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Review

Effects and mitigations of ocean acidification on wild and aquaculture scallop and prawn fisheries in Queensland, Australia

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ABSTRACT

Ocean acidification (OA) is caused by increasing levels of atmospheric CO_2 dissolving into the world's oceans. These changes are predicted to have detrimental effects on commercial and aquaculture fisheries. Here we examine the implications of OA on the prawn and scallop fisheries in Queensland, Australia, and compare the adaptive capacity of wild and aquaculture fisheries to address and mitigate its effects. We do this by reviewing the available OA literature for scallops and prawns to determine the likely impacts, and our confidence in these impacts, on Queensland prawn and scallop species. The tolerance of scallops and prawns to OA is determined by species-specific differences in their structure, life history, environmental preference, behaviour, physiology and sources of nutrition. Studies of similar taxa are used to supplement the sparse information available for the target species. Wild populations of prawns and scallops appear to be more vulnerable to OA and climate-induced stresses than aquaculture-based populations as ameliorating physico-chemical change in natural waters is difficult or impossible. Our analysis suggests the wild prawn fishery is more resilient to increasing OA conditions than the scallop fishery. We also conclude that aquaculture is likely to be more viable in the long term than the wild fishery as aquaculture facilities allow water quality monitoring and modification to avoid excessive exposure to the physico-chemical stresses imposed by OA and climate change.

Contents

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1. Introduction

There is wide concern within the science community about the potentially rapid changes in ocean biochemistry and its impacts on marine ecosystems, including the consequences for marine-based fisheries (Royal Society, 2005; NRC, 2010; Le Quesne and Pinnegar, 2011). Under the 'business as usual' emissions scenario (IPCC, 2007), mean global seawater pH is projected to decrease 0.3–0.4 pH units by 2100 (Orr et al., 2005; Feely et al., 2008). Calcifying organisms (Cooley et al., 2011; Weinbauer et al., 2011) and organisms susceptible to the effects of hypercapnia (Schalkhausser et al., 2012) appear to be particularly vulnerable to such a decrease in pH.

Changes in pH, $p\mathrm{CO_2}$ and calcite saturation state ($\Omega_{\mathrm{Calcite}}$) threaten an annual global fish production that exceeds 140 million tonnes and is worth approximately $150 billion USD per annum (Kite-Powell, 2009). Narita et al. (2012) estimated that the total global cost of ocean acidification (OA) to mollusc fisheries by 2100 may be as high as $141 billion USD while Cooley and Doney (2009) predicted that OA-induced declines in commercial shellfish and crustacean harvests in the US alone at between $860 million and $14 billion USD, depending on CO_2 emissions, discount rates, biological responses and fishery structure.

Given the economic value of global fisheries, there is a critical need for vulnerability assessments of fisheries around the world to explicitly include OA. Such vulnerability assessments are typically strongly quantitative, drawing upon the pool of data and knowledge that have emerged from scientific research. However, the geochemical and biological impacts of OA are not well developed (Poloczanska et al., 2011) and therefore any such assessment needs to take place in an environment of strong uncertainty and variability. Furthermore, whilst OA and fisheries sustainability are global issues, the nature of the vulnerabilities and opportunities that exist are strongly context-specific and a regional approach is needed where the 'local' conditions are taken into account. Therefore, we propose a more qualitative approach to undertaking a vulnerability assessment based on the 'expert opinions' of the authors. We have endeavoured to provide a coherent and consistent approach to this qualitative assessment by classifying the amount of evidence and the degree of agreement (in the evidence) as a means of qualifying our confidence in the validity of our findings.

The Queensland commercial (wild capture and aquaculture) fisheries may be particularly vulnerable to the effects of OA because Queensland fisheries are dominated in volume and value by calcifying species (crustaceans and molluscs) (ABARES, 2012), and the projected decreases in pH for Queensland coastal waters are similar to those projected for elsewhere in the world's oceans (Orr et al., 2005; Feely et al., 2008; Hobday and Lough, 2011).

In this paper we discuss the potential impact of OA on commercially valuable but potentially vulnerable crustacean and mollusc species that are caught in wild fisheries and/or reared by aquaculture for the coastal area of Queensland, Australia. We consider the potential implications of OA for different life-stages of wild caught and aquaculture-grown scallops and prawns. They represent two of the calcifying phyla (crustacea and mollusca) highlighted as vulnerable to OA. Furthermore, they represent established (prawns) and emerging (scallops) contributors to Queensland fisheries. Finally, both scallops and prawns are cultivated through aquaculture in Queensland, allowing an assessment of the capability of aquaculture to mitigate the effects of OA and other co-stressors.

We consider the mechanisms and biological implications of OA-induced stress on these species, a process that includes an evaluation of the role of co-stressors such as increasing sea surface temperature in exacerbating these impacts. We then consider the structure, function and regulation of the scallop and prawn fisheries in Queensland.

Finally, OA coincides with climate-induced changes in the physical environment that will mediate the vulnerability of scallops and prawns to acidification (e.g. Boyd, 2013). While our analysis considers the impacts of OA in the context of climate change, an exhaustive consideration of synergistic stressors is beyond the scope of this manuscript.

1.1. Research questions

We use four key questions to guide our assessment of the implications of OA:

1. What changes in OA and climate-induced stressors are predicted for Queensland coastal waters?
2. What are the anticipated effects of OA and co-stressors on the different life stages of prawns and scallops?
3. What are the implications of these effects for the prawn and scallop fisheries in Queensland, Australia?
4. Which management options are available to mitigate the effects of OA for these case study fisheries?

2. Background

In this section, we provide an overview of OA, including distinguishing between its chronic and acute components and highlighting both direct and indirect pathways for impacts. Rather than an extensive consideration of the available literature regarding the physico-chemical processes and broad biological implications of OA, for which numerous reviews are currently available (e.g. Feely et al., 2004, 2009; Orr et al., 2005; Royal Society, 2005; Fabry et al., 2008; Kroeker et al., 2010; IPCC, 2011), we provide the information required as context for the assessment of OA-induced impacts on the prawn and scallop fisheries in Queensland, Australia.

2.1. The drivers of ocean acidification

Ocean acidification is a decrease in seawater pH that occurs as a "predictable consequence of rising atmospheric CO_2" (Doney et al., 2009). This trend of increasing CO_2 concentration in the bulk seawater forms a background upon which is superimposed the rapid spatial, seasonal and inter-annual variability in pH/pCO_2 that is driven by a range of biotic and environmental factors including river runoff (variability in pH and volume), the ratio of primary production to respiration, and the upwelling of CO_2-rich deep water. Thus, OA will progressively increase the extremes of changes in the carbonate chemistry of the ocean.

2.2. Biological impacts of ocean acidification

Synopses of responses by marine organisms suggest that many fishery species are vulnerable (e.g. Cooley and Doney, 2009; Hendriks et al., 2010; Kroeker et al., 2010; Cooley et al., 2011). For instance, several studies have linked increasing OA to a decrease in the calcium carbonate saturation state (Ω_{CaCO_3}) leading to weakening of calcified skeletons and/or a reduction in the net calcification rates of some marine organisms (Findlay et al., 2009; Moy et al., 2009; Ries et al., 2009; Berge et al., 2010; Hendriks et al., 2010; Kroeker et al., 2010; Whiteley, 2011). Other impacts such as changes in thermal tolerance, metabolic allocation, behaviour, motility and fertilisation success have also been observed (Munday et al., 2009a; Parker et al., 2010b; Schalkhausser et al., 2012).

Evidence of OA-induced impacts on fisheries is already apparent. Upwelling of high CO_2 deep water onto the western continental shelf of North America was reported by Feely et al. (2008). This episodic pulse of acidified water was responsible for 60–80% mortality of larval oyster in hatcheries between 2006 and 2008 (Barton et al., 2012; Service, 2012).

