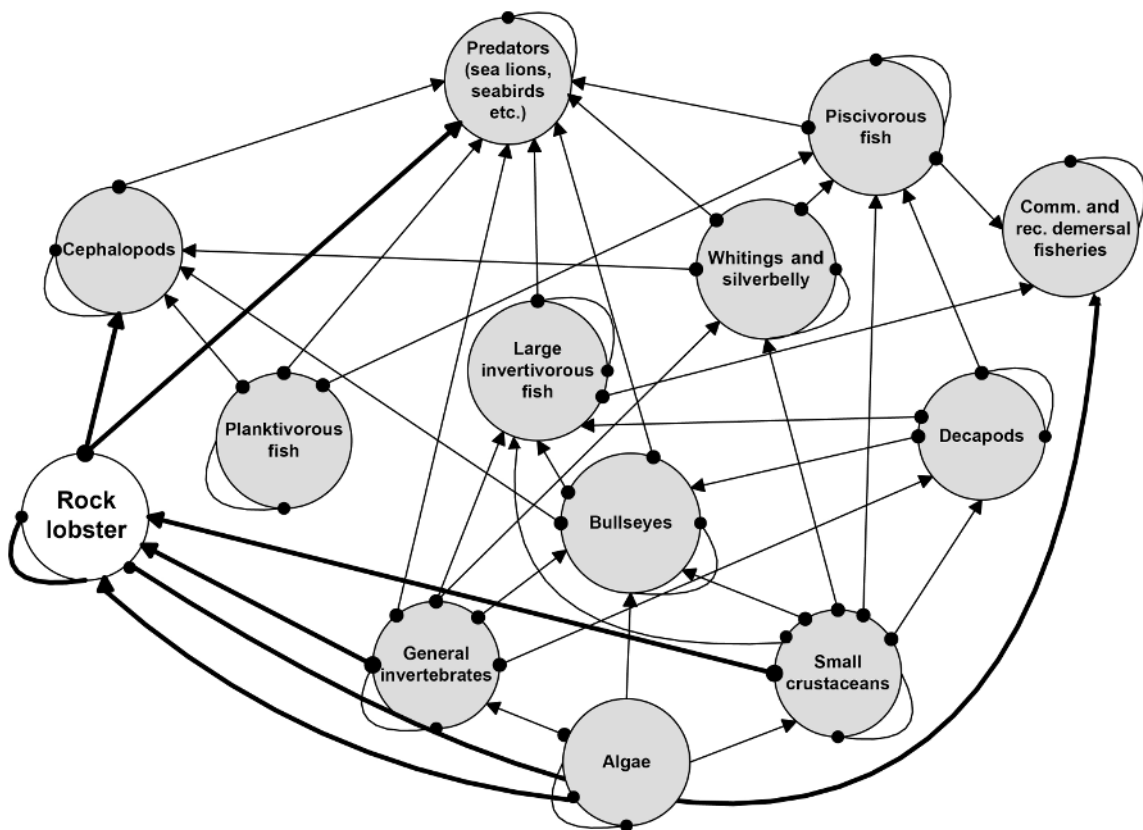


Fig. 1.4 Simplified inshore demersal model of the effects of fishing by *Panulirus cygnus* in Jurien Bay in Western Australia (from Metcalf *et al.*, 2011, with permission).

positive impacts across alternative models. Small crustaceans (amphipods and isopods) displayed positive impacts due to bait input from the rock lobster fishery and were identified as potential indicators of bait effects. Monitoring of these indicators may aid the detection of incremental changes in the present-day ecosystem that could be related to the activities of these fisheries. This study suggests useful methods for the future but no action to introduce these indicators to the fishery management system appears to have been initiated at this time. Equally, these methods are useful for current management purposes, but do not provide a basis for estimating the extent of the historical ecological impacts of these fisheries since their inception (see below).

1.3.2 *Homarus americanus*

Ecosystem structure and foodweb

The confluence of the cold southward flowing Labrador Current and the warm northward flowing Gulf Stream in the shelf area off the north-east USA and Atlantic Canada creates a dramatic latitudinal gradient across LME 7, 8 and 9. The latitudinal contrast is most evident during the summer when SSTs can be as high as 23–26°C in coastal southern New England, while temperatures in the Bay of Fundy some 200 km to the north reach maxima of only 11–12°C (see Plate 1.4). Influenced by the continental climate and prevailing westerly winds, this part of the Northwest Atlantic is strongly seasonal. Strong summer thermoclines become established with notable exceptions such as the Bay of Fundy, which is subject to extreme tidal mixing. Coastal waters freeze during the winter in large areas of the Gulf of Saint Lawrence and in smaller embayments to the south.

The coast of the Northeast USA and Maritime Canada strongly reflect the glacial history of the region. The seabed and shoreline variably consists of glacially scoured bed rock and unconsolidated gravel, sand and mud. The general distribution of bottom sediments has been well mapped, although the local detail may be sparse (Frank *et al.*, 2006, 2007).

Primary production and associated fishery productivity on the relatively broad and shallow shelf area of the north-west Atlantic LMEs 7, 8 and 9 is large and regionally variable (Sherman *et al.*, 1996; Frank *et al.*, 2006, 2007). There have been intensive studies of both the pelagic (Johnson *et al.*, 2011) and demersal biodiversity of these LMEs, demonstrating the rich and structurally complex set of habitats and species that inhabit the area, with high ecological values across the regions. A number of areas have been designated for special protection and management (<http://www.mar.dfo-mpo.gc.ca/e0009691>), and there has been intensive development of indicators for use in EBM (O'Boyle *et al.*, 2005; O'Boyle & Worcester, 2009).

Most fisheries in LME 7, 8 and 9 of the north-west Atlantic are managed as single species, although both the USA and Canada officially embrace and are gradually implementing EBFM. In Canadian waters, the lobster fishery is managed by the Department of Fisheries & Oceans, and is divided into 41 LFAs. The Canadian lobster fishery is mostly limited to <50 m depth, except on the southern Scotian shelf. The near-shore fishery includes the south coast of Newfoundland, the southern Gulf of St. Lawrence, coastal Nova Scotia and New Brunswick. Canada's offshore fishery on the south-western Scotian Shelf includes Brown's Bank, Crowell Basin, George's Basin and the north-eastern slope of Georges Bank (Fig. 2 in Moody Marine Ltd, 2010). Lobsters taken from the relatively small LFA 41 are currently MSC certified. The lobster fishery in the US Management Area 1 (Gulf of Maine) is currently undergoing an assessment to determine if it complies with the MSC standard, scheduled for completion in late 2012.

