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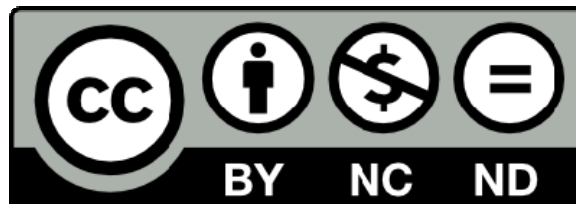
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Evaluating the ecosystem effects of variation in recruitment and fishing effort in the western rock lobster fishery

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Abstract

We used a regional, ecosystem mass-balance model (Ecopath with Ecosim) to evaluate the possible changes in flows of mass and energy between the benthic and pelagic components of the marine ecosystem of Jurien Bay in temperate Western Australia (~30°S, ~115°E). The effects of varying the biomass of western rock lobster in the system were examined by simulating changes in commercial and recreational fishing mortality as well as recruitment-driven changes in the abundance of lobster puerulus (the first post-larval stage). The model comprised 80 functional groups (more than 200 species). A simulated closure of the commercial lobster fishing was predicted to lead to an increase in lobster biomass of 160% after 20 years, with changes in biomass of up to 20% of the main prey and predators of lobster. Since 2006/2007, the puerulus settlement (recruitment to the benthos) of western rock lobster has declined to the lowest levels recorded in the fishery. The model predicted that under 2005 levels of fishing effort, a simulated depletion of 90% of puerulus biomass resulted in an ~17% reduction in the biomass of adult lobster biomass after 20 years (i.e. by 2025). In general, the model predicts that the variations in lobster biomass, whether induced from fishing mortality or declining puerulus settlement, have relatively small effects on the biomass of the main predators and prey of

lobster in the marine park. The relative biomass of adult rock lobster and their associated predators and prey was more sensitive to fishing than to variations in recruitment.

Keywords: Ecosystem modelling; Ecosystem-based management; Sustainable fisheries; Larval supply

1. Introduction

Lobster is an important food source for other marine organisms and humans (Bondad-Reantaso et al., 2012). The main producers and exporters of *Panulirus* and *Jasus* rock lobster are Australia, New Zealand, South Africa, Cuba, Brazil, Mexico and USA (Jeffs and Hooker, 2000). Globally, the catch from lobster fisheries has decreased over the past 20 years and the future of this resource is uncertain (Bondad-Reantaso et al., 2012). In Australia, there have been a number of dramatic changes in several commercial spiny or lobster fisheries in recent years, including declines in annual landings and recruitment (Linnane et al., 2010; Phillips et al., 2010). The West Coast Rock Lobster Fishery (WCRLF) in Western Australia (WA) is one of the most well known and best researched and managed fisheries in the world. In 2000, it was the first fishery to achieve Marine Stewardship Certification and has been re-certified twice since then. Despite this, it faces several challenges, due to a combination of climate change (Caputi et al., 2009), and downturns in the world market (Bondad-Reantaso et al., 2012). While the exact impact on lobsters from climate change is still unclear, analyses suggest that warmer water temperatures have historically resulted in higher levels of puerulus settlement (e.g., Caputi et al., 2001; Caputi et al., 2009). However, some lobster fisheries (e.g. the Southern New England fishery) are already experiencing sharp declines in catch despite warming waters due to a temperature-sensitive bacterial shell disease (Factor, 2005; Castro et al., 2006).

The declining biomass of lobster is one of the major problems in the management of these fisheries in lobster producing countries. Since the late 1990s, several management strategies have been adopted to avoid further declines in lobster resources, including the regulation of the Total Allowable Catch (TAC), legal size limits, fishing gear and area restrictions, and limited fishing seasons (Hilborn and Walters, 1992). In Western Australia, the fishery for *Panulirus cygnus*, the western rock lobster (WRL), is managed with a combination of these strategies (Department of Fisheries, 2009). Australia and New Zealand have adopted an effective strategy of reducing further declines in their lobster fisheries through developing predictive models of lobster biomass for stock management (Phillips *et al.*, 2003; Melville-Smith *et al.*, 2004). This method uses an index of juvenile and puerulus abundance (the last larval stage and first demersal stage of lobster) in numerical models to provide an early warning of catch declines, and allow catches to be predicted up to four years ahead (Caputi *et al.*, 1995; Caputi *et al.*, 2001). This predictive method was developed for the management of the *P. cygnus* fishery in Western Australia and it is based on the close relationship between recruitment patterns of the puerulus stage (i.e., the first postlarval stage that assumes a benthic habit) and the future recruitment of legal size lobsters into the fishery (Caputi *et al.*, 2001; Caputi *et al.*, 2003; Melville-Smith *et al.*, 2004). The recruitment and abundance of puerulus are incorporated into stock assessment models to adjust TACs of this fishery and reduce the risk of further declines in the stock.

The WCRLF was until recently, Australia's largest and most valuable single species fishery, with catches averaging 10,500 m per annum (catch varied between 8000 and 14,500 m until 2006) and valued between AUS \$200–400 million annually, representing nearly 20% of the total value of Australian fisheries (de Lestang and Melville-Smith, 2006). However, a sudden fall in puerulus numbers was recorded in 2006/07, followed by a record low puerulus recruitment in 2008/09, resulting in management action to implement significant effort reductions, as well as the introduction of a TAC that was set at half the long-term average lobster catch (by reducing pot numbers and allowable fishing days) to just 5500 metric tonnes for 2010/2011. The precautionary approach

adopted by the Western Australian government in 2008/09 aimed to control the catch and effort of lobster before the poor year-classes entered the fishery.