2.3. Queensland scallop and prawn fisheries

The Queensland commercial scallop and prawn fisheries are comprised of both aquaculture and wild capture components. The wild capture prawn fishery (the 'East Coast trawl fishery') is managed under the Fisheries Act 1994 via the Fisheries (East Coast Trawl) Management Plan 1999 and takes place on the shelf, bays and estuaries of the Queensland coastline (Fig. 1). Prawns are also harvested within the Northern Prawn Fishery (NPF), a multi-species trawl fishery that occupies Australia's northern coastline and encompasses the western coastline of the Cape York Peninsula, Queensland and is managed by the Commonwealth Government of Australia. For aquaculture, the Fisheries Act 1994 and Regulations 2008 are the platforms that Fisheries Queensland uses to guide management, develop and protect aquaculture activities.

2.3.1. Scallops

Queensland supports a burgeoning commercial mollusc fishery (ca. $2 million Australian Dollars (AUD) per year) that is predominantly comprised of scallops (ABARES, 2011). Wild-capture harvesting is based on a single species, the saucer scallop (*Amusium balloti*), located between latitude 20.5–26°S (Fig. 1), with commercial fishing concentrated within the Great Sandy Strait, located near Bundaberg.

The saucer scallop inhabits coarse and sandy substrates at water depths from 15 to 50 m (Dredge, 1981, 2006; Wang, 2007) and the bulk of the fished population is drawn from the <2 year cohort (Dredge, 2006). Spawning takes place between May and September and individuals can reach the minimum legal length of 9 cm in 8–10 months (Queensland Government, 2012).

The farming process for *A. balloti* involves the collection of 'wild' broodstock that are induced to spawn in a hatchery. The resulting progeny are maintained in a nursery before they are transferred into the marine environment where they reach maturity. This type of system is commonly referred to as sea ranching, which involves no infrastructure or addition of feed (GSRMAP, 2010). Harvesting occurs using trawling and/or collection by diving.

2.3.2. Prawns

The Queensland prawn fishery (wild capture and aquaculture) is comprised of 11 species (Table 1), has a gross value of $121 million AUD, and accounts for approximately 40% (by volume) of Queensland's total annual fishery production (Skirtun et al., 2012).

Most of the commercially sought wild-capture prawn species are found in waters north of latitude 26° South (Fig. 1) (Baldock, 1999). Of these 11 species, the annual harvest is mainly comprised of (in descending order) Eastern king (*Melicertus plebejus*), tiger (*Penaeus esculentus* and *Penaeus semisulcatus*), banana (*Fenneropenaeus merguiensis*), endeavour (*Metapenaeus endeavouri* and *Metapenaeus ensis*) and school (*Metapenaeus macleayi*) prawns (Queensland Government, 2012).

The Queensland prawn aquaculture industry has a farm gate value of approximately $55 million AUD (ABARES, 2012). Currently farmed species in Queensland are the black tiger prawn (*P. monodon*) and the banana prawn (*F. merguiensis*) (Table 1), while the kurama prawn (*P. japonicas*) was farmed in the past. These farms are mostly located on flat land adjacent to a source of seawater that maintains temperatures above 25 °C during production. The bigger farms produce prawns all year round whilst the smaller farms produce one crop per annum. The prawn broodstock is obtained from the wild and used to mate and spawn in captivity. It takes approximately six months for prawns to grow to harvestable size and most of the prawns are sold in Australia. Processing is carried out as soon as the prawns are harvested, with most farms having their own production facilities that include grading, cooking, packaging and freezing.

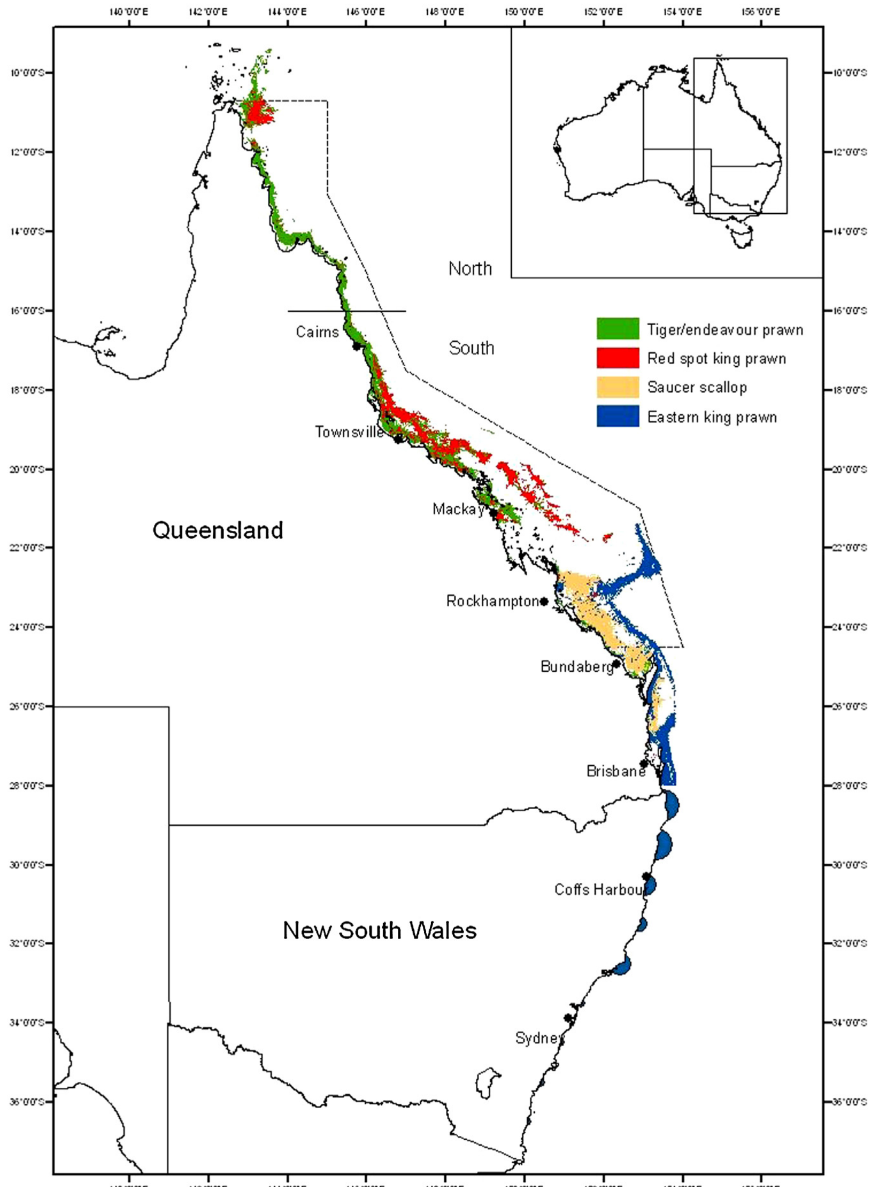

Fig. 1. Distributions of various wild-caught prawn species and the saucer scallop (*A. balloti*) along the Queensland and New South Wales coastline. *Source*: Tony Courtney, Queensland Department of Fisheries and Forestry.

3. Methods

3.1. Multidisciplinary expert workshop

A multidisciplinary team met in Brisbane (Queensland) in 2011 to integrate the available information over a range of expertise, synthesise an understanding of the biological, social, economic and fishery impacts of OA and climate stressors on the Queensland scallop and prawn fisheries, and to conceptualise critical vulnerabilities and mitigation strategies. Generic conceptual models outlining the main stages of fisheries production at enterprise and regional level were developed and used as a starting point for addressing the four key questions outlined in Section 1.

3.2. Framework for assessing the vulnerability of Queensland prawns and scallop fisheries to OA

We undertook a comprehensive review of literature to evaluate the impacts of OA on prawns and scallops targeted by Queensland fisheries. Using the available literature, the impacts of OA on scallops and prawns were tabulated in relation to their general spatial distribution, hypercapnia (acid–base regulation), calcification rate and other physiological responses. We then used this information to qualitatively assess the impact of OA on individual life stages of prawns and scallops and applied these to the Queensland fishery species.