North-west Atlantic lobster populations have undergone a substantial increase in abundance since the 1980s (Fig. 1.5), apparently as a result of environmental changes, but the relationships of abundance to environmental conditions are not understood. Predation release with decline in groundfish populations at the end of the 20th century is one hypothesis to explain the increase in lobster abundance, but the processes that might explain this have not been demonstrated clearly. Lobster fishery production throughout the north-west

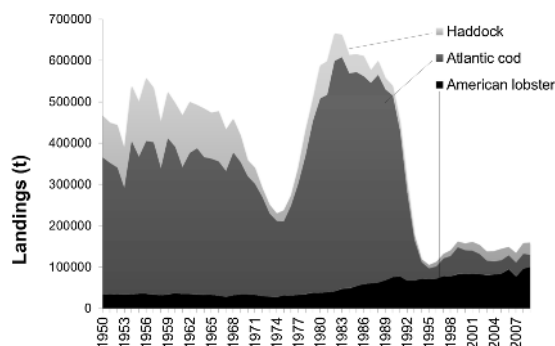


Fig. 1.5 Haddock, Atlantic cod and American lobster caught in Large Marine ecosystems 7, 8, and 9. Data from FAO (2011).

Atlantic remains very high relative to conditions from about 1920–80, despite very high fishing pressure, suggesting that productivity of lobster populations is elevated relative to conditions which prevailed during most of the 20th century. Despite this, the Atlantic States Marine Fisheries Commission has called for a 5-year closure of the fishery on the Southern New England stock, as the stock is considered to have fallen below the main trigger point in this part of its geographic range and needs rebuilding (ASMFC, 2010). Demersal and benthic fishes have long been recognized to be major predators of *H. americanus* (Herrick, 1911). The widespread depletion of groundfish, including cod, in the north-west Atlantic is strongly correlated with the upsurge in American lobster, crab (*Chionoecetes opilio*) and northern shrimp (*Pandalus borealis*) abundance in recent decades (Acheson & Steneck, 1997; Worm & Myers, 2003), suggesting the groundfish predators play a central role in population regulation. Further time series analysis of US National Marine Fisheries Service trawl survey time series in the Gulf of Maine points to a strong inverse correlation between the abundance of the American lobster (kg/tow) and the aggregated abundance of four species of groundfish (Atlantic cod, cusk, longhorn sculpin, monkfish and wolffish), as well as the singular abundance of cod (Boudreau & Worm, 2010). *Homarus americanus* is also reported from stomachs of a more near-shore

assemblage including striped bass (*Morone saxatilis*), shorthorn sculpin, (*Myoxocephalus scorpius*), cunner (*Tautoglabrus adspersus*) and white hake (*Urophycis tenuis*) (Steimle *et al.*, 2000; Nelson *et al.*, 2003).

A series of studies of trophic relationships of lobster has been conducted in the fishery area. Very young shelter-dwelling juveniles may be suspension feeders, and suspension feeding may continue with growth (Lawton & Lavalli, 1995), but suspension feeding was not found to be important in one detailed study (Sainte-Marie & Chabot, 2002). Juveniles and adults generally prey on the same species, but proportions change with growth: a wide variety of prey items has been reported including gastropods, crabs, polychaetes, fish, echinoderms and other benthic invertebrates (Lawton & Lavalli, 1995). Unidentified flesh may be important in the diet, which may come from dead fish, trap bait or live-captured fish (Lawton & Lavalli, 1995; Sainte-Marie & Chabot, 2002). Lobsters may also consume plant material (Lawton & Lavalli, 1995). Diet may vary seasonally, with the moult cycle (higher calcium prey may be sought after the moult) and with area. Earlier reports that lobsters are scavengers, unspecialized feeders or opportunistic omnivores appear unsupported based on recent studies which suggest that lobsters are selective feeders. Crab may be a particularly important part of the diet because of its high protein content, and was found to be a high proportion of the diet, particularly of adults, in one study in eastern Canada (Sainte-Marie & Chabot, 2002). Juvenile lobsters are preyed on by a variety of inshore species including other lobsters, crabs (*Cancer*), sculpins, flounders and cunners, and predation is particularly concentrated on shelter-dwelling juveniles in the period after moulting (Lawton & Lavalli, 1995).

Effects of fishing

Steneck *et al.* (2004) examined the process of ‘fishing down the food web’ in the Gulf of Maine as could be inferred from archaeological evidence, early naturalist observations and the scientific literature. They identified a Phase I as an ecosystem

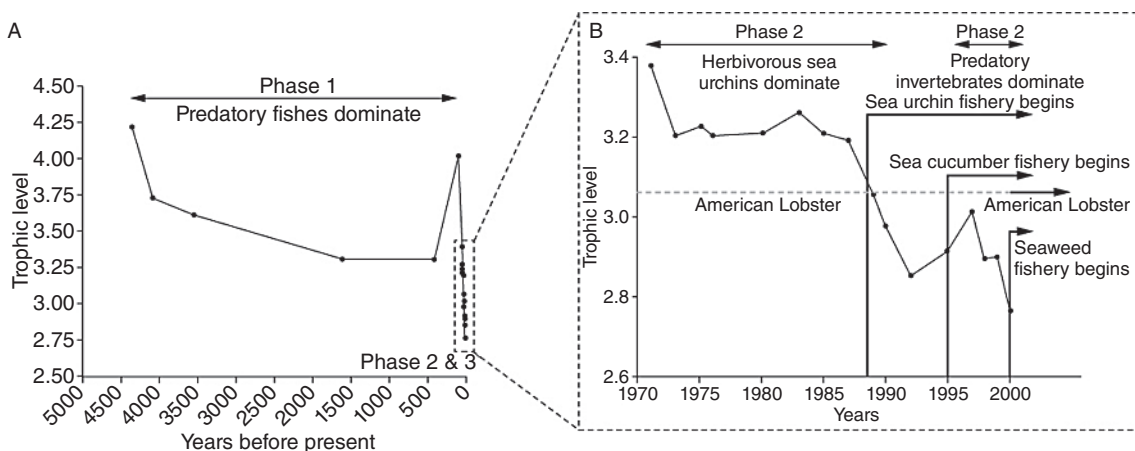


Fig. 1.6 Reconstructing the history of the coastal ecosystem - evidence of phase shifts and trophic dysfunction. Constructed from a paper by Steneck *et al.* (2004). With permission.

dominated by large apex predators, such as fish and marine mammals; Phase II where the ecosystem was dominated by sea urchins; and Phase III dominated by predatory invertebrates such as lobster and crab whose populations have been released from predation by larger (fish) predators (Fig. 1.6). Trophic analysis indicated declining average trophic level of the food web over time. Steneck refers to this serial loss of trophic levels as ‘trophic dysfunction’, pointing out that low diversity food webs like the Gulf of Maine are particularly vulnerable to such trophic cascades, and that greater functional redundancy (more species) within a trophic level confers resistance to trophic cascades.

Much of the coastal ecosystem within the geographic range of the American lobster has been subject to the serial depletion of top marine consumers, a globally classic example of ‘fishing down the food web’ (Pauly *et al.*, 1998; Conti *et al.*, 2012) and the scientific evidence has been building that this has had important consequences for the abundance of the American lobster and other large benthic crustaceans. For further discussion and evidence in relation to this issue see Worm & Myers (2003); Frank *et al.* (2006, 2007); Steneck *et al.* (2004); Boudreau & Worm (2010).

