



Socio-economic and management implications of range-shifting species in marine systems

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ABSTRACT

Climate change is leading to a redistribution of marine species, altering ecosystem dynamics as species extend or shift their geographic ranges polewards with warming waters. In marine systems, range shifts have been observed in a wide diversity of species and ecosystems and are predicted to become more prevalent as environmental conditions continue to change. Large-scale shifts in the ranges of marine species will likely have dramatic socio-economic and management implications. Australia provides a unique setting in which to examine the range of consequences of climate-induced range shifts because it encompasses a diverse range of ecosystems, spanning tropical to temperate systems, within a single nation and is home to global sea surface temperature change 'hotspots' (where range shifts are particularly likely to occur). We draw on global examples with a particular emphasis on Australian cases to evaluate these consequences. We show that in Australia, range shifts span a variety of ecosystem types, trophic levels, and perceived outcomes (i.e., negative versus positive). The effect(s) of range shifts on socio-economic change variables are rarely reviewed, yet have the potential to have positive and/or negative effects on economic activities, human health and ecosystem services. Even less information exists about potential management responses to range-shifting species. However, synthesis of these diverse examples provides some initial guidance for selecting effective adaptive response strategies and management tools in the face of continuing climate-mediated range shifts.

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1. Introduction

Present-day shifting of species' range boundaries has been documented for numerous taxa, with many of these shifts attributed to global climate change (Parmesan and Yohe, 2003; IPCC, 2007; Perry et al., 2005). In marine systems, range shifts have been described for all continents, including Antarctica, and at least one Pacific Island (Sorte et al., 2010). Although climate variability has long been recognized to influence changes in the distribution of marine organisms (e.g. Dayton et al., 1999, Roy et al., 2001), the majority of recent published marine range shifts

have been polewards in direction – symptomatic of broad-scale environmental changes such as those predicted under global climate change scenarios (Sorte et al., 2010; Perry et al., 2005). In light of even the most conservative future climate change projections (IPCC, 2007), and mounting evidence that climate change is at least partially responsible for shifts in many marine species' biogeographic ranges, examining the diverse consequences of climate-induced range shifts is essential for the development of adaptive management responses. In particular, there is remarkably little understanding of the ecological (but see Sorte et al., 2010) or socio-economic consequences of these shifts, despite mounting evidence that significant, global-scale consequences to socio-ecological systems may occur as a result (Cheung et al., 2010). Likewise, the appropriateness of existing or potential management responses to range-shifting species has not been comprehensively explored, again despite observed (Perry et al., 2005) and projected (Cheung et al., 2010) changes to many managed commercial fisheries globally. Range shifts

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caused by climate variability, while important, will not likely necessitate long-term socio-economic or management responses because these range shifts are not likely to be permanent. Given that the processes of and responses to range shifts caused by climate change versus climate variability are fundamentally different, we have restricted our analyses to the former. Importantly, as the global climate continues to change, range shifts driven by this globally ubiquitous process will likely broaden in both number and geographic extent (Cheung et al., 2010). Considering the socio-economic and management implications of these changes before they occur may help to mitigate their negative effects and develop effective adaptive response strategies.

Based on definitions used by Parmesan et al. (2005) and Sorte et al. (2010), we define 'range shift' as a change in the distribution of native species' boundaries from their previously recorded boundaries (i.e., expansions or contractions along range edges). This definition includes range contractions, range relocations and range extensions (Fig. 1), and we use the term range shift to denote any changes in the boundaries of a species' range (whether contraction, relocation, extension, or where the specific type of change is unknown) unless otherwise noted.

Australia presents an ideal location in which to explore the socio-economic and managerial implications of species' range shifts. It encompasses a wide latitudinal range spanning tropical to temperate ecosystems. It encompasses a diverse range of ecosystems, spanning tropical to temperate systems, within a single nation, thus allowing the socio-economic and management consequences of a diverse suite of examples of range-shifting taxa to be compared in the absence of confounding major differences in governance paradigms and economic structures. Furthermore, Australia's two major ocean boundary currents along the east and west continental slopes, the East Australian Current and the Leeuwin Current, play important roles in structuring marine communities along the coasts. These currents also provide an interesting case study of continental eastern and western boundary flows which are uniquely both poleward-flowing, thus increasing the likelihood of poleward range shifts in response to climate change on both sides of the continent. Historical observations and climate change projections suggest probable strengthening to both of these currents (Ridgway, 2007; Caputi et al., 2010), thereby presenting particularly useful opportunities to examine and compare the resulting ecological, socio-economic, and managerial consequences along these two coastlines.