We draw on the methodology used for the consistent treatment of uncertainties outlined for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010) to standardise our literature review and to assist in communicating the degree of confidence in our findings. Specifically, we employ a simplified version of their qualitative ranking matrix (Fig. 2), using the metrics of Evidence (e.g. mechanistic understanding, theory, data, models, expert judgement) and the degree of Agreement to establish the level of Confidence in the findings about the species responses. Evidence and Agreement were classified as *Weak*, *Moderate* and *Strong* and these classifications were then used to determine a Confidence

Table 1
Distribution and habitats of prawn species that are commercially harvested in Queensland (Baldock, 1999 and references within; Montgomery, 1990; Zeller et al., 2002).

Species	Range	Juvenile	Sub-adult/Adult
Melicertus plebejus (Eastern king prawn)	Southern Queensland, fished from southern end of Great Barrier Reef – New South Wales border (21–28°S)	Coastal but briefly occupies shallow brackish estuaries, (Coles and Greenwood, 1983)	Highly migratory (Montgomery, 1990), mainly fished from 20 to 250 m depth over sandy bottom
Penaeus esculentus (Brown tiger prawn)	Entire Queensland coast, mainly fished north of Mackay (22°S)	Beds of seagrass and algae	Adults generally trawled from 10 to 35 m depth over sandy or muddy sand substrate
Penaeus semisulcatus (Grooved tiger prawn)	Northeast Queensland.	Beds of seagrass and algae	Adults generally trawled from 10 to 50 m depth over mud or muddy sand
Penaeus monodon (Black tiger prawn) Farmed species	Tropical to subtropics, brackish waters	Hatchery for up to 20 days, then transferred to stocking ponds	Stocking ponds
Fenneropenaeus merguiensis (Banana prawn) Farmed species also	Entire Queensland coast, fishery mainly from Cairns to Moreton Bay (17–27°S)	Mangrove lined creeks and rivers. Farmed prawns: hatchery-raised for up to 20 days, then transferred to stocking ponds	Generally trawled in coastal areas adjacent to mangroves from <30 m depth Farmed prawns: stocking ponds
Melicertus longistylus (Red spotted king prawn) *Melicertus latisulcatus* (Blue-legged king prawn)	Northeast Queensland, fishery mainly north of Mackay (22°S).	*M. longistylus* juveniles restricted to coral reef lagoons *M. latisulcatus* juveniles occur in shallow coastal areas	*M. longistylus* generally trawled from 30 to 60 m depth, sandy sediments and hard substrate near reefs. *M. latisulcatus* adults are generally trawled from 10 to 40 m depth
Metapenaeus bennettae (Greentail prawn/greasyback prawn)	Southern Queensland, south of Hervey Bay (25°S)	Shallow coastal to brackish estuarine waters.	Generally trawled from 5 to 20 m depth, soft muddy bottom of organic-rich estuaries and bays
Metapenaeus ensis (Greasyback)	Entire Queensland coastline	Shallow coastal to brackish estuarine waters	Generally trawled from 10 to 30 m depth, substrate >60% mud
Metapenaeus macleayi (School prawn)	Southeast Queensland rivers and coast	Shallow coastal to brackish estuarine and fresh-waters	Generally trawled from 10 to 30 m depth, preference for turbid waters, soft muddy substrate
Metapenaeus endeavouri (Endeavour prawn)	Entire Queensland coast, mainly fished north of Cairns	Beds of seagrass and algae	Generally trawled from 10 to 40 m depth, sandy or muddy sand substrate

AGREEMENT			
	Strong agreement Weak evidence ***Medium Confidence***	Strong agreement Moderate evidence ***High confidence***	Strong agreement Strong evidence ***High confidence***
	Moderate agreement Weak evidence ***Low Confidence***	Moderate agreement Moderate evidence ***Medium Confidence***	Moderate agreement Strong evidence ***High confidence***
	Weak agreement Weak evidence ***Low confidence***	Weak agreement Moderate evidence ***Low confidence***	Weak agreement Strong evidence ***Medium confidence***

EVIDENCE

Fig. 2. Evidence–Agreement matrix used to determine the degree of Confidence in the validity of findings (based on Mastrandrea et al., 2010).

level for the anticipated responses to OA of *Low*, *Medium* or *High*.

Criteria for assigning states to the degree of Evidence and the level of Agreement are presented in Table 2. These criteria (and their respective states) reflect the paucity of species-specific data that characterises OA while also recognising that the responses of organisms can vary in even closely related species (e.g. Ries et al., 2009; Miller et al., 2009). This review includes studies carried out to determine the OA sensitivity of taxa with a range of relatedness to the target species. Greater weight is given to results for the target species and progressively lower weight given for taxonomic ranks of family and then class.

Table 2
Criteria used for classifying Evidence and Agreement based on literature review.

Metric	Criteria	
Evidence	Weak	Species is from same class or better (but different family)
	Moderate	Species is from same family or better (but different species)
	Strong	Same species used in the study
Agreement	Weak	Divergent findings or no comparative study available
	Moderate	Similar findings
	Strong	Convergent findings

3.3. Time horizon and OA projections

We selected a time horizon of 2070 for carrying out the assessment of the vulnerability of Queensland prawn and scallop fisheries

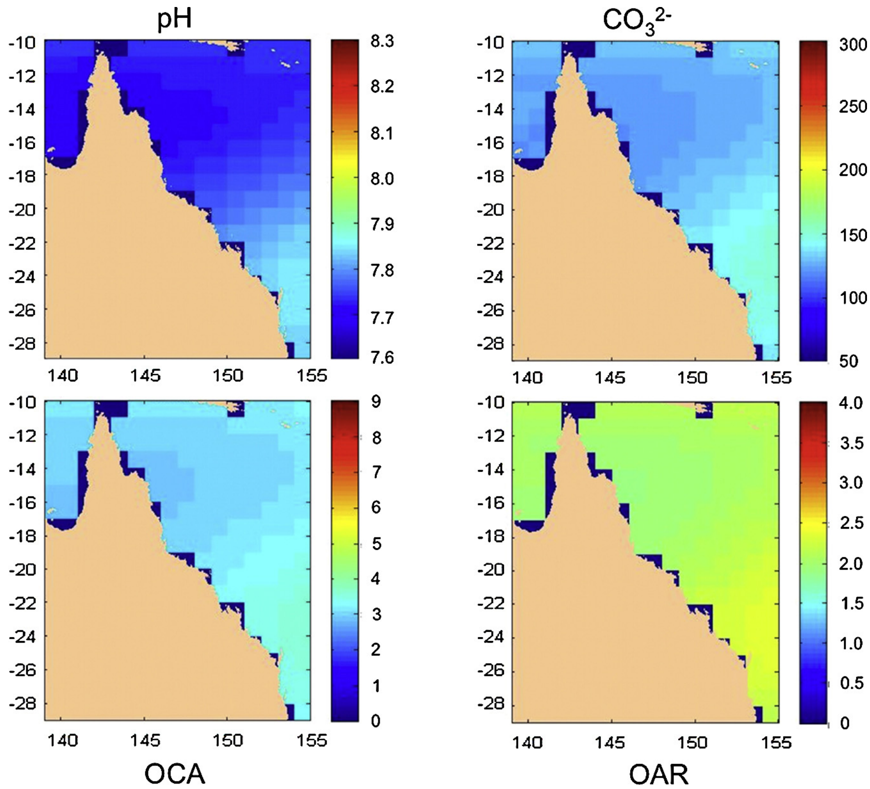

Fig. 3. pH, $CO_3{}^{2-}$, OCA (calcite saturation state) and OAR (aragonite saturation state) projections (2070) for Queensland, Australia.
Data courtesy of Richard Matear and Alistair Hobday, CSIRO using the RCP8.5 emission scenario (Riahi et al., 2011) using the Mk3L-COAL model (Zhang et al., 2014; Matear and Lenton, 2013).

to OA. This date was selected largely because it aligns with many OA and climate change projections (thus enabling future conditions to be envisaged).