Ecosystem modelling

Gulf of Maine Ecopath model

Zhang & Chen (2007) developed an Ecopath model to evaluate changes in the Gulf of Maine ecosystem over a period of considerable groundfish depletion by harvesting. Their studies showed the Gulf of Maine has undergone a switch from a groundfish-dominated to a crustacean-dominated system, with American lobster and crabs at historic high levels of abundance. Several hypotheses have been developed to explain such a switch, ranging from trophic interactions between groundfish and crustacean species to increased food availability to crustacean species due to discarded baits in the lobster fishery. The study developed a mass-balance ecosystem model separately for the two time periods (1980s and 1990s) using Ecopath with Ecosim (EWE). The model has 24 function groups including lobster, the focal species of the analysis as a mid-level consumer and prey of groundfish. Other important groups in the ecosystem such as zooplankton, phytoplankton and detritus were also included in the model. The input data on abundance and vital rates were obtained from published papers and reports. The trophic structures of the ecosystem in the mid-1980s was found to differ

from that of the mid-1990s, when a decrease in top predator biomass coincided with an increase in the biomass of mid-level consumers (Plate 1.6). Ecosim was also used to predict the response of the lobster population to the recovery of the top predator, Atlantic cod (*Gadus morhua*), in the Gulf of Maine. Although the full-scale recovery of cod and other depleted groundfish is predicted to adversely impact lobster production, it would help restore the spectrum of fisheries available to the fishing industry as well as probably a more naturally resilient ecosystem structure and function of the ecosystem.

The ecosystem model developed in the Zhang & Chen (2007) study, although preliminary, provides us with a new approach to evaluate the trophic interactions of lobsters and other organisms, helps us better understand the ecosystem dynamics, and provides information critical to the development of an EBM strategy for the interdependent lobster and groundfish fisheries. More studies of this type are needed, however, to reduce uncertainties in input data, to evaluate the performance of the model, to better develop ecological indicators and benchmarks, and to better understand the long-term history of shifts in ecosystem structure and function.

Link *et al.* (2011) reviewed current and ongoing ecosystem modelling efforts in the North US shelf LME with emphasis on how they are being used in a living marine resources management context. An external independent peer review of these modelling approaches (Smith, 2011) confirmed that there were a number of modelling approaches underway in, and directly relevant to, LMEs 7, 8 and 9. However, many of these model types and modelling approaches were of limited value for EBFM in the region. The core issues of EBFM relating to reference points and other practical management tools that will provide for appropriate and agreed maintenance of the structure and functions of the ecosystem have yet to be established. While many of the modelling approaches have the basic architecture that will enable them to include lobsters, so far there has been very little progress in the development of ecosystem models that do include lobsters and the lobster fisheries. Further, given the presumed relationships between groundfish popu-

lations and lobster populations, and the associated socio-economic relationships, it could be well argued that any ecosystem modelling that does not include lobsters will fail to meet the basic requirements of EBFM for these LMEs.

1.4 Human role in ecosystem dynamics

1.4.1 Institutional structures

A recent trend to emerge in EBM has been the recognition that in order for this process to be successful the economic and social spheres must be better incorporated (see for example O'Boyle & Worcester, 2009). While some authors have felt that there has been perhaps an overemphasis on the ecological aspect of EBM and the major gaps are now in dealing with the social and economic issues (Rosenberg *et al.*, 2009), there now seems to be a rebalancing being achieved as economic and societal objectives are more frequently mentioned as key components in the successful implementation of EBM (Curtin & Prellezo, 2010). This gap is perhaps best represented by the difficulty that EBFM systems have in creating processes and structures that result in the effective involvement of stakeholders from a wide range of institutions and civil society into the decision-making processes about resource harvesting. Garcia *et al.* (2003) alluded to this perception of imbalance when they noted that humans cannot be looked on as external influences on the ecosystem. They noted that the interdependence between ecosystem well-being and human well-being requires the conservation of habitats, reducing human impacts and the maintenance of ecosystems for current and future populations.

The fishery sector has not been immune to the wide-ranging nature and pressures brought about by globalisation. Aided by technological advances, globalisation has resulted in a greater exploitation of high-value fisheries for export products and the emergence of environmental and social standards that ensure the survival of by-catch species and greater resilience of ecosystems, and promote responsible codes of fishing practice. In Australia,

an increasing number of studies have been conducted on the changing social and economic conditions in rural communities, focused on areas connected with, if not wholly dependent upon, primary industries. However, much of the research has focused on the agriculture sector and on broad-acre agricultural regions. This research gap is also evident in Canada where, as Troughton (1995) observed, 'Despite their major regional economic significance, there are very few studies of change in forestry, mining, and fishing industries, especially the changing nature of technology and its impacts on employment and communities.'

In a study of the western rock lobster fishery, Huddleston & Tonts (2007) stress the contribution that the western rock lobster fishery makes to the economies of many coastal communities in Western Australia and the important contributions of rock lobster fishers and their families to the social fabric of these communities. In that case, the important contribution and legacy of the fishery to the development of these communities was considered able to continue to be enhanced if fishery stakeholders engage in a more proactive media and communications campaign capitalizing on local and regional media to foster a positive impression of and build up future support for the fishery.

In an attempt to further address this seeming imbalance, one of the first comprehensive studies of industry restructuring in the fisheries sector in Western Australia focused on the linkages and implications of restructuring on the social, economic and cultural facets of coastal communities in Western Australia (Huddleston, 2009). The western rock lobster fishery is the most valuable single species fishery in Western Australia with a sizeable financial and employment contribution to coastal communities along the Western Australian coast. The study presented a snapshot of this fishery at a time when fishery managers were deliberating changes in management arrangements and its effects on coastal communities that historically had depended, and to a great extent still depend, upon rock lobster fishing. It provides empirical evidence that lends support to the view that the pro-market policies promoting competition and entrepreneurialism have resulted in a spatially uneven development and distribution of benefits in regional

Australia. The study emphasizes that while specific localities can deal with the changes brought about by globalisation and policy change, the manner in which these communities deal and cope with these changes depends on, among others, the level of diversification of the local economy, demographic and social structures, and other factors such as the level of resilience and the base of social capital within the community.

1.4.2 Direct effects of management

The lack of compliance with regulations is an obvious threat to the sustainability of any commercial fishery, and compliance programmes (detecting non-compliant activities, at-sea fishery-independent observers, educational programmes and professional development for fishers, etc.) are usually an important aspect of any fisheries management regime. For example, this was addressed early in the development of the western rock lobster fishery. In the 1960s, effort limitations were introduced and it was probably not a coincidence that illegal fishing activity became widespread. Subsequently, under-sized animals and egg-bearing lobsters stripped of their brood were being processed and this illegal market spread from the local markets to markets in eastern Australia. As a result, measures were introduced to counteract the problem, specific legislation to restrict processing to licensed establishments, more inspectors, increased fines for offences, convictions recorded against the vessels rather than their skippers, and licenses cancelled after the third offence. These measures helped to make this fishery a highly compliant industry. Even today, much effort goes into ensuring compliance and research into improving the efficiency of compliance (McKinlay & Millington, 2000; McKinlay, 2002). As few as two from every 1000 animals checked by enforcement officers are found to be illegal.