The aim of this paper is to summarise the known examples of Australian range-shifting marine species and, based on these examples and others from the global literature, present a forward-looking analysis of observed and potential future socio-economic

and managerial implications of climate-induced range shifts in marine taxa. We use a suite of marine ecosystems in Australia as a lens through which to evaluate potential effects and their interactions with other system attributes. First, we review the state of knowledge with regard to range shifts in Australian marine taxa. Next, we describe the observed and potential socio-economic effects and managerial responses and discuss their possible implications. Lastly, we outline which management approaches and tools may be more or less appropriate for reducing negative impacts and maximizing opportunities of marine range shifts in the face of ongoing global climate change.

2. Methods

An exhaustive search of range shifts in the Australian marine environment revealed 49 examples of reportedly range-shifting species (Table 1; Appendix 1) in the peer-reviewed literature. Additional reports of apparently range-shifting taxa were collated from non-peer-reviewed sources (and are categorized as such). ISI Web of Knowledge and Google Web and Scholar were used to search for peer-reviewed and grey literature (search terms included *range**, *marine*, *Australia*, and *climate change*). Verified citizen science observations were collated from the REDMAP database (Range Extension Database and Mapping project, available at www.redmap.org.au) and anecdotal accounts were drawn together from the authors' collective knowledge.

To ascertain realized and projected socio-economic implications and management responses to range shifting marine species, we took a two-pronged approach. First we reviewed the above-mentioned studies of Australian marine range shifts (Table 1; Appendix 1) for discussion of socio-economic or management implications or considerations. Second, because there were very few Australian examples that mentioned these, we then broadened our search to analogous global examples to consider potential socio-economic implications and management responses. We did this through a global literature review, as well as by drawing on our collective expertise.

3. Evidence, drivers, and ecological impacts of marine range shifts in Australia

The overwhelming majority of Australian range shift examples documented in the peer-reviewed literature are from eastern Australia, and, notably, only two examples from the tropics were identified (Appendix 1). This is perhaps at least in part a result of a disparity in research effort, rather than a reflection of actual patterns of range shift intensity/distribution. The examples span a range of trophic groups, including apex predators, carnivorous and

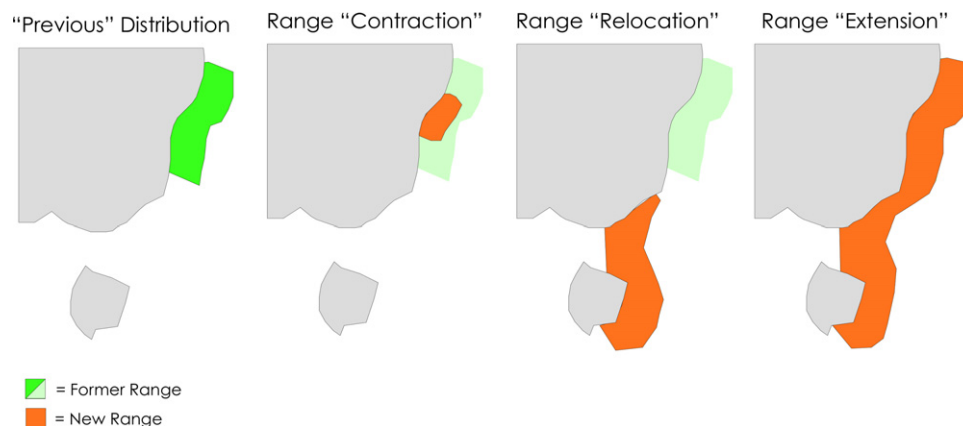


Fig. 1. Hypothetical examples of range shift categories.