OA projections for 2070 were produced using the Mk3L-COAL model based on the RCP8.5 emission scenario. The simulations are described in Zhang et al. (2014) based on the ocean carbon cycle described in Matear and Lenton (2013). Briefly, the OA projections come from the prescribed atmospheric CO_2 simulation using a representative concentration pathways (RCP) scenario to drive an earth system model. The RCP8.5, which represents increasing greenhouse gas emissions over time, was used as it provides the baseline scenario that does not include any specific climate mitigation target (Riahi et al., 2011).

3.3.1. Life stage approach

We have focused on different life-stages of prawns and scallops because there is emerging evidence that some species have higher sensitivity to OA at an early life stage (e.g. Byrne, 2011). Furthermore, many benthic invertebrates, including scallops and prawns, have life stages that are morphologically and ecologically distinct and therefore may respond differently to OA throughout their lifecycle (Dupont et al., 2010). We did not include the accumulation of these effects over successive stages. However, poor or delayed development in early life stages can reduce foraging, limit developmental rates and increase the vulnerability of an organism to predation and disease (Allen, 2008). Even small changes in growth and survival rates can significantly affect population dynamics and the sustainability of fisheries (Byrne, 2011).

3.3.2. Augmenting knowledge gaps using other species

We have endeavoured to contextualise our assessment of OA impacts on prawn and scallop species currently targeted by Queensland fisheries. However, little is known about the biological implications of OA for taxonomic genera let alone for particular species, even for those that are ecologically and/or economically important (Whiteley, 2011). To address this, we have augmented our assessment of Queensland scallop and prawn species with knowledge from similar, related, or where necessary, quite distantly related organisms to help fill in the knowledge gaps. We acknowledge that closely related species are likely to have different responses to OA (e.g. Ries et al., 2009; Miller et al., 2009) and differences in the vulnerability of a single species can even sometimes vary among studies (Parker et al., 2010b vs Kurihara, 2008). However, as highlighted already, we have addressed this by assigning the degree of confidence in our findings based on the evidence and agreement on the evidence, which takes into account the taxonomic affinity. Therefore estimates of the vulnerability of Queensland scallop and prawn fishery species to OA should only be regarded as indicative where these estimates are extrapolated from the responses of other species.

4. Results and discussion

4.1. OA projections for Queensland, 2070

Projections of chemical characteristics for Queensland waters by 2070 show spatial variation, with higher values of pH, carbonate ($CO_3{}^{2-}$), calcite (OCA) and aragonite (OAR) saturation state to the south (Fig. 3). Projections of pH range from 7.7 in the northern Queensland waters to 7.9 in the southern waters (Fig. 3a), while spatially, OAR ranges from pH 2 in the north to 2.5 in the south (Fig. 3d). Thus northern waters are projected to be more acidic and corrosive for calcium carbonate structures by 2070 than southern waters.

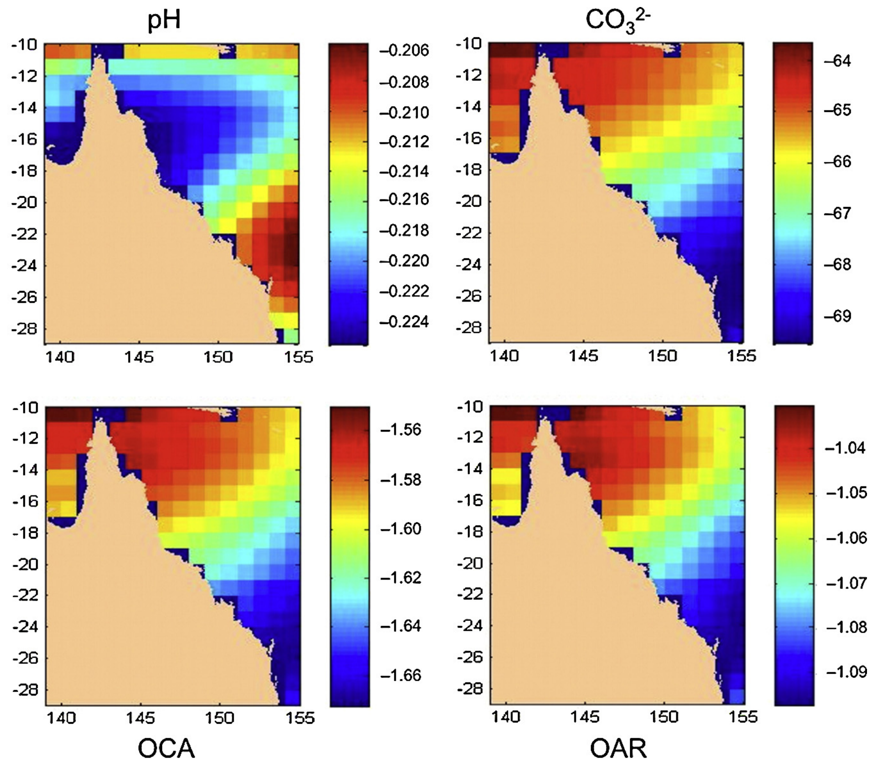

Fig. 4. Projected changes in pH (ΔpH), CO_3^{2-} (ΔCO_3^{2-}), OCA (ΔOCA; calcite saturation state) and OAR (ΔOAR; aragonite saturation state) between 2000 and 2070. Data courtesy of Richard Matear and Alistair Hobday, CSIRO using the RCP8.5 emission scenario (Riahi et al., 2011) using the Mk3L-COAL model (Zhang et al., 2014; Matear and Lenton, 2013).

4.2. Projected change in OA conditions for Queensland from 2000 to 2070

This spatial pattern projected for changes in OA by 2070 contrasts with the predicted net changes in carbonate chemistry between 2000 and 2070 (Fig. 4) where the largest change in CO_3^{2-}, OCA and OAR (Fig. 4b–d) occurs along the southern half of the coast.

4.3. The biological responses of prawns and scallops to OA

Tables 3 and 4 respectively highlight the response of prawns and scallops to OA based on our qualitative review of existing literature. These responses are categorised in terms of the effect on their ability to maintain extracellular acid–base equilibria (hypercapnia), their calcification rate and other physiological responses and sensitivity of different lifecycle stages.

4.3.1. Prawns

The following sections provide details (summarised in Table 3) on the impacts of OA on prawns. Overall, this information highlights that prawns, like other crustaceans, might be able to withstand large changes in OA conditions (pCO$_2$, pH), at least in the short-term. However, there is emerging evidence that this apparent capacity to cope might be compromised by the synergistic effects of increased water temperatures such as its effect on acid–base regulation.

4.3.1.1. Acid–base equilibria. We have medium confidence that Queensland fishery prawns will display strong compensatory responses in response to OA conditions. Whilst no species-specific information could be found regarding hypercapnia and acid–base regulation for Queensland fisheries species specifically, many crustaceans, including penaid shrimp (Dissanayake et al., 2010), are typically strong ion regulators and this attribute is likely to make them less vulnerable to hypercapnia (Whiteley, 2011). *Penaeus serratus* and *Penaeus elegans* have shown strong and rapid iono-regulation, allowing them to control internal pH and ameliorate the effects of hypercapnia (Taylor and Spicer, 1991; Dissanayake et al., 2010). However, such compensatory measures cost energy and there is medium confidence that this will reduce investment in other metabolic processes including reproduction and swimming performance (Pörtner et al., 2004; Wood et al., 2008; Dissanayake et al., 2010; Dissanayake and Ishimatsu, 2011).

4.3.1.2. Calcification rate. Studies of the Queensland prawn species *M. plebejus* and *Penaeus monodon* by (Wickins, 1984; Ries et al., 2009) show with a high level of confidence, that these species will maintain or even increase their calcification rates under increasing OA. The absence of studies means that there is only medium confidence that similar responses will be observed for other Queensland prawn species.