An early assessment by the Department of Fisheries in Western Australia concluded: 'Overall, the (western rock lobster) fishery is unlikely to cause significant trophic ('food web') cascade effects, as the protected sub-legal-sized lobsters and breeding stock components form a relatively constant significant proportion of the biomass which remains

from year-to-year, and the catch, particularly in inshore areas, is less than the annual variability in biomass due to natural recruitment cycles.' Nonetheless, the rock lobster-specific ecological risk assessment (completed in 2008) considered that, due to the lack of information, the removal of lobster in deep-water regions might be having some level of impact on the surrounding ecosystem, and this was classed as a moderate risk. Consequently the deep-water areas of the fishery have become a focus of research, with preliminary work, now completed, and continued monitoring and research to underpin management of the Capes Marine Park has been initiated to expand on these preliminary findings (Fletcher & Santoro, 2011). However, since most of the lobster biomass (the sub-legal sizes and ages) actually occurs in the shallow waters, any effects of fishing on the legal-sized parent stock is likely to have a major ecological impact in these shallow water ecosystems (MacArthur *et al.*, 2007). The sub-legal biomass is likely to have been heavily reduced by the cumulative effects of many years of fishing, relative to the natural situation. Although the extent of this reduction has not been estimated it is likely to be similar to the level of reduction of breeding biomass by the fishery relative to the unexploited level, which is targeted by the fishery to be retained at about 25% of unfished biomass – a 75% reduction. This infers that the trophic ecological impacts on other species from reduction of the sub-legal biomass by the fishery could be very substantial, and an important ecological consequence of fishing stocks down to levels as low as 25% of the unexploited lobster biomass.

MacArthur *et al.* (2007) also report that studies have found relative levels of western rock lobster biomass more than 300 times higher, and levels of egg production 100 times higher, inside unfished shallow water sanctuary areas relative to nearby fished areas. It is therefore likely that studies of the deep-water ecological interactions will not give a complete picture of the ecological effects of the fishery on food chains that would have existed prior to the commencement of fishing, or that would have existed under very light fishing pressure. Estimating these impacts requires a comparison of the distribution of the modern-day biomass across the

age spectrum with the estimated biomass and structure that would have existed prior to fishing (see Chapter 6), models of the food chain effects of the historic lobster removals relative to the unfished conditions, and models of the impacts of the current level of lobster harvests in the modern-day ecosystems.

The legislated design of western rock lobster pots, the materials they are made from and the strict control of replacement pots prevent 'ghost fishing' problems for lobsters arising as an issue. A study of human impacts on the marine environments of the Abrolhos Islands estimated that potting might physically impact only small areas of fragile coral habitat at the Abrolhos, where fishing is only allowed for 3.5 months of the year. Generally, throughout the coastal fishery, rock lobster fishing occurs on sand areas around robust limestone reef habitats covered with coralline and macro-algae such as kelp (*Ecklonia* sp.). This type of high-energy coastal habitat is regularly subjected to swell and winter storms and so is considered highly resistant to physical damage from rock lobster potting. The significant recent reductions in fishing effort to protect the level of breeding stock will also have reduced these risks even further.

1.4.3 Indirect effects – top-down forcing by predator removal

Marine food webs throughout the North Atlantic appear to have been altered dramatically by the depletion of large predatory groundfish (Frank *et al.*, 2006, 2007). Frank and co-workers observed that increases in the abundance of mid-level consumers such as forage fish and crustaceans responding to relaxation in levels of predation has been most evident in simpler, less diverse ecosystems where fewer unexploited predator species can play the functional role of those removed. While there have been some limited modelling studies in the Western Australian situation, and 20 species have been identified as known or potential predators on lobsters, there have been no studies of the effects of predator removal directly affecting abundance of *P. cygnus*.

1.4.4 Indirect effects – bottom-up forcing by bait subsidies

While the evidence for top-down forcing as the explanation for the boom in lobster abundance in LME 7, 8, and 9 has been gathering force, bottom-up effects may also play a role, primarily as bait subsidies to the lobster energy budget. Because traps in the Canadian and US fishery have escape vents, small lobsters may enter a trap, consume bait and leave. Herring bait can be detected in stomach analysis. As it is assimilated over time it gives an altered nitrogen stable isotope ratio in lobster tissue compared with that observed in lobsters feeding on a bait-free natural diet.

In the Western Australian LME 44 situation, there have been several studies of the role of bait in the lobster fishery. The conversion ratio of bait to landed lobster biomass in the fishery is about 1:1, across fishing seasons 2007–10, equivalent to an annual input of about 8540 t of bait in these fishing years. Estimates of the bait subsidy to lobsters vary from 13% to 80%, depending on the methods used and sample design of the studies. The most recent studies from inshore habitats where lobsters spend most of the early life and are in rapid growth phase indicate that lobsters may derive up to 30% of their energy supply from bait (Macarthur *et al.*, 2011). This also indicates that this extensive input of bait also has the potential for a significant ecosystem level impact on other species that feed on fish carcasses and the other forms of bait used in this fishery. The bait is primarily fish waste sourced from other countries (comprising 86% of the bait used in the 2009/10 fishery) and from other states of Australia, but also includes pig fat (1.3%) and kangaroo parts (0.2%). Modelling studies suggest that the bait provisioning for the ecosystems and species other than lobsters potentially results in enhanced populations of a wide variety of species, potentially disrupting natural species and ecosystem level structure and function (Metcalf *et al.*, 2011), supporting the earlier studies indicating significant ecosystem disruption by the use of bait in this fishery (Waddington & Meeuwig, 2009). An important impact of this bait subsidy in this ecosystem is likely to be for octopuses, which have been observed to enter the traps and consume bait.

The octopus population is emerging as a subsidiary fishery in the region, and the enhanced octopus populations may also have ecological impacts on other benthic species in the shallow inshore reef ecosystems.

1.4.5 Climate change impacts

This is a development for lobsters and their fisheries that has been recognized over the last 10 years. However, oceanographic aspects have been studied for much longer. It is also important to distinguish between climate dynamics and climate change trends. Aspects of both climate change and climate dynamics include changes in sea level, temperature, salinity, acidity, ocean circulation and consequent medium- to long-term changes in the ecology of species in the marine environment (see also discussion in Chapter 4 and Chapter 8).