Table 1

Summary of range shifts documented from the Australian marine environment as revealed by an exhaustive search of the peer-reviewed literature. Examples known by the authors from grey literature and unpublished sources are also included, however this portion does not represent an exhaustive list. For particular sources, examples were included only if they met the following criteria: (Last et al., 2010) classified as 'expanding range,' 'expanding range and abundance,' or 'colonisers' (i.e., if classified as category 3, "range expanders"); (REDMAP) verified sightings (i.e., species identification was made by a taxonomic expert based on a clear photograph). See Appendix 1 for details of each of the examples and studies included.

Category	Number of species studied	Number of unique studies/sources	Number of studies discussing management implications (%)	References
Peer reviewed literature				
Coastal birds	4	1	0 (0)	Dunlop (2009)
Marine fishes	22	2	1 (50)	Last et al. (2010)
Marine invertebrates	19	7	3 (43)	Stuart-Smith et al. (2010) Caputi et al. (2010) Pitt et al. (2010) Ling (2008) Ling et al. (2009a) Ling et al. (2009b) Ling and Johnson (2009) Thomson (2010)
Marine plants and algae	4	4	1 (25)	Hallegraeff et al. (2008) Hallegraeff (2010) Phillips et al. (2008) Johnson et al. (2011)
Verified community sightings, non-peer reviewed accounts and anecdotal observations (i.e., species observed outside expected range limits)				
Marine fishes	8+	2	0 (0)	Barry Hutchins (Western Australian Museum) REDMAP website (http://redmap.org.au)
Marine invertebrates	4	2	1 (50)	REDMAP website (http://redmap.org.au) Poloczanska et al. (2007)
Marine plants and corals	2	3	1 (33)	ABC Online; <i>Fishing Today</i> , 2005, vol. 18 (www.abc.net.au) Edyvane (2003) Kelpwatch website (www.geog.utas.edu.au/kelpwatch)

herbivorous fishes and invertebrates, planktivorous fishes, filter-feeding invertebrates, and primary producers, highlighting the pervasive nature of apparent range shifts in Australia's marine taxa. Temperature was overwhelmingly the most commonly implicated or presumed driver of range shifts. Within those studies citing temperature as the ultimate mechanism facilitating a range shift, the East Australian Current appeared to be one of the primary mechanisms facilitating the southward (poleward) movement of species by aiding larval transport and bringing tropical water further south (e.g., Last et al., 2010; Ling et al., 2009b; Booth et al., 2011). However, other human-induced stressors may also help facilitate range shifts (e.g., changing oceanographic conditions; fishing-mediated reduction in competing apex predators; Zeidberg and Robison, 2007; see also Box 1). Although evidence of the ecological impacts of range shifting species in Australia is sparse, the range-extending sea urchin, *Centrostephanus rodgersii*, provides an excellent example of some of the potential impacts which may occur (see Box 1 for more details).

Despite notable examples, a surprising paucity of studies exists providing clear evidence of range shifts in Australia. Specifically, based on our search protocol, only 14 peer-reviewed studies were found to exist, five of which relate to the southward incursion of the sea urchin *C. rodgersii* in Tasmania (Table 1; Appendix 1). Much of the remaining evidence of possible range shifts in Australia is anecdotal, often derived from fisher and/or scientist observations (see Poloczanska et al., 2009; Hobday et al., 2008). However, this relative lack of clearly documented examples is not unique to Australia (Booth et al., 2011). It is reflective of a global paucity of evidence for climate-induced biological changes in marine versus terrestrial systems, despite emerging evidence that marine organisms are likely to respond more rapidly to changing climatic conditions than their land-based counterparts (Richardson and Poloczanska, 2008). This lack of clear-cut evidence renders it difficult to disentangle multiple, potentially confounding factors,

such as changes in fishing pressure and increased observer awareness, from potential climate drivers (see Last et al., 2010). Although some efforts are now underway, the lack of large-scale, long-term monitoring studies in Australia that might provide strong evidence of range shifts if and when they occur hampers efforts to infer taxonomic or geographical patterns in the observed range shifts. Nonetheless, mounting evidence suggests that range shifts are occurring over relatively recent timeframes in Australia's marine environment. Given these changes, coupled with the many

Box 1. Ecological impacts of *Centrostephanus rodgersii*.