Management actions in the WCRLF to protect lobster biomass provided support to obtain an independent re-certification by Marine Stewardship Council for a third time in 2012 (previously certified in 2000 and 2006). However, conditions of the re-certification by MSC, included ensuring that the target population is preserved in a healthy state, but also that there are no unforeseen or undesirable indirect impacts of the fishery on supporting ecosystems. It is now realised that fisheries have the potential to change the ecosystems in which they operate (Pitcher, 2001). By removing a large proportion of the harvested populations, they affect the population dynamics of the exploited species, and may change the structure and function of entire ecosystems (e.g., Pauly *et al.*, 2001; Worm *et al.*, 2009; Hammer *et al.*, 2010; Smith *et al.*, 2011). For example, during the 1980s in the Gulf of Maine (USA), intense fishing on the top demersal predatory fish, the ground fish Atlantic cod *Gadus morhua* changed the energy flows and fractured the biomass pyramid of this ecosystem, which reduced the top-down forces and increased the production of lower trophic levels (i.e. decapods and pelagic fish). This resulted in a change in the ecosystem from one dominated by a high trophic-level groundfish to one dominated by the lower trophic-level American lobster (*Homarus americanus*) (Zhang and Cheng, 2007). Intense fishing could produce important top-down trophic cascades that have the potential to drive regime shifts in marine ecosystem as detected in the Black Sea at the end of the 1990s (Daskalov *et al.*, 2007). However, the global fishing of low-trophic level species (e.g., plankton feeders such as sardines, pilchards and anchovies) also has the potential to produce large impacts on other parts of the ecosystem, including top predators such as marine mammals and seabirds (Smith *et al.*, 2011).

Understanding the impacts of fishing on the trophic structure of ecosystems where the WCRLF operates has become increasingly important. The second certification of the Marine Stewardship Council of this fishery in 2006 recommended an ecosystem-level performance assessment which led to the development of an ecosystem model for Jurien Bay. We built a biomass-based dynamic model of park (JBMP) using Ecopath with Ecosim (Christensen *et al.*, 2009) to identify trophic linkages and

the role of both low and high trophic level groups within the marine park (Lozano-Montes et al., 2011), and evaluate the potential impacts of spatial closures on target species and food webs (Lozano-Montes et al., 2012). The Jurien Bay ecosystem model provided a valuable mechanism for evaluating management scenarios and synthesising the current understanding of this region, identifying gaps and priorities for research (Lozano-Montes et al., 2012).

In this study, we use the Jurien Bay ecosystem model to evaluate the possible changes in flows of mass and energy at lower trophic levels, and among the benthic, pelagic and demersal parts of the JBMP ecosystem as result of reducing the biomass of western rock lobster (*P. cygnus*) by commercial fishing and from a reduction in the abundance of the post-juvenile stage of lobster. The ecosystem dynamics explored with this model provide a greater understanding of the structure, processes and functions of this ecosystem, located close to the centre of the WCRLF (~30°S), an essential step towards a more robust ecosystem-based fishery management of this fishery in Western Australia.

2. Methods

2.1. Study area

Jurien Bay (31°N–30°N; 114.95°E–115.05°E) is near the centre of the WCRLF, which extends from Kalbarri in the north to Cape Leeuwin in the south (Fig. 1). Jurien Bay is characterised by its unique combination of offshore reefs, islands, and sheltered lagoons with calcareous and limestone reefs dominated by the Laminarian alga *Ecklonia* and other macroalgae (Wernberg et al., 2006). The limestone reefs covered by algae in near shore areas of the region (<30 m depth) provide an excellent habitat for the returning swimming puerulus to settle and develop. The high diversity of flora and fauna in the region is a result of the influence of the Leeuwin Current, a warm ocean current of tropical origin which flows southwards near the coast of Western Australia (Feng et al., 2003; Fig. 1). This current transports tropical marine larvae southwards and raises winter water temperature, enhancing the survival of early life-history stages of fish and crustaceans, including rock lobster (Feng *et al.*, 2003; Caputi, 2008). A large multiple-use marine park is located in the centre of the area

and the effects of this different zones in the park on ecosystem function are reported elsewhere (Lozano-Montes et al., 2012).

2.2. Model development

To evaluate the impact of fisheries in the Jurien Bay Marine Park ecosystem, we used ecosystem-based modelling based on the software Ecopath with Ecosim (EwE; www.ecopath.org). The Ecopath model of the JBMP used in this study, and the starting values for the model, are described in detail by Lozano-Montes et al. (2011). This model simulates the biomass dynamics of 80 groups (~200 species) for the average 2005–2007 period, some of them aggregated by their functional roles (e.g. zooplankton feeders) or biology (e.g. reef-associated herbivores). The structure of the model includes 31 fish groups, 26 invertebrates, 11 primary producers, two marine mammals, two seabirds and eight non-living groups. Ecosim allows time-dynamic simulations of the initial parameters of the Ecopath model through a series of differential equations to represent changes in the biomasses and energy flows of the interacting groups (Christensen et al., 2009). A number of single species functional groups were defined for species of significance to commercial or recreational fishing fishers (e.g., lobster, pink snapper *Pagrus auratus*, dhufish *Glaucosoma hebraicum*, baldchin groper *Choerodon rubescens*, breaksea cod *Epinephelides armatus*). The western rock lobster was further subdivided into four ontogenetic stages to give a total of four lobster groups (post-juvenile, juveniles, pre-adults and adults) due to the significance of the species in the region.