In the LME 44 region, Caputi *et al.* (2010) and Caputi *et al.* (2010) reported that climate change is causing an increase in water temperature that is seasonally variable, a weakening of westerly winds in winter, and an increase in the frequency of El Niño events. Rising water temperatures over 35 years are hypothesized to have caused a decrease in size at maturity and size of migrating lobsters from shallow to deep water, increases in abundance of undersized and legal-sized lobsters in deep water relative to shallow water, and shifts in catch from shallow to deep water. The size of migrating lobsters is hypothesized to be related to the water temperature about the time of puerulus settlement (4 years previously). Climate change effects on puerulus settlement, catchability, females moulting from setose to non-setose, timing of moults, and peak catch rates were assessed. As climate change models project that the warming trend will continue, these biological trends may also continue. The changes may have negative (increasing frequency of El Niño events) or positive (increasing water temperature) implications for the fishery, which need to be taken into account in stock assessments and management.

Cheung *et al.* (2011) reported on the development of an approach that applies the projections of global climate change impacts on marine biodiversity, fisheries and socioeconomics to develop

EBFM that is relevant to regional and local scales of management. This approach is being trialled for the West Coast Bioregion in Western Australia. There are no data arising from this project to date.

Projected climate change impacts on natural resource and socio-economic sectors of the north-east USA were examined in Northeast Climate Impacts Assessment (Frumhoff *et al.*, 2007), which featured the American lobster as a case study. The assessment modelled impacts under a range of carbon emissions scenarios projected by the International Panel on Climate Change (IPCC). The study employed three global atmosphere–ocean general circulation models: U.S. National Atmospheric and Oceanic Administration’s Geophysical Fluid Dynamics Laboratory (GFDL) Model CM2.1, the United Kingdom Meteorological Office’s Hadley Centre Climate Model, version 3 (HadCM3) and the National Center for Atmospheric Research’s Parallel Climate Model (PCM). Model output included projections of precipitation, air and seawater temperature, pressure, cloud cover, humidity, along with other climate variables downscaled to sub-regions of interest in the north-east USA. Downscaling of model output to these sub-regions involved coupling the coarse scale climate models with finer-scale regional models of ocean dynamics.

1.5 Single species to ecosystem management – how far have we come?

The essence of the shift from the more traditional single-species management approach to the EBM of fisheries is to manage the targeted species and the impacts of fishing in the context of the broader ecosystem and its condition. This is so that fishing does not directly, inadvertently or indirectly degrade the condition of the ocean ecosystems, and gives both the biodiversity of the oceans and the populations of the fished species the highest level of resilience to both the impacts of fishing itself and other environmental impacts. The EBFM approach also recognizes that there are multiple fisheries that operate in an ecosystem, and that they may interact

with each other in direct and indirect ways, and they may have cumulative impacts on non-target species in the ecosystem. By using objectives and values for ecosystem and fishing in equal part, this creates a coupling between natural and social systems that has been missing from the traditional systems of single-species management and is key attribute of effective forms of EBFM (Essington & Punt, 2011).

It is normal for the fisheries management systems (such as often described in EBFM) to be responsible for designing and delivering many of the management actions, but the key difference between what is now emerging as EBFM and what is considered to be EBM is the full integration of the social and ecological values of the ecosystems into the resource harvesting systems. It turns out that taking a comprehensive approach to EBM in fisheries management involves taking a more precautionary approach to stock management, recognizing that there are many uncertainties that are practically unknowable, and explicitly incorporating non-targeted aspects of the ecosystem into the setting of fishing objectives to ensure that high levels of resilience are maintained in the ocean ecosystems. This benefits the natural systems and also the social systems, as it usually requires a rebuilding of target stocks to higher levels, from which, in most cases, greater harvest can also be taken than is currently the case.

Many of the key issues and steps towards a more effective EBM approach to fisheries management were described by Ward *et al.* (2002), and there have been various subsequent interpretations and proposed developments of this approach. However, the implementation of the various aspects of marine EBM and EBFM is far from uniform or agreed. A complete issue of the journal *Fish and Fisheries* was recently devoted to discussing the topic (Essington & Punt, 2011), and it is clear that there are still a number of disagreements about what the concept of EBFM means in practice and how it represents the broader practice of EBM for marine ecosystems. In lobster fisheries, there are no standard approaches to EBFM that have yet been adopted, although there are a number of research programmes underway studying various elements that will be needed in a complete EBFM (such as

Fletcher *et al.*, 2010). The main stumbling block to adoption of a complete and effective form of EBFM – such as the approach described for Antarctic fisheries by Constable (2011), and demonstrating the features advocated by Rice (2011) – in lobster fisheries is the very low level of current lobster populations, and the complexity and variety of scales of the ecological and social systems that lobster fisheries operate within.

Significant reductions in total fish biomass through high levels of fishing can affect ecosystems, since species of one or more higher trophic levels are effectively removed allowing other lower trophic levels to expand, and eventually become the focus of fishing ('fishing down the food web'; Pauly *et al.*, 1998, 2002). Similarly, the excessive reduction of the biomass or species making up other lower trophic levels can also result in a flow-on effect at higher trophic levels, reducing the food available for predators that would have otherwise preyed on these lower trophic level species. While this effect is perhaps most easily observable with effects on large predators (sharks, billfish, birds, etc.), the trophic consequences of excessive fishing of middle and lower trophic order species also flows to all life stages, including the newly spawned and juvenile individuals, which are themselves preyed upon by small predators. This includes lobsters, which may be best classified as middle order trophic order species, despite their ontogenetic shifts in dietary preference and relatively broad range of food items at specific ages (MacArthur *et al.*, 2007). Such 'trophic cascade' effects are most likely to be observed in ecosystems that do not have highly effective fishery management controls, or where management systems do not retain appropriately high stock biomass levels and avoid the fish-down of stocks of target species to ecologically low levels. Fishery management systems in general do not give any significant priority to maintaining predator abundance at levels that will maintain top down trophic function, or to monitoring or avoiding trophic cascades (Rice, 2011).

1.5.1 *Panulirus cygnus*

All fisheries in Australia's LME 44 region are subject to management plans that embrace the prin-

ciples of EBFM as opposed to single target species management approaches (Smith *et al.*, 2007). For the 21 managed fisheries in the region, 15 have published Stock Assessments and 16 have published Ecological Risk Assessments (Fletcher & Head, 2006). Of those with published Ecological Risk Assessments, one fishery had inadequate spawning stock levels, one had moderate bycatch species impacts, one was assessed as having moderate protected species (marine mammal) interaction, two were assessed as having moderate food chain impacts, and one had moderate habitat impacts.