The southward incursion of the sea urchin *C. rodgersii*, a native of southern mainland Australia, into Tasmania is the most well studied case of a range shifting species in Australia (see Appendix 1). Although the range shift is thought to be temperature-mediated (Johnson et al., 2011 and references therein), research also suggests that the shift has been facilitated by the fishing-related removal of natural urchin predators (large southern rock lobsters, *Jasus edwardsii*) (Ling et al., 2009a). This voracious grazer and habitat modifier has resulted in a phase shift in ecosystem function from productive kelp beds to urchin barrens in eastern Tasmania (Ling et al., 2009b). Grazing activity of *C. rodgersii* has been shown to result in an estimated net loss of approximately 150 taxa typically associated with kelp forests in this region (Ling, 2008). Field experiments have also shown that increased densities of *C. rodgersii* cause increased mortality rates in the native abalone species, indicating that the urchin is a superior grazing competitor (i.e., a generalised versus specialised herbivore) (Strain and Johnson, 2009). Interestingly, six fish species, all with eastern mainland Australian affinities, have apparently shifted southward in association with *C. rodgersii* and its resultant barrens (Last et al., 2010). In effect, this habitat modifying species, via its presumed climate-driven range shift, is now appearing to facilitate, in its own right, range shifts in Tasmania.

ecosystem services provided by coastal marine biodiversity (Worm et al., 2006), exploring the potential and realized subsequent socio-economic effects of these changes is a timely exercise.

4. Socio-economic implications of range-shifting species

Few studies of Australian range-shifting species mention their realized or potential social and/or economic impacts. This lack of information could be because shifts are too recent for associated socio-economic impacts to be evident, or because studies have focused solely on ecological implications. Consideration of potential socio-economic consequences of documented Australian examples of range-shifting species indicates that these will primarily be negative for key aspects of human society (Table 2), and will include both positive and negative feedback loops between range-shifting species and industries they affect.

Given the dearth of documented examples of realized socio-economic implications of range-shifting species globally, we explore here potential socio-economic implications, including both those perceived as positive and negative, of range-shifting species (Table 2). Our intent is to highlight the range of possible socio-economic implications so that (1) policy makers can be aware of potential repercussions, (2) future studies can seek to provide empirical evidence to determine the most likely scenarios, and (3) mitigation measures can be implemented to minimize negative consequences. Where applicable, we draw upon international examples to illustrate potential socio-economic implications. We propose that range-shifting species would affect three interlinked aspects of human lives: economic activities, human health, and ecosystem services. Furthermore, how these interlinked aspects affect humans depends in large part on peoples' response to the changes.

4.1. Economic implications

Marine industries most likely to be financially affected are those directly linked to the marine environment: fisheries (artisanal,

recreational, commercial), aquaculture/mariculture, tourism, and marine education (e.g., research stations, field courses). Indirect economic effects may also be felt by marine industries that would be affected by changing regulations implemented to manage range-shifting species. For example, if more stringent guidelines are implemented to reduce stressors on marine ecosystems, marine shipping might be affected by stricter ballast water regulations, offshore mining by additional monitoring requirements, and so on.

Several examples of potential negative economic consequences due to range-shifting species exist within Australia. The western rock lobster fishery of Western Australia is likely to be negatively affected by climate change, due to the predicted shift of this commercially valuable species into deeper waters (Caputi et al., 2010) and associated increased costs of fishing, as surface water temperatures increase. Likewise, predicted extension of deadly jellyfish (i.e., box jellyfish and irukandji, both potentially deadly to humans) ranges into southern Queensland and central Western Australia would have negative impacts on tourism and local recreational users in addition to obvious deleterious effects on human health (Richardson et al., 2009b). The only documented international example of negative economic consequences due to range-shifting species that we are aware of comes from South Africa, where an invading rock lobster virtually eliminated the local sea urchin, and hence severely impacted the urchin fishery (Blamey et al., 2010). Nonetheless, projected changes in diverse fisheries' catch potential under warming ocean scenarios demonstrate that this problem is likely to be globally widespread in the future, with some regions and countries experiencing projected increases in fisheries yields and some experiencing decreases (Cheung et al., 2010). Importantly, these projections suggest that many tropical communities, which are highly dependent upon marine resources for food security, may be hit hardest (Cheung et al., 2010).