Overall, these responses in the prawns may be due to the concentrations of CO_2 and HCO_3^- both increasing as a result of OA and their role in the formation of $CaCO_3$ in crustaceans (Cameron, 1989). However, like iono-regulation (above), greater investment in calcification may divert energy from other metabolic functions.

4.3.1.3. Other physiological responses. The duration of OA exposure appears to be a primary factor controlling how it affects prawn physiology. Prawns can reportedly tolerate short exposure to OA (e.g. Dissanayake et al., 2010), but long-term exposures to OA combined with increased temperature can reduce their growth (high confidence for *P. monodon*, medium confidence for the other prawn species), survival (medium confidence for all prawn species) and swimming ability (low confidence for all prawn species) (Wickins, 1984; Kurihara et al., 2008; Dissanayake and Ishimatsu, 2011). Given the predicted OA (Figs. 3 and 4) and warming of seawater of at least 1 °C by 2070 (Hobday and Lough, 2011), it would appear

Table 3
Summary of impacts of ocean acidification on prawns (species shown bold are target species for Queensland fisheries).

Category	Response	Species	Reference
Hypercapnia	Strong/rapid compensatory capacity [medium confidence]	*Penaeus serratus, P. elegans*	Taylor and Spicer (1991) Dissanayake et al. (2010)
	Compensatory impacts on other processes (e.g. exoskeleton dissolution, swimming, repro-duction) [medium confidence]	*P. serratus*	Pörtner et al. (2004) Wood et al. (2008) Dissanayake et al. (2010) Dissanayake and Ishimatsu (2011)
Calcification	Maintain/increase rate [high confidence]	***Melicertus plebejus*, *Penaeus monodon***	Ries et al. (2009), Wickins (1984)
	Maintain/increase rate [medium confidence]	*P. occidentalis*	Wickins (1984)
Other physiological responses	Decreased growth rate [high confidence]	***P. monodon***	Wickins (1984)
	Decreased growth rate [medium confidence]	*Penaeus occidentalis, Palaemon pacificus*	Wickins (1984), Kurihara et al. (2008)
	Decreased survival rate [medium confidence]	*P. pacificus, Metapenaeus joyneri*	Kurihara et al. (2008), Dissanayake et al. (2010)
	Decreased swimming ability and metabolic scope [low confidence]	*M. joyneri*	Dissanayake et al. (2010)
Lifecycle	Suppressed egg production [low confidence]	*P. pacificus*	Kurihara et al. (2008)
	Delayed development of larvae [low confidence]	*Pandalus borealis*	Bechmann et al. (2011)
	Other crustacean larva – minimal impact [low confidence]	*Homarus gammarus* *Hyas aranus*	Arnold et al. (2009), Walther et al. (2010)

that prawns in coastal Queensland waters are likely to experience increasing physiological impairment over this period.

4.3.1.4. Lifecycle effects. Prawns have several developmental stages in their lifecycle (Fig. 5). While different stages of a species can occupy different habitats and these habitats can vary among species (refer Table 1 for summary information for the Queensland prawn species), generally the post-larval and juvenile life stages inhabit inshore areas while adult and planktonic larval life stages occur offshore.

Studies on the effects of OA on the early life stages of prawns are lacking and therefore there is low confidence for all prawn species on the impacts during this period. Instead, existing literature shows a focus on the effects of OA on adult prawns (e.g. Wickins, 1984; Ries et al., 2009; Dissanayake et al., 2010; Dissanayake and Ishimatsu, 2011), as summarised in Table 3, Fig. 5 and discussed above. Whilst negative impacts have been observed on the early life stages for two shrimp species (*Palaemon pacificus* and *Pandalus borealis*), other crustacean species have shown no impact (*Homarus gammarus* and *Hyas aranus*).

4.3.2. Scallops

Scallops (and other mollusc species) are typically poor ion regulators (low confidence) and have routinely displayed adverse responses to even short exposures of OA conditions (low to high confidence) (Table 4).

4.3.2.1. Hypercapnia. There is little information on the capacity of scallop species to regulate their extra-cellular acid–base levels in response to OA and therefore there is low confidence regarding the

Table 4
Summary of impacts of ocean acidification on scallops.

Category	Response	Species	Reference
Hypercapnia	Adjusted haemolymph parameters (pH, pCO_2) and aerobic scope [low confidence]	*Pecten maximus*	Schalkhausser et al. (2012)
	Low capacity of other mollusks for extracellular acid-base regulation [low confidence]	*Crassostrea gigas* *Mytilus galloprovincialis*	Lannig et al. (2010), Michaelidis et al. (2005)
Calcification	Decreased calcification rates [high confidence]	*Argopecten irradians*	Ries et al. (2009), Talmage and Gobler (2010), White et al. (2013)
Physiological response	Impaired growth and survival [high confidence]	*A. irradians, P. maximus*	Talmage and Gobler (2010), Schalkhausser et al. (2012), Andersen et al. (2013), White et al. (2013)
	Impaired hinge development [low confidence]	*P. maximus*	Andersen et al. (2013)
	Reduced clapping performance [low confidence]	*P. maximus*	Schalkhausser et al. (2012)
Lifecycle	*Fertilisation*: reduced success [low confidence]	Broadcast spawners	Havenhand et al. (2008), Morita et al. (2010), Parker et al. (2010b).
	Larvae: increased mortality, reduced growth, impaired development, shell deformities [medium confidence]	*A. irradians, P. maximus*	Talmage and Gobler (2010), Andersen et al. (2013), White et al. (2013)
	Post larvae: decreased net calcification [low confidence]	*A. irradians*	Ries et al. (2009)
	Post larvae: poor acid–base regulation capacity, reduced aerobic scope [low confidence]	*P. maximus*	Schalkhausser et al. (2012)

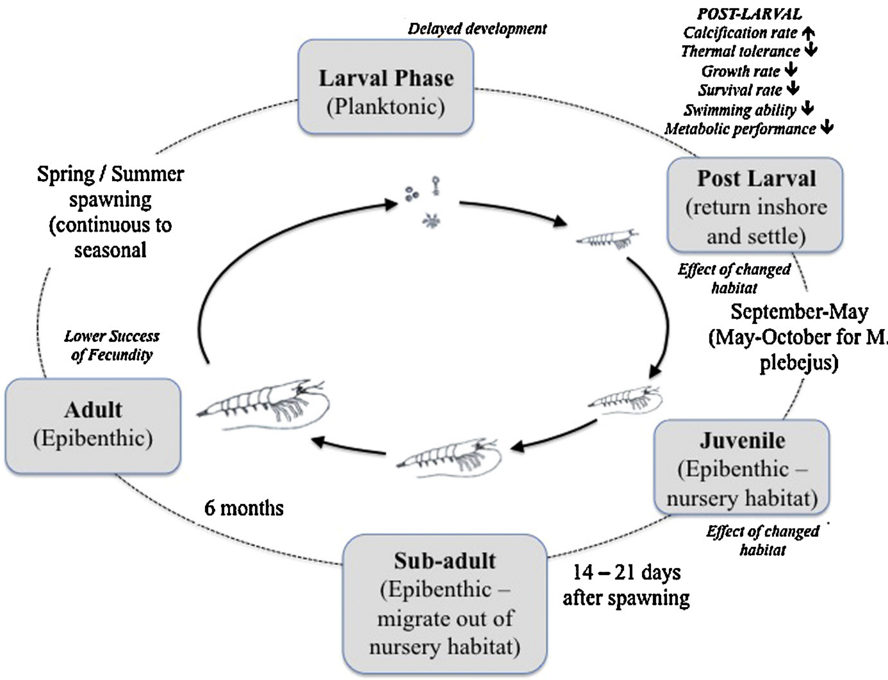

Fig. 5. Schematic of the lifecycle of prawns showing generalised locations and timing of life stages (after Baldock, 1999). Also shown are the potential impacts of ocean acidification on the different life stages based on current knowledge.

response of *A. balloti*. The only available study showed *Pecten maximus* adjusted the pH, and pCO_2 of its haemolymph when exposed to OA conditions (Schalkhausser et al., 2012). Yet molluscs are considered poor regulators of their internal pH (Whiteley, 2011) as demonstrated by *Crassostrea gigas* (Lannig et al., 2010) and *Mytilus galloprovincialis* (Michaelidis et al., 2005), which casts uncertainty on the resilience of *A. balloti* to the effects of hypercapnia.