2.3. Estimation of model parameters

Much of the data on biomass in the model comes from empirical studies in the region (see Lozano-Montes et al., 2011 for details of studies) and the pedigree of the model, i.e., the proportion of data coming from the region of the model, is high compared with other ecosystem models around the world (Lozano-Montes et al., 2011). For example, the biomasses of most of the fish groups (>80%) were estimated mainly from local studies using underwater visual census (Fairclough et al., 2011), recording more than 124,000 reef-associated fish and 70,000 seagrass-associated fish within the park from 2005 to 2007. The biomass of WRL was also estimated locally by depletion analysis (Wright et

al., 2006). The biomasses of primary producers and invertebrates on reefs and in seagrass meadows, were based on stratified benthic-quadrat sampling and were provided from researchers in the region. Biomass estimates for sharks, based on information from commercial fishing, recreational fishers and visual diver surveys, were provided by Rory McAuley (Department of Fisheries, WA).

In the Ecopath mass-balanced model, the ratio of production to biomass, P/B is assumed to equal total mortality, Z (Allen, 1971). Therefore, this production parameter was calculated for commercially exploited stocks as the total of fishing (F) and natural mortalities (M) (see Table 2 for the estimates of F and M for the four stages of WRL). The natural mortality (M) of unfished species was used to represent the P/B rate. For target species (i.e., those with an annual catch recorded in a fishery), P/B was estimated as the sum of M and F . Values of M were taken directly from the literature wherever possible or from FishBase (Froese and Pauly, 2011). When estimates of M could not be found, the regression equation of Pauly (1980) was used to determine M (Eq. (1)), which requires growth information: the von Bertalanffy growth constant (K) and the asymptotic length at infinity (L_∞). These values were obtained for most species from FishBase. When L_∞ was unavailable, it was estimated from the maximum specimen length observed L_{MAX} by assuming that $L_\infty = 0.95 \cdot L_{MAX}$

$$M = K^{0.65} \cdot L_\infty^{-0.279} \cdot T^{0.463} \quad \text{equation(1)}$$

See Lozano-Montes et al. (2011) for full details of the sources of data and estimation of the relative consumption rates (Q/B) and ratio of production to biomass (P/B). A supporting online material that extends the structure, calibration, key parameters values, model performance and sensitivity of the model is included.

2.4. Modelling effects of fishing and puerulus depletion

Fourteen fisheries were included in the Ecopath model: eight of them were commercial fisheries (lobster potting, beach seine, drop lining, gill-netting, hand-lining, traps, haul netting and abalone fishing) and the remaining six were recreational fisheries (beach anglers, boat anglers, netting, diving, potting and spear fishing). Most of the datasets (catch and effort) for commercial fisheries used in the

model were provided by the Department of Fisheries, WA. Data on the recreational catch were obtained from the 2006 Recreational Fishing Guide published by the Department of Fisheries WA and the 12-month survey of coastal recreational boat fishing between Augusta and Kalbarri during 1996–1997 (Sumner and Wilson, 1999). Four Ecosim scenarios were created (Table 1) to explore the impacts of fishing lobster in the JBMP. The first scenario involved maintaining fishing at 2005 levels i.e. status quo. The second involved a simulated a closure of all lobster fishing (i.e., both commercial and recreational fisheries), introduced over 3 years (i.e., a reduction in F of 33.3% per year) and evaluated after a 20 years (Table 1). The third scenario considers a 50% reduction in fishing mortality by the WCRLF (representing a reduction in F of 2.5% year⁻¹) over 20 years. Even though recreational fishing is a small component of the fishing mortality of rock lobster in the Jurien region, we created a fourth scenario which simulates a 50% increase in the fishing mortality imposed by recreational fishing in the main finfishes species and rock lobster in the marine park over a 20-year period (this was represented by an increment in F of 2.5% year⁻¹) (Table 1). In all scenarios, we present the changes in biomass at the end of 20-year simulation for lobster adults and the main prey (e.g., coralline algae, urchins, epifauna, crabs) and predators of lobster (e.g., octopus, pink snapper and sea lions) (Table 2).

In the model, compensatory recruitment effects for lobster are only represented through the ‘split pool’ representation of the four stages: post-juvenile, juvenile, adolescent and adult stages.

Recruitment is expressed as a flat or dome-shaped relationship between numbers of juveniles recruiting to the adult pool versus parental abundance (stock–recruitment relation). The mechanism to create this effect in the model is basically to use non-zero feeding time adjustment for the juvenile pool in the Ecosim model (a value of 2.0 was used), combined with fixed time in juvenile stage and high ecotrophic efficiency (=0.95, maximum possible theoretical value = 1.0). In this way, density-dependent changes in juvenile mortality rates are represented in the model by changes in feeding time and predation risk for the different stages.

To model the impact of low puerulus settlements in the stock and catch of WRL, we designed two additional scenarios to evaluate the impact of low puerulus settlement and a change in harvest strategy

to WCRL: Scenario 5 – a 90% depletion of puerulus biomass (based on 2008/09 puerulus abundances) under a constant fishing pressure (as 2005); and Scenario 6 – which combines a 90% puerulus depletion with a 50% reduction in fishing effort of WRL (Table 1). Each of these two scenarios were run for a 20-year period (2005–2025).