Conversely, some range expansions may have positively perceived socio-economic consequences. While we were unable to locate documented examples from within or beyond Australia,

Table 2
Potential socioeconomic implications of range-shifting species.

Category of implication	Example of positive implication	Example of negative implication
<i>Direct economic</i>		
Fisheries (commercial and recreational)	New commercially and/or recreationally important species arrives and adds a new fishery, leaving existing fisheries unaffected	New arrival displaces important species or affects changes in ecosystem function, which are detrimental to existing fisheries (e.g., <i>C. rodgersii</i> and commercial reef species)
Aquaculture/mariculture	Changes in SST allow for increased suite of species to be cultivated in situ in a given location	Ocean-based aquaculture production may decrease due to new species (e.g., <i>Noctiluca</i> in Tasmania may impact salmonid industry) and/or altered physical conditions
Tourism	New species of interest to tourists expands tourism opportunities and increases tourism revenues (e.g., poleward expansion of tropical coral reefs)	New species or altered ecosystems less conducive to tourism activities or is directly harmful to tourists (e.g., the jellyfish irukandji) causing collapses in tourism ventures
<i>Human health</i>		
	Range of a species harmful to humans contracts, decreasing health risks to humans in that part of the range	New species harmful or deadly to humans directly (e.g., irukandji) or indirectly through consumption of affected seafood (e.g., harmful algal blooms)
<i>Ecosystem services</i>		
Provisioning	New species increase output of edible seafood	Ecosystems altered to decrease seafood production
Regulating	New species increases efficiency of regulating services such as climate regulation and disease control	New species acts as pest or introduces disease, negatively affecting ecosystem function, resulting in a less complex and less desirable (from a human perspective) ecosystem
Supporting	Efficiency of supporting services enhanced, such as through increased primary production	Supporting services decreased because of breakdown of ecosystem functioning
Cultural	Cultural experiences (such as recreational values, indigenous values, quality of life) increased through new opportunities presented by new species	Cultural experiences and values decreased as a result of loss of culturally-important species, habitat, or ecosystem function
Existence/bequest value	Likelihood of species' persistence increased through range shifts	Some species driven to extinction because arrival of new species

we can speculate about some potential positive examples emerging in Australia. The apparent range extensions of both snapper (*Pagrus auratus*) and yellowtail kingfish (*Seriola lalandi*) into Tasmania have been positively received by the recreational fishing community because of the highly prized nature of these species (Table 2). Possession limits for these species in Tasmanian waters have recently been introduced, indicating that these species are now present in significant enough numbers in Tasmania to warrant regulation. The need for regulation of this emerging fishery therefore provides indirect evidence that their ranges have indeed shifted to include Tasmania. Likewise, anecdotal evidence exists from fishers and other individuals that the octopus *Octopus tetricus*, formerly known only in NSW to the north, has begun appearing in Tasmanian waters (Appendix 1). If *O. tetricus* populations shift southwest into Bass Strait and closer to the existing fisheries' key landing areas of northwest Tasmania, this could have positive implications for the local octopus fishery, as *O. tetricus* is more valuable than the 'native' octopus species, *O. pallidus*. Increased human harvest of this species, however, could lead to a regulating feedback loop in which the level of harvest regulates *O. tetricus* populations if harvest increases concomitantly with *O. tetricus* population growth over time. Similarly, although it is generally not considered highly palatable, *C. rodgersii* is classified as an edible urchin species and it is conceivable that a new fishery could emerge in Tasmania for it, thus likely leading to a new source of profits for some fishers. Importantly, however, any profits that might emerge from increases in this species would come at a cost of decreased profits for local rock lobster and abalone fishers, since these urchins consume the habitat-forming kelp upon which the latter species depend. Likewise, urchin roe (eggs) would likely only be harvestable from the 'advancing front' of its range, because saleable roe requires urchins to consume significant amounts of primary producers (e.g., kelp) and kelp forests have thus far been denuded by this species as it advances. This example therefore provides an example of a range-shifting species that could potentially have some very limited positive socio-economic consequences initially, but subsequent negative consequences as kelp forest ecosystems (and the ecosystem services they provide) disappear. Despite the lack of observed examples, global projections for increases in catch potential in many communities (particularly in high-latitude areas) with warming oceans (Cheung et al., 2010) suggests that these areas in general may experience considerably increased fisheries catches for a variety of species in the near future.