Australia is committed to fisheries ecosystem management but the use of fisheries ecosystem management is not arranged around the LME boundaries. The defining basis for EBFM as practised in Western Australia is that the scope of issues covered is restricted to those that can be managed by the relevant fisheries management agency (hence the 'F'), as well as those that need management reaction and can be influenced (as opposed to delivered) by the fisheries management agency. In this sense, EBFM can therefore cover either part of a fishery, all the issues affected by an entire fishery, up to managing the full collection of fisheries operating in a region (which would then also deal with their cumulative impacts and the allocation of resource access amongst the individual sectors), but only to the extent that this can be influenced by the fisheries management agency. The level chosen for management intervention will depend upon the scope of the assessment required and the jurisdiction of the agencies involved. However, to implement EBFM fully would not only require the management of all fishing-related activities, but all other activities operating within the region that potentially affect fishing (Fletcher, 2008). This contrasts with the broader ecosystem management approach, which deals explicitly with all issues across an ecosystem or region, and includes the management of all aspects of fishing and fisheries management as an integrated component of EBM (Ward *et al.*, 2002). This broader approach mandates the involvement of a wider range of agencies and stakeholders than the narrow approach of EBFM with its focus on fisheries production, and potentially results in more inclusive processes of

consultation and more robust area-based management arrangements and outcomes.

In Western Australia the Department of Fisheries recognizes the West Coast, South Coast, Gascoyne, Pilbara and Kimberley bioregions. The West Coast Bioregion is approximately equivalent to the boundaries of LME 44. Within the Australian West Coast Bioregion the department has identified the biological resources that are to be managed. These resources include the ecosystems and their constituent habitats, captured species and protected species. The risks associated with each individual ecological asset are examined separately in the EBFM framework using a formal qualitative risk assessment system based on judgements by the fishery managers about the consequences of an event and the likelihood of that event occurring, or more-simple problem assessment procedures (Fletcher *et al.*, 2010).

Fletcher *et al.* (2010) report on a study using the West Coast Bioregion in Western Australia to assess if a regional framework could assist in providing for better natural resource management planning at a regional level and could also meet the legislative responsibilities for managing fisheries and aquatic ecosystems in a more holistic manner for EBFM purposes. They found that the framework that they used was able to meet both of these objectives because a pragmatic, management-focused approach was taken. The potential complexity of EBFM was addressed using a step-wise, risk-based approach to integrate the issues identified and information gathered into a form that could be used by the fisheries management agency. The levels of knowledge needed for each of the issues were matched to the level of risk and the level of precaution adopted by the fisheries management system. Uncertainty in estimating the risks is a significant issue when considering the ecological, social and economic risks but implementing the EBFM approach used by Fletcher *et al.* (2010) made pragmatic decisions about risk and uncertainty, and did not automatically generate the need to collect more ecological, social or economic data or require the development of complex ecosystem models. This EBFM framework also accommodated to some extent the expectations of stakeholders by using a hierarchical approach so

that stakeholder groups could input their issues. However, the EBFM process subsequently consolidated these to be effectively used in specific fishery management planning issues. This approach, being able to determine the relative priority for management of all fishery assets in a region, allowed the framework to provide for an efficient use of government resources to manage the fisheries of the region because expenditure currently directed towards low-risk elements can be redirected towards higher risk elements.

In addition to the developing EBFM framework, all fisheries in Australia's West Coast Bioregion within LME 44 are subject to management plans that are intended to embrace the principles of EBFM as opposed to single target species management approaches. The fishery management plans have components that identify the interactions with the various other fishery resources that either coexist in the area or may have significant interactions. This includes ensuring that impacts of fishing gear on habitats that may be important spawning or nursery grounds for another fished species are restrained or avoided, and that the impacts of introduced pests or industrial sites on habitats that are important for the fisheries are avoided as far as possible.

The form of EBFM being developed in Western Australia is an important first step towards development of an effective framework for the spatial management of all fisheries that occur in a region of the LME scale. The next phase in the development of this fishery management process is to identify mechanisms to further engage with other agencies involved in the management of activities within the marine environment in LME 44 and to determine how their processes link to the EBFM framework to be applied in LME 44. For this to be successful, prior agreement will be required on these aspects to facilitate the process:

- the determination of the spatial structure and distribution of the ecosystems and habitats in the region – there are currently two widely accepted but different regionalizations that are used for different management purposes in the LME
- what constitutes the key areas and elements of the ecosystems – this is currently in develop-

ment by the federal government and disputed by the state-level fisheries managers

- what standards are to be applied in managing the ecosystems and species – there are no national or state-wide standards other than production standards for fished species, and
- what monitoring and reporting systems will be implemented to confirm compliance – there are only limited national or state-wide monitoring systems in place, principally for stocks of fished species.

Eventually this should lead the design and implementation of an effective system of EBM for LME 44 that incorporates the fishery management systems currently being planned and implemented as EBFM.

Other specific improvements in recent years for the *P. cygnus* fishery include the development of a model for the fishery that can include aspects of climate change (Cheung *et al.*, 2011) and the development of a larval advection model to assess the relative contribution of larval production from different areas of the breeding stock to the abundance and distribution of puerulus settlement (Feng *et al.*, 2011).

While Australia and some other nations are beginning to implement aspects of EBFM for all their fisheries, including those for lobsters, there is no doubt that much work remains to be carried out (Essington & Punt, 2011). Pitcher *et al.* (2009) reviewed progress towards the implementation of effective mechanisms for EBFM, and found that more than half of the top fishing nations (including Australia) failed to demonstrate an acceptable level of implementation of the basic principles of EBFM, and did not have appropriate performance assessment indicators in place. The management system for Western Rock Lobster performs only weakly against the Pitcher *et al.* (2009) criteria (see below).

The process of extending the single-species fishery management concepts into the EBM of whole ecosystems using EBFM approaches has proved to be fraught with many difficulties, and there are no documented successes involving lobsters. Much of this is caused by the failure of the concepts of EBM to be fully recognized within the fisheries context (as expressed in EBFM), and is

related to the well-recognized problem of dealing effectively with the complexity of ocean ecosystems within a fishery management system that has arisen historically from managing a single species. This will continue to remain a problem if the ecosystem complexity remains primarily a matter to be addressed in the existing domain of EBFM governance (Rice, 2011) rather than extending the conceptual approach to be more inclusive, and more closely resemble EBM as a whole. Central ecosystem complexities to be resolved include the difficulty that fishery management systems have in meeting the trade-off that must be achieved in providing allocations of stock to meet the demand for harvesting while simultaneously meeting the ecological demands for high stock levels to be retained to provide for other ecosystem services such as an abundance of the fished species for predators and related dependent species, and the retention of the natural biodiversity attributes (such as the natural form of age/size structure) of fished populations to provide for high levels of natural resilience and ecosystem function. These, and a range of similar ecological attributes of populations, are important as management endpoints for a system of marine EBM to be effective, and are important indicators of the success of EBFM in maintaining the resilience of ocean ecosystems and species diversity in the face of many interacting fishery and non-fishery pressures and the highly complex uncertainties within the fisheries management systems themselves (Ward *et al.*, 2002; Rice, 2011).

Rice (2011) identifies the critical importance of extending governance systems and stakeholders beyond the usual fishery and existing EBFM models if the goals and objectives of EBM of the oceans and their resources are to be achieved. The concept proposed by Rice (2011) draws on the principles of EBM and outlines four requirements for EBFM (or EAF as preferred by Rice) if it is to be effective:

- take account of the main extrinsic forces on the dynamics of fished stocks
- be accountable for the full suite and magnitude of the impacts of fishing
- be governed by processes that are comprehensive, inclusive and participatory

- have decision-making integrated across all sectors that impact the same ecosystem and its values.