4.3.2.2. Calcification rate. Reduced calcification rates in response to increasing OA conditions have been observed for the bay scallop (*Argopecten irradians*) in several studies for both larvae (Talmage and Gobler, 2010; White et al., 2013) and post larvae individuals (Ries et al., 2009) (Table 4). This supports the general trend of molluscs exhibiting impaired calcification under OA conditions (Ries et al., 2009; Gazeau et al., 2010; Waldbusser et al., 2010; Talmage and Gobler, 2010), and suggests with high confidence that the calcification rate of *A. balloti* will be similarly affected.

4.3.2.3. Other physiological functions. Table 4 summarises the range of physiological functions observed in other scallop species (*P. maximus* and *A. irradians*) when exposed to OA conditions. There is high confidence that *A. balloti* will show a similar decline growth and survival to that of *P. maximus* and *A. irradians* due to OA by 2070s. However, the lack of studies on the effects of OA on hinge development and 'clapping' performance (one study found for each) means that there is currently low confidence that these responses will be observed in *A. balloti*.

4.3.2.4. Lifecycle assessment. Scallops reproduce through broadcast spawning, releasing unfertilised eggs and sperm into the water column (Fig. 6). The fertilised eggs quickly develop into semi-planktonic larvae before metamorphosing into spat, where they attach themselves to substrate via byssal threads (Dredge, 2006). As the scallops grow in size they detach from the substrate and move to the seabed where they progress to juveniles after approximately three months and adulthood after approximately twelve months.

We could find no published studies that investigated the potential effect of OA on fertilisation success for scallops. However, increased pCO_2 can lead to potentially negative effect on fertilisation success for broadcast spawners (Havenhand et al., 2008; Morita et al., 2010; Parker et al., 2010b).

The studies on scallops have largely focused on the impacts of OA on larval stages, although these are generally sparse (for each impact type) and none are available for *A. balloti.* Therefore, there is low confidence in the response of *A. balloti.*

Other scallop species (*A. irradians* and *P. maximus*) have shown sensitivity to OA conditions, causing increased mortality, reduced growth and the occurrence of shell deformities (Table 4). Similar deleterious effects have also been reported for the larvae of other mollusc species (e.g. Kurihara et al., 2007; Gazeau et al., 2010; Parker et al., 2010b; Talmage and Gobler, 2010; Crim et al., 2011), suggesting that the response of *A. balloti* larvae will be similar.

As shown above, the response of post-larval life stages to OA has been linked to decreased rates of net calcification (Ries et al., 2009), low capacity for extracellular acid–base regulation (Schalkhausser et al., 2012) and reduction in the aerobic scope, specifically affecting its metabolism and 'clapping' ability (Schalkhausser et al., 2012).

4.3.3. Role of food supply on OA impacts

Organisms can reportedly avoid the adverse effects of OA on calcification, growth and condition if they have sufficient food to sustain the energetic costs of tolerance (Rodolfo-Metalpa et al., 2011). Thus, the direct effects of OA on scallops and prawns may be outweighed by the indirect effects of CO_2- and climate-induced changes in the relative abundance of their prey (Ries et al., 2009). There is ample evidence showing differences in protistan tolerance of enhanced CO_2 among species and strains (Hinga, 2002; NAP, 2010). Consequently, OA is likely to cause changes in the composition, abundance and nutritional content of marine protists, though the nature of these changes remain uncertain (NAP, 2010 and references therein). Studies in tropical and sub-tropical waters indicate that increased temperature and/or OA will enhance the growth and production of cyanobacteria and other picoeucaryotes (0.2–2 μm

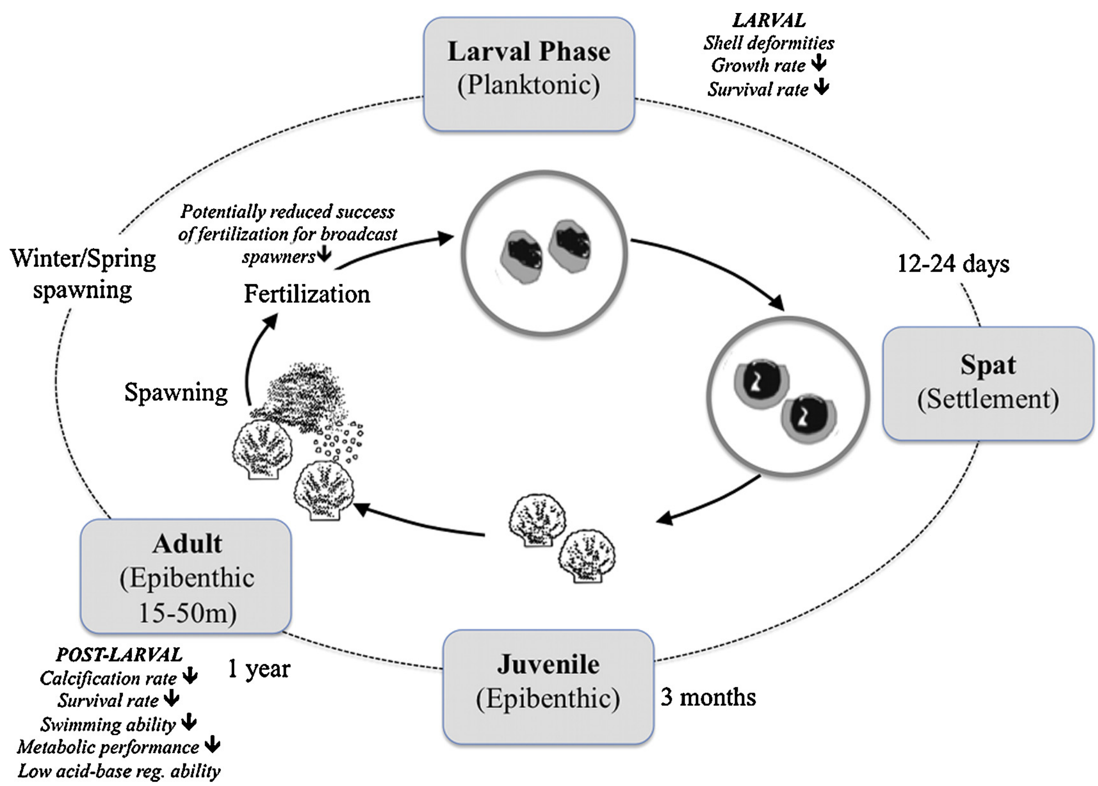

Fig. 6. Schematic of the lifecycle of Ballot's scallop (*A. balloti*) showing the location and timing of key life stages (after Rose et al., 1988; Kailola et al., 1993). Also shown are the potential impacts of ocean acidification on the different life stages based on current knowledge.

diameter) (Fu et al., 2007; Paulino et al., 2008; Lomas et al., 2012). Any OA-induced decrease in the particle size of prey available to grazers could profoundly change the quality, quantity and availability of food for higher trophic levels, especially scallops where particle size affects food capture and ingestion (Zhang, 2010).

4.4. Queensland's wild fisheries

In this section we discuss the potential responses of Queensland's commercially-targeted prawn and scallop species to OA based on the impacts identified in Sections 4.3.1 and 4.3.2.

4.4.1. Impact on spatial distribution of Queensland fishery stocks

Projected changes in the biogeochemical environment (Figs. 3 and 4; Hobday and Lough, 2011) for Queensland coastal waters may facilitate a southward shift in the distribution of wild prawns and scallops. However, this will depend on whether increasing OA conditions act as a stimulus for migration, and/or ontogenetic changes are closely related to chemical cues. Conversely, if decreased pH does not act as a chemical cue for migration, then the condition of the stocks could decline due to the impacts of OA outlined in Tables 3 and 4.