2.5. Verification of model performance

The WRL biomasses predicted by the Ecosim model were tuned using a time series of absolute lobster abundances estimated by depletion analysis from 1983 to 2005 (see Wright et al., 2006). Relative abundances (e.g., catch per unit effort CPUE) of the main target fishes from 1995 to 2005 were also used to verify the performance of the model. This process, known as ‘tuning’, provides adjusted models that can track changes in biomass that are known to have occurred in the past (Christensen et al., 2009). The fishing mortalities of WRL from 1984 to 2006 were estimated using the Ecopath base year as $F_{jio} = Y_{jio}/B_{i0}$, where Y_{jio} is the mean catch (1984–2006) of group i by fleet j , and B_{i0} is the mean biomass during the year, estimated by depletion techniques (see details in Lozano-Montes et al., 2011). In general, the predicted lobster biomasses were within 20% of the observed values (Lozano-Montes et al., 2011).

3. Results

3.1. Ecopath model

The trophic levels, estimated by the model from the weighted average of prey trophic levels, varied from 1.0 for primary producers and detritus to 4.25 for piscivorous fish (e.g., dhufish) and top predators (e.g., large sharks) (Fig. 2). Top predators fed mostly from trophic levels II and III, while rock lobster (TL = 2.7) fed mostly from trophic levels I (algae and bait) and II (e.g., urchins and other invertebrates) (Fig. 2). The ratio of the biomass of benthic primary producers (e.g., corraline algae, macroalgae and seagrass; TL = 1.0) to that of fish and top predators (e.g. mammals and sharks) was about 6.

Benthic primary producers contributed $\sim 553 \text{ t km}^{-2}$ (58.9%) of the total biomass in the system of 1081.2 t km^{-2} . The mean trophic level of the catch from all fisheries was 3.14, as the fisheries exploit mainly lobster. More than 80% of the fish catch was confined to trophic level 3 (e.g., Pink Snapper, Baldchin Groper, King Wrasse, and Breaksea Cod). The total primary production required to sustain the WRL catch was estimated to be 11.6% and 4.2% to sustain the total fish catch.

3.2. Effects of fishing

Adult rock lobster had a relative low biomass ($\sim 0.71 \text{ t km}^{-2}$) in the Jurien Bay model (706.8 t km^{-2} from the 72 living groups) although lobster are eaten by many groups (16 out of 72 living groups), they are not the dominant prey item for any functional group (Fig. 2). Hence, fishing this species had a relatively modest impact on the predators and prey of lobster. Results from the dynamic simulations (with recruitment held constant at 2005 levels) suggest that the biomass of adult lobster could decline by $\sim 10\%$ from the 2005 levels if the 2005 fishing pressure is maintained for the next 20 years. This change in lobster abundance would result in a modest impact ($<10\%$) on the biomasses of its prey and predators and a decline ($\sim 6\%$) in the catch of lobster in the marine park (Fig. 3). However, in this status quo scenario, pink snapper was predicted to decline by $\sim 15\%$ of the 2005 abundance as a result of recreational fishing (Fig. 3 and Table 3). A simulated closure of the commercial lobster fishing (Scenario 2, Table 1) was predicted to lead to an increase in lobster biomass of 160% (relative to the 2005–2007 levels) in 2025. Under this scenario, some of the main predators of adult lobster (e.g., octopus) increased $\sim 15\%$ in abundance as a result of increased prey availability (Fig. 3). In contrast, some species consumed by adult lobster (e.g., sea urchins, gastropods and epifauna) declined up to 26% of the 2005 biomass levels. High trophic level species such as sea lion showed minor changes $<3\%$ of biomass as result of the large increase in biomass of lobster (Fig. 3 and Table 3). The model results from scenario three, reducing the WCRLF fishing pressure by 50% (Table 1), predicted a significant increase of up to 70% in lobster biomass at the end of the 20-year run (Fig. 3 and Table 3).

The direct effects of increasing recreational fishing were simulated with a 50% increment (over 20 years) of the fishing mortality imposed to lobster and main finfishes of Jurien Bay. The biomasses of

these groups were predicted to decline in all cases; 32% for pink snapper and 10–20% for dhufish, and baldchin groper and 14% for adult rock lobster (Fig. 3). These declines had only minor predicted effects (~5%) on the biomass of lobster prey and predators (Fig. 3). Of the lobster prey, only the infauna, and urchins showed a modest increase in biomass of up to 8% as a result of their release from lobster predation. No major changes (<10%) in the total catch or lobster catch were predicted from this simulated increase of recreational fishing pressure (Fig. 3 and Table 3).

3.3. Effects of low recruitment

The effect of continuing low recruitment level of lobster was evaluated with a simulated depletion of 90% of puerulus biomass in two fishing regimes: *status quo* (as 2005) and a 50% reduction of fishing mortality from the WCRLF (Scenarios 5 and 6, Table 1). With a decline in puerulus biomass only, the adult lobster biomass was predicted to decline by about 17%. In contrast, when the depletion of puerulus was combined with a 50% reduction in commercial fishing effort for lobster, lobster biomass was predicted to increase by ~8% after 20 years (Fig. 4). The model predicts that under the levels of fishing effort of 2005, the depletion of puerulus biomass alone resulted in relatively small changes (<10%) in the biomass of the main predators and prey of lobster (Fig. 4).