These requirements for a fishery to implement an effective form of EBFM are also reflected in the elements of a successful EBM framework as outlined by Ward *et al.* (2002) and Pitcher *et al.* (2009). Many of the issues identified by Ward *et al.* (2002), Pitcher *et al.* (2009) and Rice (2011) remain to be substantively addressed in lobster fisheries. This includes issues such as the intense harvest of new recruits, where high fishing mortality rates are annually applied, apparently leaving only very limited biomass to grow through to the older age classes, the extent of which is considered by Ward *et al.* (2002) and Rice (2011) to be an important indicator of the success of the EBM approach.

The western rock lobster fishery for *P. cygnus*, assessed using the scoring criteria applied by Pitcher *et al.* (2009) (which also represent most of the features raised by Rice, 2011) in their global assessment of EBM (Table 1 in Pitcher *et al.*, 2009) does not demonstrate the elements of an effective form of EBM. The weakest aspects of the present-day system of EBFM in this fishery, assessed using the criteria of Pitcher *et al.* (2009) are

- lack of a broad base of stakeholders from outside the fishing sector who are actively engaged and participate in the setting of shared vision, objectives and targets based on intended outcomes for the ecosystems;
- limited understanding of the ecological role of the target species in the ecosystem, and the consequent lack of knowledge about the direct and indirect effects of the fishery on the ecosystem;
- limited understanding of the ecosystem values and the major factors that impact those values in LME 44;
- a limited performance assessment and review system for environmental impacts of the fishery, with only minimal information about this matter placed in the public domain; and
- a minimal education and training system in place for fishers in respect of ecosystem and resource values across LME 44 – there is only

limited set of processes to inform and maintain current awareness about ecosystem issues in the fishery participants, and there is no formal or informal process/programme for updating and up-skilling the fishery participants, or for redeployment of displaced fishers into other fields of activity.

On managing externalities, there is a strong recent focus in this fishery on the relationships between climate change and variability and recruitment, which is important for setting of harvest strategies, although little apparent focus on of climate factors on growth and natural mortality, both likely to be more important features of an effective stock assessment system operating within a competent EBFM context (Rice, 2011). Other fishing pressures that may have had some impacts on LME 44 in the past include the destructive fishing practices of foreign distant water trawling and long lining fleets, but these have been virtually fully eliminated by strong federal government action to prohibit entry without strict licence conditions.

1.5.2 *Homarus americanus*

In contrast to the collapsing American lobster population in the southern part of the species range, abundance of the lobster in the Gulf of Maine and parts of Atlantic Canada have surged to unprecedented levels in the past few decades in the wake of severe groundfish depletion. While other contributing factors cannot be ruled out, the strong correlation between the decline in fish and the increase in lobster has been taken to indicate a cause–effect relationship (Acheson & Steneck, 1997; Worm & Myers, 2003; Boudreau & Worm, 2010; Wahle *et al.*, in press). The need for an EBM framework, incorporating a broad range of species and their interactions with each other and lobsters, and the environment, is therefore obvious. Managing the ecosystem to recover the fish populations will, if the negative causal relationship between fish and lobster abundance is as strong as is postulated, be likely to suppress the population recovery of *H. americanus*. This could have significant consequences for the population and the lobster fishery

in all parts of its range, as well as other ecological consequences.

The focus of management of *H. americanus* has so far been on developing a better understanding of the ecological relationships and the environmental drivers of the population. In many ways, this parallels the research initiatives for *P. cygnus*, and despite the large difference in the sizes of the two populations and the associated fisheries, progress on development of a more integrated and EBM system is similar for both species. Emphasis in US waters has been on securing a workable institutional structure, with the establishment and operations of the state and cooperative federal structures, and on securing protection for sensitive and iconic habitat types, such as deep-water corals. Despite intensive research activities in development of ecosystem-based modelling systems (Link *et al.*, 2011), these have been only developed for fish, and have not included the invertebrates, and so progress towards fully effective forms of EBFM has been slow. As in the *P. cygnus* fishery, key issues revolve around bringing the institutions and values of all relevant stakeholders into the management process, as well as the ecological and environmental drivers. This is to establish an acceptable set of trade-offs among the various competing interests while simultaneously ensuring that the structure and function of the ecosystem itself is retained to provide resilience to changes in climate and trophic interactions in the medium and long term.

Considerable further activity is required to develop an effective EBFM system for both *H. americanus* and *P. cygnus*. In the case of *H. americanus*, the global review of EBM in fisheries (Pitcher *et al.*, 2009) found that while the USA was ranked as ‘good’ (score of >60%) on the overall set of EBM criteria (along with Norway), implementation of EBM was not ranked highly. This is consistent with the explanation that although there is considerable technical capacity and underpinning theory for the development and implementation of EBFM (in both the USA and Canada) as it could be applied to *H. americanus*, uptake of the principles of EBM into the actual management process for these lobster fisheries has been lagging. This also applies in the case of *P. cygnus* in Australia.

1.6 Implications for management and research

1.6.1 Top-down, bottom-up ecology

The relationships among the world’s lobster species and their predators and prey at the different stages of their life cycle is universally considered to be poorly understood, yet is central to the advancement of understanding the ecological effects of lobster fishing (the real footprint of the fishery). The ecological interactions are only weakly understood – from the role of the pelagic 0+ year class as food for other zooplankton and juvenile fish, to the predation of 20+ age class of lobsters on benthic communities in offshore water and their predation by large fish. Knowledge of these relationships is a major impediment to understanding the ecological effects of the major reductions in population biomass as a result of fishing, and is a major impediment to developing an effective system of both EBFM and ultimately EBM for the ecosystems and habitats utilized by the lobsters.

Other important aspects of the lobster trophodynamics includes further analysis of the significance of bait input to the ecosystems where lobsters are fished using baited traps/pots. There is evidence that, at least in the *P. cygnus* population, the bait may be contributing significantly to local production, and this may also be having significant broader ecological impacts on other species (MacArthur *et al.*, 2011). It is unclear if this is having a beneficial or detrimental effect on either the lobster populations or their fisheries, or on the associated ecosystems through alteration to food webs and energy flow.

1.6.2 Inclusive governance systems

Probably the major single failing common to all commercial lobster fisheries is the lack of an effective system of governance that contains all the necessary elements to provide for both EBM and the subset that is EBFM. This is both institutionally difficult and, at least initially, may be expensive to implement to secure the required trade-offs between production and the environment. However,

continuing with governance systems that are both dominated and controlled by fisheries management institutions is not likely to be a successful approach to implementing EBM that includes fisheries, and there are no demonstrated successes. In contrast, where there is inclusive governance, of which fisheries management is part but is not the controlling component, there are demonstrated successful examples of EBM and EBFM.