The role of migration in sustaining viable wild populations for fisheries of prawns and scallops will depend on the availability of suitable habitat, food supply, connectivity between pelagic and benthic phases, the existence of appropriate reproductive and settlement cues, and the benefit to their survival relative to changes in rates of predation.

4.4.1.1. Prawns. In general, prawns require a pH that is commonly >8.0 (Baldock, 1999) and therefore the projected decrease in pH by 2070, especially in northern Queensland waters (Figs. 3 and 4), could prompt a southward drift in the distribution of the more tropical species (e.g. *P. esculentus*, *P. semisulcatus* and *F. merguiensis*). Such a shift could be exacerbated by any concomitant increase in water temperature (as predicted by Hobday and Lough, 2011), which has been linked to increased sensitivity of *Metapenaeus joyneri* to OA (Dissanayake and Ishimatsu, 2011).

In terms of an indirect habitat effect, mangroves and seagrass are expected to flourish and expand their range southward in response to increased pCO_2 and temperature (Gilman et al., 2008; Hall-Spencer et al., 2008; DOCC, 2009), which may benefit Queensland species that favour these habitats and/or foraging grounds (e.g. *P. esculentus*, *P. semisulcatus* and *M. endeavouri*).

4.4.1.2. Scallops (A. balloti). The current distribution of *A. balloti* along the southern end of the Queensland coastline (Fig. 1) coincides with the area where projected pH levels will be highest in 2070 (Fig. 3) and the change over time will be lowest (Fig. 4). However, a change of ca. 0.2 pH units in the average conditions is still projected in this area (Fig. 4) and this could elicit impacts on *A. balloti* of the type highlighted in Table 4. Furthermore, the observed reduction in thermal tolerance of the scallop *P. maximus* when exposed to OA conditions (Schalkhausser et al., 2012) suggests that *A. balloti* will struggle to maintain a viable fishery stock in its current location given the projected change in water temperature (Hobday and Lough, 2011). This appears particularly pertinent when *A. balloti* growth and survival rates are sensitive to relatively small changes (1–2 °C) in water temperature (Wang, 2007). Therefore, even without a synergistic effect between OA and SST, the ca. 0.2 °C decline in SST per degree of latitude projected for the Queensland coastline (Lough, 2008) indicates that the thermal window for scallops could move south by 7.5–12.5 degrees of latitude, carrying it beyond Queensland's southern border. However, this does not consider the potential of the scallops to adapt to increased water temperatures over this period.

4.4.2. Impact of co-stressors on OA vulnerability

The potential co-stressor effect of water temperature (prawns and scallops) and habitat distribution (prawns) has already been covered in previous sections. However, other factors such as changed ocean currents and predator–prey relationships also emerged from this review as likely to be important co-determinants in the future distributions and viabilities of prawn and scallop fisheries along the Queensland coastline.

Projected strengthening of the East Australian Current (EAC) may affect the physical characteristics and flow of seawater off southern Queensland. The EAC current influences shelf waters seaward of the Great Barrier Reef (GBR) off Queensland at latitudes exceeding 25°S. Its southward flow is projected to strengthen by 2060 (Sun et al., 2011), transporting waters containing lower pH and higher temperature down the Queensland coast. The northerly location of Queensland's scallops and prawn fisheries, together with their occurrence in waters landward of the GBR, may protect these fisheries from changes in the EAC. However, changes in the EAC could still affect inshore currents (Lee et al., 2007; Munday et al., 2009b), which would affect the dispersion and recruitment success of species located within the GBR lagoon (including *A. balloti*). Deep-water species such as *M. plebejus*, together with species that are located, or have moved, south of the GBR would be exposed to an enhanced EAC, with consequences for the dispersion, survival and settlement patterns of the pelagic life phases (Munday et al., 2009b).

OA could cause important changes in predator–prey interactions, altering rates of mortality. For example, starfish are a major predator of scallops (Dredge, 2006) and have exhibited strong resilience to increased OA conditions (Ries et al., 2009). Whilst little is known about the impact of OA on common predators of prawns (e.g. fish and elasmobranchs) and scallops (e.g. Moreton Bay Bugs), it is reasonable to posit that hypercapnia and/or increased energetic costs of calcification may increase predator-mediated mortality.

4.4.3. Resilience of Queensland's wild prawn fishery

Queensland's wild prawn fishery is likely to display some biophysical resilience towards the OA conditions projected for 2070 (see Section 4.3.1). This assertion is based on the relatively low sensitivity of prawns to OA (see Table 3) and high phenotypic diversity of Queensland prawns (Table 1). Phenotypic and geographic plasticity are important attributes that allow organisms to tolerate evolutionary pressures such as OA and climate change (Jablonski, 1987; Talmage and Gobler, 2010; Sunday et al., 2011).

Commercially targeted prawn species that are currently distributed along the entire Queensland coastline (*F. merguiensis*, *P. esculentus*, *M. ensis* and *M. endeavouri*) or inhabit the tropical coast (*P. semisulcatus* and *M. longistylus*) have scope to move south in response to environmental change and remain within Queensland fisheries zone.

Conversely, prawn species located towards the southern boundary of the Queensland fisheries region could potentially move and/or be carried southward out of the Queensland fishery zone by a strengthening EAC (see Section 4.4.2). However, this group does include the Eastern King Prawn (*M. plebejus*), which is the most economically valuable trawl fishery resource in Queensland (Queensland Government, 2012).

4.4.4. Resilience of Queensland's wild scallop fishery

Unlike the wild prawn fishery, the scallop fishery is composed of a single taxon (*A. balloti*) whose distribution is limited to the southern areas of the coastline (Fig. 1). Thus, it is reasonable to assume that the phenotypic and genotypic plasticity of scallops, which is critical in dictating the vulnerability of a species to OA (Sunday et al., 2011), is substantially less than for prawns. As mentioned earlier (Section 4.4.1.2), OA and water temperature conditions projected for 2070 might reduce the suitability for sustaining viable stocks at the current location of *A. balloti*.

The main population of *A. balloti* supporting the wild fishery is located in a gyre that limits dispersion of its larvae and ensures recruitment to the local adult population (Wang, 2007). Consequently, the productivity of scallop beds further south of this location, if the scallops were to move or be relocated, might depend on whether similar currents (gyres and eddies) facilitate the recruitment of larvae to the metapopulation (Sinclair et al., 1985; Bogazzi et al., 2005).

4.5. Queensland's aquaculture

4.5.1. Aquaculture prawn fishery

Except for the broodstock, the entire lifecycle of Queensland farmed prawns is sustained within an aquaculture facility. The physical, chemical and biological attributes of the water imported into the aquaculture facility can be manipulated (e.g. monitored and adjusted and/or regulated), leaving only the brood stock exposed to unconstrained changes in OA and other co-stressors (e.g. water temperature) in the natural environment. Recent studies indicate that prawns are quite resilient to short-term exposure to OA (refer Section 4.3.1). Thus, the reliance on wild-caught broodstock may not pose an immediate threat to prawn aquaculture but may need to be changed in the long-term to ensure the industry's continuing viability. Even though the cost of monitoring and adjusting the water quality is currently unknown, the aquaculture prawn industry will be pressed to undertake detailed economic assessments and investment analyses to estimate the impact of this adaptation to their long-term business viability.

4.5.2. Aquaculture scallop fishery

For aquaculture, only larvae and juveniles are reared in dedicated aquaculture facilities (hatchery and nursery) after which the scallops are transferred to the natural environment using 'sea ranching' (no addition of infrastructure or food).