4. Discussion

The complexity of the Jurien Bay Marine Park ecosystem makes it difficult to evaluate interactions among different species without using quantitative modelling approaches. The Ecopath model developed in this study, based on the model by Lozano-Montes et al. (2011), provides an effective tool for analysing the rock lobster ecosystem in the Jurien Bay region and testing hypotheses on the trophic interactions of different species, recruitment levels and fishing regimens. This model provides not only a summary of our current knowledge of the biomass, consumption, production, food web and trophic flows in Jurien Bay Marine Park for the 2005–2007 period, but also displays its capacity for integrating important ecosystem aspects in an easily understandable way.

The Jurien Bay ecosystem is dominated by benthic functional groups, which represent the main components of the biomass for the total system and the catch of fisheries as well as the energy flows in the system (see also Lozano-Montes et al., 2011). The results from our study are likely to underestimate the sensitivity of Jurien Bay to changes in the biomass of groups such as *Ecklonia*, which in addition to contributing to trophic flows, have an important role as habitat for other flora and fauna. For example, rock lobster (adult and juvenile) and other benthic invertebrates, responded strongly to changes in the biomass of *Ecklonia*, which could, in part, be explained by its provision of both substrata for food such as epiphytes and epifauna (Crawley *et al.*, 2006; Crawley and Hyndes, 2007) and shelter from predators (Vanderklift et al., 2007). Experimental studies in the Jurien Bay Marine Park have shown that the overall density of lobsters and the level of habitat utilisation are much greater in the vicinity of macroalgal dominated reefs than areas adjacent to other habitats (MacArthur et al., 2008). Similar patterns have also been observed for fish immediately adjacent to reefs (Vanderklift et al., 2007), presumably because of increased protection from predators in these habitats, enhancing the survival of fish and crustaceans species.

The dynamic simulations of the management scenarios identified some top-down interactions flowing from reductions in fishing mortalities of fish groups at the top of the food web e.g. sharks, dhufish and pink snapper. The simulated total closure to lobster fishing revealed an interesting consequence of top-down interactions: the predicted biomass of lobster reached its maximum (~180% of the 2005 levels) during the first 10 years of simulation, followed by a ~15% reduction in biomass, presumably because the increase in biomass of lobster predators compensated for the decrease in fishing mortality on lobster. Lobster mortality due to predation is almost as great as that due to fishing in Jurien Bay (Howard, 1988; Lozano-Montes *et al.*, 2011).

The low trophic level of the catch in the Jurien region (3.14) compared with those in other temperate, rocky reef systems, such FL, USA, (Okey et al., 2004), is explained by the dominance of WRL in both the commercial and recreational catches in Jurien Bay (see also Lozano-Montes et al., 2011).

The trophic level of the catch could be used as an ecosystem attribute to evaluate future changes in the system by fishing. However, the dominance of lobster in the catch means that such an index would be

relatively insensitive to changes in the biomass of other fished species. Fishing has also been shown to indirectly affect primary producers by removing the predators of grazing benthic invertebrates. In some cases, this has led to a massive increase in their biomass and a corresponding reduction in the biomass of primary producers e.g., the formation of urchin barrens in marine ecosystems where lobster were once abundant in the North Pacific (Estes and Palmisano, 1974; Behrens and Lafferty, 2004), New Zealand (Babcock et al., 1999); North Atlantic (Steneck et al., 2004) and south-eastern Australia (Pederson and Johnson, 2006). The benthic ecosystem modelled at Jurien Bay appears to respond quite differently to reductions in lobster biomass, with multiple relatively weak responses in the biomass of lobster prey, rather than a few strong interactions with grazing taxa. No overgrazing effects by sea urchins were predicted in Jurien Bay as a result of reduced lobster abundances. This pattern differs from that observed in Southeast Australia where a spread of sea urchins barrens resulted from a combination of lobster overfishing and climate change are triggering catastrophic overgrazing of reefs (Ling et al., 2009). Rock lobster is not a predominant prey in the temperate limestone reefs of Jurien Bay. Howard (1988) found that six fish species ingested rock lobster in this temperate reef system and was <5% of the dietary volume in five of the six species. It exceeded 5% of the diet for only sand bass, *Pseudolabris waigiensis* (sand bass). Conversely, the Jurien Bay model suggests that changes in the biomass of benthic primary production by macrophytes would lead to strong bottom up effects flowing to higher trophic levels of the ecosystem (Lozano-Montes et al., 2011). Caution is necessary in drawing conclusions from the simulations in the current study because of uncertainty in some of the parameters in the model (e.g., fishing mortalities). Despite this qualifier, some general important points emerged. For example, after 20-years of continuous low puerulus biomass, the biomass of adult, mature lobster was predicted to decline by ~17%, which appears much lower than might be expected by a drastic 90% reduction in puerulus biomass. However, it is consistent with the empirical relationship between pueruli abundance and the recruitment to the fishery (e.g., Caputi *et al.*, 2003; Phillips *et al.*, 2003). This much lower predicted decline in adult lobster biomass could be partially explained because the model assumes that the dynamics of all the species are governed by trophic interactions, in particular that they are food-limited. This assumption does not consider other density-dependent mechanisms (e.g., competition among pueruli for suitable

habitat) that could affect the relationship between pueruli recruitment and adult lobster abundance. Furthermore, the post-pueruli stages (i.e., juveniles, sub-adults and adults) of *P. cygnus* are flexible in their use of habitat, making use of “less than perfect” shelter at times to reduce the risk of predation and mortality (Phillips et al., 2003). Predicting lobster abundance and catch involves not just the fishing activity, but also environmental variations (Caputi et al., 2001). For example, the number and distribution of puerulus settling of the west coast of Australia varies greatly between years as a result of changes in environmental factors associated mainly with the strength of the Leeuwin Current, represented by the El Nino-Southern Oscillation Index and the mean sea level height at Fremantle (Caputi et al., 2001). The implementation of the new quota-based management system for the WCRLF in 2011 introduced a Total Allowable Commercial Catch for lobster (TACC), which represents a more precautionary harvest strategy as it includes current breeding stock levels and egg production levels in setting the TACC (DoF, 2012).