Nonetheless, further research is urgently needed to better analyse and understand the successful elements of the existing EBM models that are being at least moderately successful, such as that of CCAMLR (Constable, 2011). This is research that couples the ecological, biological, social and institutional issues and their effective resolution with outcomes that provide for the long-term security of lobster stocks and other species sharing the same ecosystems, including high levels of population and ecosystem resilience. There are simple rules of thumb to guide assessments of the effectiveness of such governance systems (Ward *et al.*, 2002; Rice, 2011), but studies of how specific aspects of governance systems can be developed and implemented in the various environmental, social and economic contexts of a variety of the world's lobster fisheries remains as a very high priority.

1.6.3 Stock rebuilding strategies

Fished lobster populations worldwide are low, compared with both their own intrinsic benchmarks and those established for other marine species. While it is well understood that being highly fecund, broadcast spawners, and having widespread distributions confers a measure of resilience against the effects of fishing, and most likely avoids species extinction in the short term, these attributes have not prevented other species from coming under severe population pressures from the combined impacts of excessive fishing and environmental change. In the concept of EBM, populations of targeted species fulfil several important functions in addition to providing for continuing harvests, and particularly for maintaining ecosystem structure and function, and providing resilience in the face of the changing climate. Rebuilding lobster populations to higher levels offers the further

benefit of permitting catches to be progressively increased from their currently depressed level (in most places), albeit probably not to the historically highest ever levels of yield. Further, while the global catch of lobster is increasing, this is primarily driven by the increasing yield from the northern populations of *H. americanus*. In this case, the increase in yield is not uniform across all areas of the fishery, and is thought to be confounded with the effects of fishing activities for the finfish species.

It is clear that incrementally increasing the absolute size of lobster populations, even if maintaining the current level of fishing mortality relative to population biomass, is likely to be the most appropriate long-term precautionary approach to increasing overall yield from the world's lobster fisheries. To enable this to happen, new approaches to population rebuilding need to be designed and trialled. This could include, for example, explicit allocation of long-term rebuilding targets within harvest strategies, passive allocation of closed areas for enhancement of breeding biomass, setting escape-limit limits for age/size classes, setting aside areas for enhancing settlement success, and increasing legal catch size limits to promote increased reproductive success. Irrespective of the specific strategy, these and other likely effective approaches need to be trialled across a number of the world's managed lobster fisheries, lobster species, and ecosystem types.

1.6.4 Environmental drivers of settlement patterns

The environmental factors that affect the distribution and then ultimately the settlement of young lobsters from the planktonic phase, while different for each species and in some cases different among areas, is a major component of uncertainty that affects the management of all lobster species. Further research is needed to build better models of behaviour and distribution of the planktonic stages, to provide for ultimately a better understanding between the abundance and distribution of breeding biomass and the eventual recruitment of mature lobsters into the fishery that have survived the planktonic phase. This is a central and substantial

uncertainty that plagues lobster fishery management at all levels. The continuing studies on the environment and recruitment of *P. cygnus* by Feng *et al.* (2011) and *H. americanus* (Wahle *et al.*, 2004, 2009) are important steps in this direction.

1.6.5 Historical ecosystem structure

The structure and function of the ecosystems, the dominant predator–prey relationships, and the trophodynamics of the unexploited ecosystems are largely unknown in LME 44 in Western Australia, and not well understood in LME 7, 8, 9 in Canada and the USA. While knowledge of these matters is currently embryonic, it is central to developing a long-term understanding of the dynamics of change in these ecosystems that has affected lobster abundance and distribution, and also for developing a better understanding of the drivers and causes of broader ecosystem changes that have been observed. In recovering populations of species that have been heavily fished, such as these two lobster species, it is critical to be able to compare present-day conditions in both their populations and their ecosystems to the conditions of the past. This involves developing models of past conditions and dynamics, and preparing benchmarks against which the modern day conditions can be compared. For each of the lobster species, for an effective use of the EBM approach, estimates of the historic habitat-based distribution, abundances, size structure in the population and patterns of migration would be needed. This knowledge can then be used in ecosystem models with productivity parameters to develop a better understanding of the current condition of the lobster populations relative to their long-term history, and better inform both the likelihood of being able to rebuild both populations and productivity to former levels and management approaches that might be most successful. For example, for *H. americanus*, determining the strength and patterns of top-down population control that has been applied by the fish predators that have now been reduced to low abundances will allow a considerably improved level of resolution to be applied in bio-economic models designed to rebuild fisheries (lobster and finfish) across the region in both a systematic and timely manner. These models should

also be able to predict the recovery of other important population parameters such as the diversity of age and size structures, which is important to rebuilding resilient structures and functions in the lobsters' ecosystem. The alternative is to remain transfixed by the single-species management systems of the past, which search for simple population relationships and drivers, and then proceed to erect complex collections of individual and weakly connected corrective management arrangements that may not achieve the desired outcomes, falling foul of the system complexity.

The LME region 7 (North eastern US shelf) is now considered to have a strong theoretical basis for modelling the complexity, and early results (Link *et al.*, 2011; Smith, 2011) indicate important implications for policy development. These include confirmation of the obvious outcomes that the maximum sustainable yield (MSY) single-species approach to setting harvest limits cannot be used individually for a group of species that have ecological interactions. In short, the sum of the individual MSY is greater than the MSY developed for the combination of species (Smith, 2011). This infers that use of multiple single-species MSY limits for fisheries will result in overharvesting when taking into account the suite of ecological interactions amongst the ecologically related species and the effects of ecosystem dynamics.

1.7 Conclusions

Mahon *et al.* (2010) studied the governance characteristics of LMEs. They reported that LME 44 and LMEs 7, 8 and 9 are among the LMEs considered to have high capacity for good governance in that they are among the least complex LMEs with a highly functional institutional environment and capacity for effective governance. This, coupled with low heterogeneity among countries, will probably reduce the likelihood of conflict. The LMEs considered here (44 in Western Australia and 7, 8 and 9 in Canada and the USA) would probably be most amenable to conventional hierarchical governance through interplay of national/international instruments, supported by strong technical inputs. The countries of these LMEs are also those most

likely to have the enforcement capacity required for this approach. The indication is simply that these are the LMEs where this approach would have the greatest chance of successful governance.

Pitcher *et al.* (2009) made an evaluation of progress in implementing EBM of fisheries in 33 countries. Of the six indicators chosen to measure the readiness to implement EBM only the USA, Norway, New Zealand, South Africa, Australia and Canada had scores suggesting that they were likely to achieve reasonably effective implementation of EBM. Clearly, development of institutional systems

that provide for good governance that is consistent with the principles and practice of EBM can be most easily developed in these countries, but, even there, a lot of challenges remain. In other countries, efforts to implement EBM, and effective forms of EBFM, need to be redoubled, perhaps with institutional reforms and improvements to provide effective forms of governance that are agreed and appropriate to local cultural, social and economic conditions, but still deliver the principles and practice of EBM, and the various models of EBFM that are nested within EBM.

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