The fertilisation and rearing of juveniles could avoid exposing many of the vulnerable life stages of scallops to OA (Section 4.3.2). Like prawns, the water quality used in the hatcheries and nurseries can be monitored, regulated and adjusted to avoid exposing the eggs, sperm, larvae, spat and early juveniles to physical and chemical stress. Thus, such aquaculture would prolong the scallop fishery in Queensland waters beyond that expected for the wild fishery. However, unlike prawn aquaculture, sea ranching exposes scallops to the natural environment for approximately 1.5 years prior to harvesting where they need to grow from juveniles to scallops of marketable size. During this time there is no opportunity to control or manipulate the quality of the water the scallops are exposed to. Therefore OA-changes (along with co-stressors) in the physical, chemical and biotic properties of the coastal seawater will have a greater impact on sea ranched scallops than for aquaculture prawns.

Therefore, it would appear that to strengthen the long-term (2070) resilience of the aquaculture scallop industry in Queensland to OA, all life stages would need to take place in dedicated aquaculture facilities so that the water quality can be monitored and controlled. Again, the economic viability of such an approach is currently unknown and the biological and economic feasibility of adapting the aquaculture fishery to a closed-loop system will need to be determined to ensure long-term business sustainability.

5. Management options available to mitigate the effects of OA

As outlined in previous sections, OA will likely, to varying degrees, affect the wild and aquaculture fisheries of prawns and scallops. OA itself cannot be mitigated through fisheries management, however management can be used to reduce the negative effects and take advantage of positive effects associated with this phenomenon.

5.1. Building the scientific knowledge base for OA

A priority for effective adaptation is to increase knowledge of the effects of OA on commercially exploited species of prawns and scallops in Queensland waters. As evidenced in our study, there is a dearth of current information about these effects on prawns and scallops. Despite this, the few available studies provided important insights into the potential effects of increasing OA and coincident climate stressors (specifically temperature) for Queensland fisheries.

It is important that the knowledge base for a targeted fishery includes measuring and projecting (modelling) physical and chemical changes in water quality, together with government- and/or industry-based measurements of critical indicators of fecundity, recruitment, growth and survival. The benefit of having downscaled OA projections in assessing future conditions for commercial fisheries has been demonstrated in this study as it has allowed our assessments to be made against the projected spatial variation in pH and Ω_{arag} along the Queensland coastline. However, it is also critical to continue long-term monitoring of temperature and carbonate chemistry parameters at appropriate temporal (i.e., daily and annual ranges) and spatial scales (i.e., surface and sub-surface measurements) to understand the duration, frequency, and intensity of environmental variability that target species experience in their natural habitats. The installation of various monitoring equipment under the Integrated Marine Observing System (IMOS) since 2007 will help considerably in obtaining critical data at the required temporal and spatial scales. Field measurements should also be augmented through laboratory studies used to determine the limits of tolerance and adaptation of different life stages of *A. balloti* and key prawn taxa to OA.

5.2. Explicit inclusion of OA in fisheries management

We recommend that OA be included in fisheries management/risk assessments for both wild-capture and aquaculture in order to help meet future fishery and broader ecological objectives. Specifically, information about the predicted rates of environmental change and the biological responses to these changes needs to be made available to the stakeholders involved (government, managers, processors and both wild and aquaculture fishers) so that they can make informed decisions about their fishery. These decisions may include identifying future habitats that will be suitable locations for wild and aquaculture fisheries and adopting practices that could be used to establish/enhance populations at these sites. There also needs to be ongoing evaluation to ascertain whether current fishing seasons, fishing zones, target species and permanent closure areas (used to protect nursery areas and/or to replenish fishery stocks) need to change in response to OA- and climate-mediated changes in species distribution and recruitment patterns.

5.3. Flexibility of wild capture fisheries management

Management of wild fisheries requires the flexibility to rapidly respond to environmental change and scientific knowledge. For the Queensland wild capture prawn and scallop fishery, the current demersal fisheries management plan allows manipulation of fisheries endorsements through adjusting the number of operating licenses, effort quota (time spent fishing), length of season, fishing areas, equipment (including fishing method and boat size) and incidental catch. Such regulation of the wild catch will need to be continually monitored, refined, and adjusted to accommodate OA and climate-induced effects on fisheries. Where the fleet size decreases as a consequence of decreasing species abundance due to OA, plans for possible exit strategies and re-skilling may need to be developed.

5.4. Management of aquaculture

The challenge of managing OA for aquaculture is slightly different to wild harvest because of the levels of control that can be exerted over the environmental conditions. Specific interventions to OA in aquaculture include the capacity to modify the quality of ambient seawater pumped to aquaculture facilities. The physico-chemical properties of this water, can be monitored and modified to mitigate against decreased pH, increased temperature and/or increased solubility of $CaCO_3$. Such monitoring of temporal variation in ambient condition also allows the pumping of seawater to be timed to coincide with temporal minima in OA and temperature to maximise the well-being of the eggs and larvae (Service, 2012). Selective breeding might also improve the resilience towards the effects of ocean acidification (Parker et al., 2010a). However, this process reduces genetic diversity and capacity for genetic adaptation, leading to reduced resilience to other stressors such as disease (Durand et al., 1993; ISU, 2011). These types of adaptation can be led by the aquaculture sector but supported by governments.

5.5. Transitioning from wild capture to aquaculture

Changes in the abundance and location of the wild fishery, together with the ability to monitor, control and mitigate effects of OA in aquaculture facilities may increase the pressure for approvals of new and/or larger aquaculture facilities. Transition to greater reliance of the fishing industry on aquaculture enterprises, would require changing practices and social perceptions on the quality of their product to minimise adverse environmental impacts, particularly land-based aquaculture operations for prawns. There is also likely to be pressure to increase approvals for sea ranching type operations for scallops, driven by the necessity to exert control over the physico-chemical environment of the critical life stages (eggs and larvae) to maintain commercially viable stocks of adult fish.

Finally, transitioning of fisheries from wild-caught to aquaculture as a potential adaptation option against the impacts of OA may have profound effects on the nature of the community and the fishery upon which they rely. The resources required to sustain an aquaculture-based fishery differ from those required for wild harvest. Importantly, facilities need to be located where aquaculture enterprises can reliably access staff and seawater of sufficient quality and quantity. Unconstrained by defined fishing seasons, the temporal nature of the demand for staff will change. Moreover, the type of labour demand will change as the types of skills that are core to aquaculture differ from those of working on a fishing vessel. Furthermore, transition to aquaculture allows these enterprises to mitigate against interannual fluctuation in the wild catch due to uncontrolled environmental factors. This influences the number and effort of fishers involved in the industry, be that harvest of sea ranched scallops or drain- or seine-harvesting of prawn stocking ponds.

6. Summary and conclusion

In this paper, we used a multi-disciplinary expert panel and available literature to make qualitative estimates about the impacts of OA on the wild and aquaculture prawn and scallop fisheries in

Queensland, Australia. This evaluation was used to identify the vulnerability of the fisheries to OA and climate change, predict possible changes in the fisheries and identify management options to mitigate the effects of these environmental changes.

Wild populations of prawns and scallops appear more vulnerable to OA than aquaculture-based populations as conditions in the natural environment such as food quality and quantity cannot be easily managed. Aquaculture prawns and scallops are currently not immune to the effects of OA because they still rely on seawater pumped in from local estuaries, but may prove more resilient than the wild fishery because of the interventions that can be used to control the physico-chemical environment of the fish.

The resilience of the wild prawn fishery to OA appears to be greater than that for scallops as prawns appear to be more tolerant to OA conditions, there is greater diversity of species available for fishing, and prawn species are distributed over a larger geographic area (i.e. the entire Queensland coast). Queensland's commercial scallop fishery appears more vulnerable because scallops appear to have lower tolerance for OA than prawns and because it consists of a single species for which the harvested populations are geographically restricted.

Finally, our analysis clearly shows that both fisheries are vulnerable to OA to different extents but that there are intervention points, especially in the prawn and scallop aquaculture fisheries. The sooner potential future vulnerabilities are addressed, the more likely OA impacts can be adequately dealt with. Conversely if no pre-emptive adaptation is undertaken (i.e. "business as usual") this will likely result in a reduced Queensland prawn and scallop harvest, and could even mean local extinctions of these commercially important species.

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