The performance of the model and its representation of the structure and trophic interactions of the Jurien Bay ecosystem are affected by many factors. For example, the biomass of some functional groups in the JBMP was not known (mainly benthic invertebrates such as crabs, abalone, cuttlefish, octopus, chaetognaths), and their biomasses were estimated by the model. These estimates solve the core equations of the model to achieve balance, but the biomass estimates may not be realistic for the system and need to be verified by empirical studies of these groups, particularly for octopus, a major reported predator of lobster (Joll, 1977). The diet compositions in the model will also influence the performance of the model. Dietary data were not available for all functional groups from studies carried out in Jurien Bay and for these 17 groups, diet compositions were used from other temperate reef systems where possible. These uncertainties could introduce errors in the predicted outputs of the model and its use for forecasting ecosystem dynamics and evaluating the biomass of rock lobster under different fishing regimens and puerulus depletion. The Jurien model can be used to assist decision makers (such as planners, managers, stakeholders groups) in preparing for the future, given high levels of uncertainty associated with climate change, which is likely to impact both the fished species (e.g., affecting the size and location of stocks) and their supporting ecosystems. In this study,

the model was used to assess the cumulative impacts of different fishing regimes under low puerulus abundance and settlement rates. Trophic ecology plays an important role on understanding rock lobster population dynamics in relation to other key components of the Jurien Bay ecosystem. It is important to incorporate this species into ecosystem models to evaluate its responses to changes in fishing pressure and levels of puerulus settlement for a more robust ecosystem-based management of human activities and climate variability.

5. Conclusions

The model indicated that the variations in lobster biomass, whether induced from fishing mortality or declining puerulus settlement, have relatively small effects on the biomass of the main predators and prey of lobster and it is unlikely to produce major trophic cascades in the marine park. The relative biomass of adult rock lobster and their associated predators and prey was more sensitive to fishing than to variations in recruitment.

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Fig. 1. Location of the Jurien Bay Region on the central coast of Western Australia. The marine park was gazetted in 2003 with an area of 823.75 km². Black arrows represent the southward flow of the tropical Leeuwin Current.

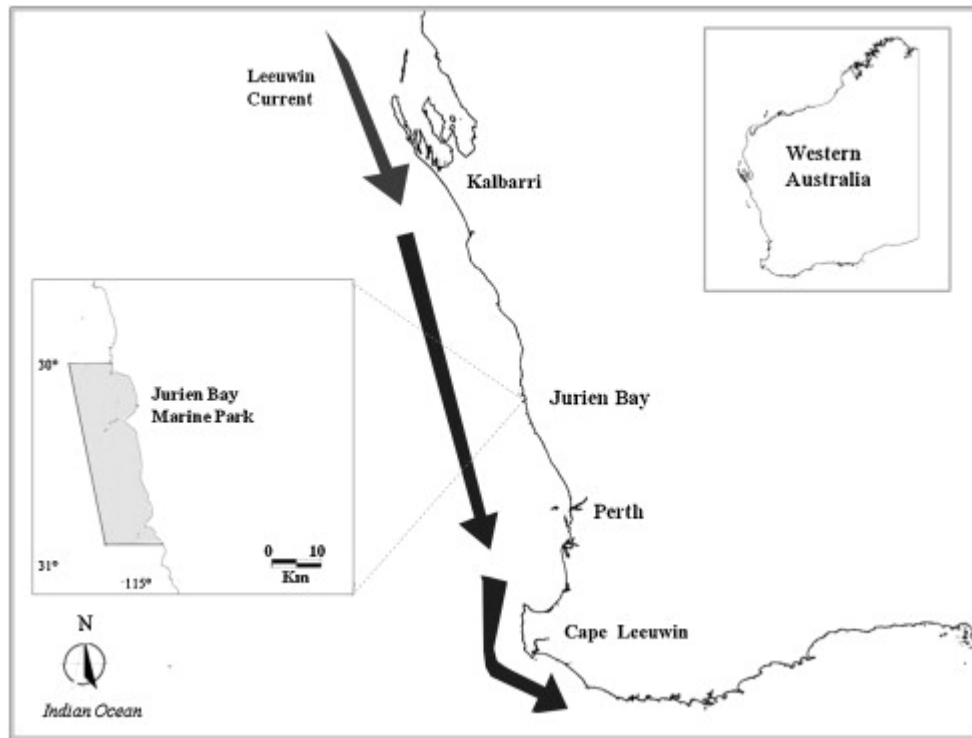


Fig. 2. Overview of the flow diagram and trophic levels of the 72 living functional groups in the Ecopath mass-balance model of Jurien Bay Marine Park. Trophic levels of each functional group (vertical axis) were estimated by the model. The area of each circle is proportional to the biomass of each functional group. See Lozano-Montes et al. (2011) for summary of each functional group and their starting parameters.