4.2. Human health implications

Negative human health impacts are anticipated from the arrival of range-shifting species that harm humans, for example the two jellyfish species discussed above and harmful algal blooms. Jellyfish cause harm through direct contact with humans, whereas harmful algal blooms can affect seafood and indirectly cause harm (e.g., through brevetoxins associated with red tides that cause respiratory problems in some humans, as documented in Florida, USA (Moore et al., 2008)). As jellyfish populations are projected to expand their ranges (Richardson et al., 2009a), and harmful algal blooms are becoming increasingly prevalent in new areas (Moore et al., 2008), their deleterious health effects on humans will likely also expand.

4.3. Ecosystem services implications

The effect of range-shifting species on ecosystem services – the benefits people derive from ecosystems (Daily et al., 1997) – remains relatively unexplored and is likely closely interlinked with novel ecosystems. Differential rates and direction of shift among

co-occurring species can potentially result in altered spatial overlap among species or spatial mismatches (Perry et al., 2005; Schweiger et al., 2008), disrupting trophic interactions and altering competitive networks. This, in turn, may affect ecosystem services (e.g., supporting, regulating, provisioning, and/or cultural services). For example, in Tasmania, experiments have shown that increased densities of *C. rodgersii* cause an increase in abalone mortality rates (see Box 1 also) (Strain and Johnson, 2009), suggesting that abalone catches may decline as *C. rodgersii* abundances increase. Decreased competition for resources (i.e., benthic algae) that *C. rodgersii* would then face could potentially lead to increased rates of population growth, providing an example of a potential positive, or reinforcing, feedback loop that would affect both species' fisheries. Similarly, if *Perkinsus*, a microparasite which affects commercial mollusk species such as oysters and abalone, were to undergo a poleward range extension in Australia as it has in the USA (Ford and Chintala, 2006), it would likely have damaging effects on aquaculture operations and wild fisheries based on its host species. Furthermore, some species of jellyfish can cause significant problems for salmon farms, including suffocation and toxicity (Battaglene et al., 2008), indicating a reduction in the regulating services on which these farms depend.

4.4. Peoples' response to changes

There is an emerging recognition that feedbacks between social and ecological systems will ultimately drive social-ecological changes (e.g., Cinner et al., 2011; Cinner, 2011). Although to our knowledge this has not been examined for range-shifting species specifically, we suggest that human responses will also be a main contributor to driving resulting social-ecological changes. As Cinner et al. (2011) suggest, human responses to disturbances to the flows of goods and services, such as might be induced by range-shifting species, can reinforce, continue or dampen ecosystem trends. Thus social adaptation to changes can undermine or build social-ecological resilience, depending on the response, and further research is needed to assess whether conservation or development projects could steer those responses to lead to desired outcomes (Cinner et al., 2011).

4.5. Perceptions of positive and negative changes

Whether the expansion or contraction of species' ranges is perceived as positive or negative will vary by stakeholder group and depend on the context (e.g., snapper and *O. tetricus*). For example, one fishery may be negatively affected by a newly arrived species, whereas a new fishery might be developed to target the newly arrived species. Thus, fishers from the established fishery would likely view the range shift as negative, whereas fishers engaged in the new fishery would perceive it as positive. Similarly, benefits of a new fishery might equal or offset losses due to the reduction in a previous fishery for fishers switching from one to the other. Likewise, arrival of a new commercially important species might be nonetheless viewed by ecologists and/or conservationists as a net negative consequence for the ecosystem if it alters the structure or functioning of the ecosystem it colonizes. Furthermore, different stakeholder groups have varying levels of political leverage (e.g., Agrawal and Gibson, 1999), and therefore the perspective of one or a few vocal groups is likely to shape the debate around how change is perceived and what management responses are should occur.

5. Management implications of range-shifting species

A number of existing management tools could potentially be applied to respond to range-shifting marine species. We divide these tools into six categories (Table 3). Four of the six categories

Table 3

Potential management tools and strategies for range-shifting species.