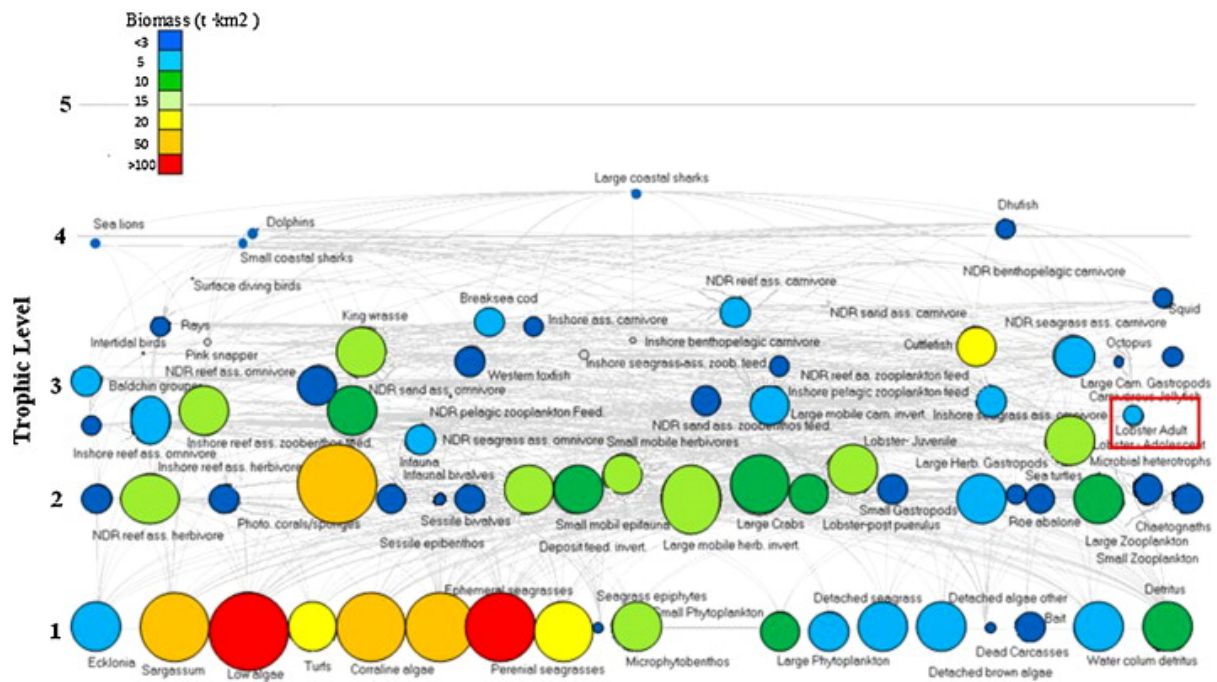


Fig. 3. Predicted percentage changes in biomass of important functional groups in the Jurien Bay Marine Park ecosystem after 20-year simulations using Ecosim for four different scenarios (scenarios 1–4, see Table 1 for details).

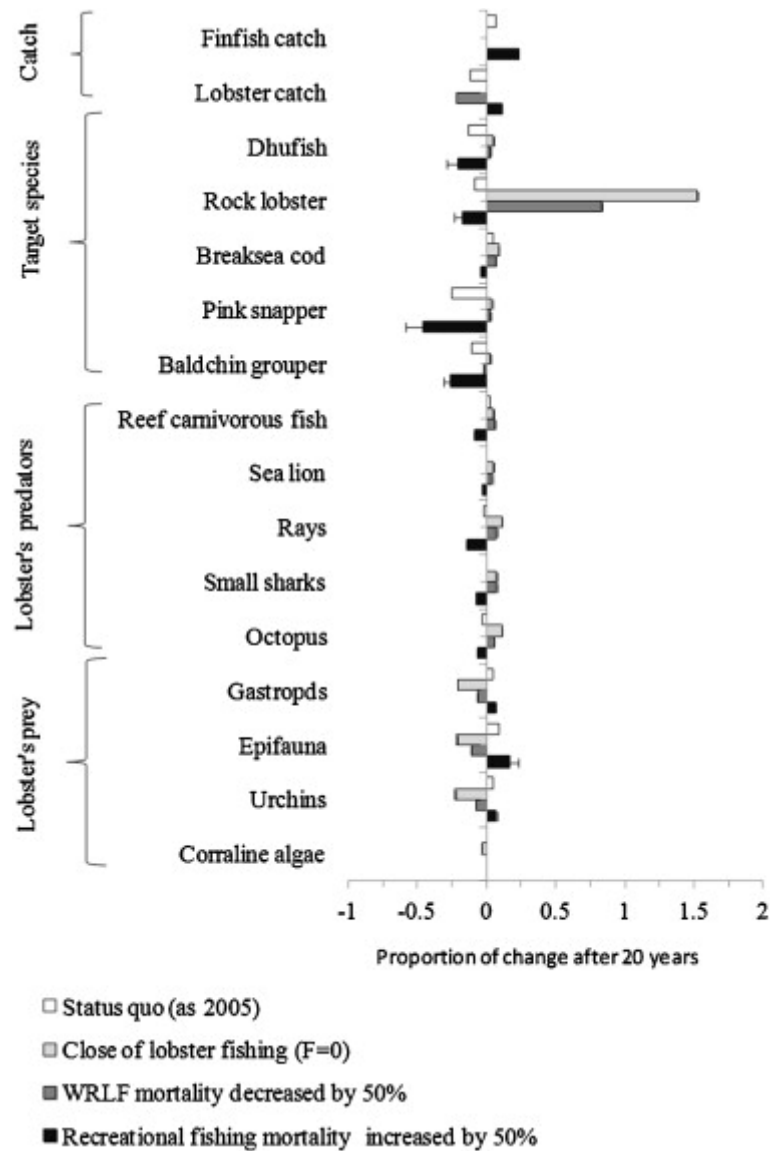


Fig. 4. Relative changes in biomass of important functional groups to adult rock lobster after 20-year simulations for two scenarios of reduction in puerulus (scenarios 5 and 6, Table 1).

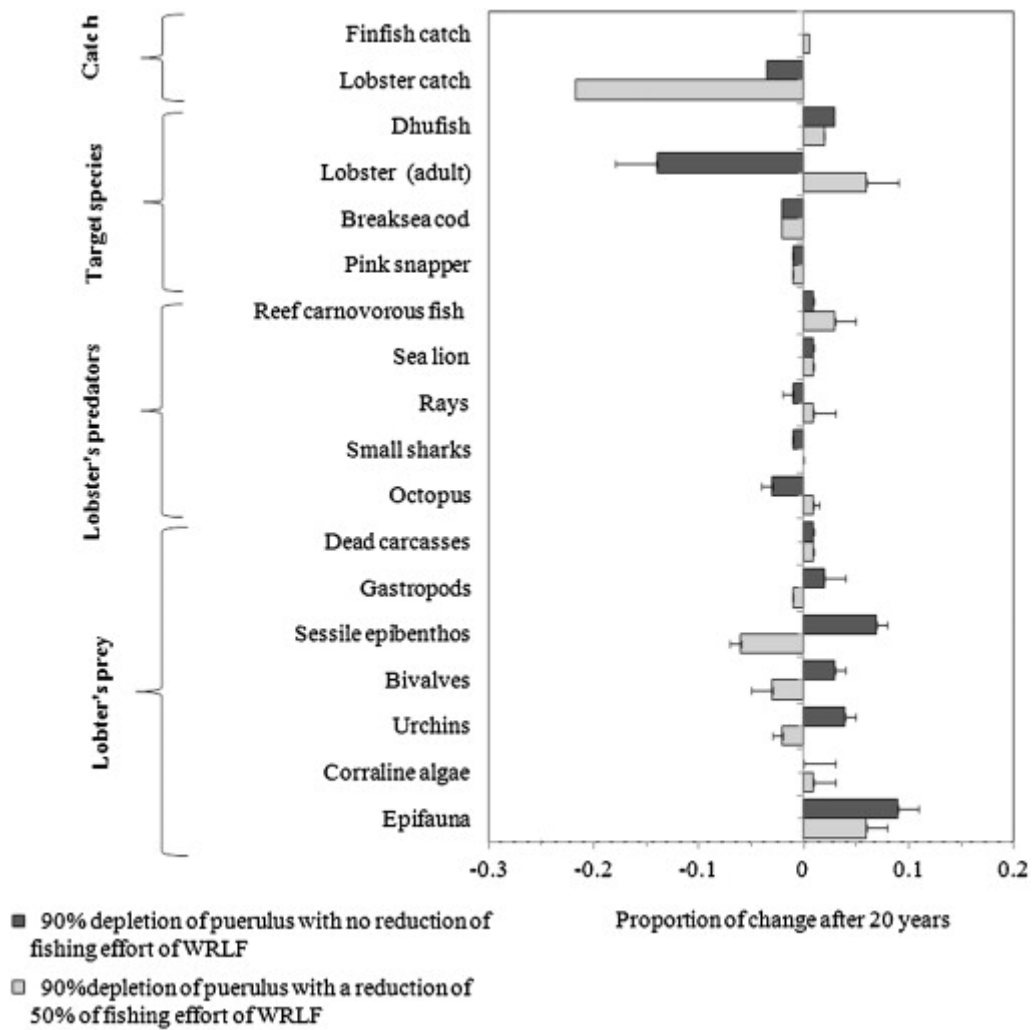


Table 1. Ecosim scenarios designed to explore the impacts of the West Coast Rock Lobster Fishery and puerulus depletion in the Jurien Bay Marine Park.

Scenario	Rationale
1. Status quo (as 2005)	Long-term effects of commercial rock lobster fishing
2. Close of fisheries of rock lobster in the system	Magnified long-term the ecological role of lobster in the system
3. Reduction of 50% commercial fishing mortality of rock lobster	Ecosystem effects of commercial rock lobster fishing
4. Increase 50% recreational fishing mortality	Increase in recreational fishing mortality due to a better road access from Perth
5. Reduction of 90% of puerulus biomass	Impacts of low puerulus settlement within the marine park
6. Reduction of 90% of puerulus biomass combined with a 50% reduction of fishing mortality	Multiple drivers: Low puerulus settlement and fishing pressure

Table 2. The total mortality rate (Z) and rates of fishing mortality (F) and natural mortality (M) for each of the four rock lobster stages in the ecosystem model for the JBMP. TL = Trophic level (calculated from the diet matrix by the model) and biomass of each stage are also shown.

Rock lobster stage	TL	Biomass (t km ⁻²)	Z (year ⁻¹)	F (year ⁻¹)	M (year ⁻¹)
Post puerulus	2.01	4.16	2.76	0	2.76
Juvenile	2.18	23.56	0.68	0	0.68
Sub-adult	2.51	10.32	1.26	0.002	1.26
Adult	2.68	0.72	2.15	0.62	1.53

Table 3. Summary of the results of each of the scenarios developed for the key species in the model.