Strategy/tool	Description	Potential applicability to range-shifting species	Relevance for managing range-shifting species (high, med., low)
1. Protection			
a. No-take areas	Defined area where extractive activities are prohibited	May increase resilience of ecosystems to perturbation of ecosystem function by arrival of new species; provides ecological baseline in absence of potentially confounding human impacts	Medium
b. Multiple-use marine protected areas	Defined area where extractive activities are limited and/or managed for biodiversity conservation	May increase resilience of ecosystems to perturbation of ecosystem function by arrival of new species	Medium
2. Management of the matrix (i.e., outside MPAs)			
a. Fisheries management: Input controls; and/or output controls	Commercial and recreational fisheries managed through measures that control the input of effort, e.g., limits on number of boats, licenses, fishing gears; or output controls such as quotas minimum or maximum size limits, bag limits	Manages components of ecosystems to ensure sustainability of fisheries; could be used to manage catches of new species directly	High
b. Species and habitat restoration	Restoration of species or habitats through breeding programs, re-introductions or plantings, etc.	Direct intervention to manage ecosystems affected by new arrivals, e.g. re-introduction of large lobsters to predate on newly arrived urchins	High
c. Transplantations	Moving native species that are unable to disperse unaided into new suitable habitats	Move native non-shifting species if they are likely to be driven to extinction by range-shifting species; move the range-shifting species?	Low
d. Ex situ protection	Zoos, aquaria or gene banks where individuals or samples are kept to safeguard genes or species	Potential last-resort management approach if species are likely to be driven to extinction by range-shifting species	Low
3. Law and policy			
a. Legislation and treaties	National laws or international treaties that provide management tools such as endangered species acts	Existing or new legislation and international treaties adapted/ developed to apply to range-shifting species	Medium
b. Compliance	Programs to encourage voluntary compliance to existing laws and regulations, e.g., watchdog programs	Encourage compliance to existing management tools relevant to range-shifting species, e.g. protection and fisheries management	Medium
c. Litigation	Legal proceedings for in compliant activities, e.g., illegal fishing or dumping in MPAs	Assists enforcement of existing management tools relevant to range-shifting species	Low
d. Enforcement	Activities such as patrols to ensure compliance of existing management tools, Develop or alter policies	Enforcement of existing management tools relevant to range-shifting species	Medium
e. Policy development and reform		Adjust or develop policy specifically designed to be enable management of range-shifting species	Medium
4. Education and awareness			
a. Formal and informal education	Education through program such as school curricula, signage along the coastline, brochures in national parks	Awareness of shifting ranges and appropriate precautionary measures for human encounters with new species	High
b. Moral persuasion	Peer pressure to abide by laws and regulations	Peer pressure to abide by laws and regulations of relevance to range-shifting species	Low
c. Communication	Dissemination of information, e.g., through direct mail campaigns, media, etc.	Dissemination of information on newly arrived species	High
5. Changing incentives		Possibly linked indirectly to range-shifting species, hence not directly relevant	Low
a. Conservation enterprises	Enterprises that are eco-certified or certified as sustainable (e.g., Marine Stewardship Council)	May promote/prevent markets from developing for range-shifting species in new systems, depending on management objective	Low
b. Using market pressure	Market pressure applied to change demand, e.g., through boycott campaigns	May promote/prevent markets from developing for range-shifting species in new systems, depending on management objective	Low
c. Economic alternatives	Alternative livelihood strategies available to allow people to switch careers away from unsustainable industries	May promote/prevent markets from developing for range-shifting species in new systems, depending on management objective	Low

Table 3 (Continued)

Strategy/tool	Description	Potential applicability to range-shifting species	Relevance for managing range-shifting species (high, med., low)
d. Conservation payments	Payments to undertake biodiversity conservation, e.g., payment for ecosystem services	May promote/prevent markets from developing for range-shifting species in new systems, depending on management objective	Low
e. Non-monetary values	Belief systems that encourage sustainable actions and activities	May promote/prevent markets from developing for range-shifting species in new systems, depending on management objective	Low
6. Infrastructure and operational changes			
a. Temporary or permanent infrastructure	Infrastructure to minimize conflict between wildlife and people	e.g., netting of beaches	High
b. Medical responses, capabilities	Training to appropriately respond to human health risks	e.g., lifeguards trained in first aid actions of irukandji syndrome, vinegar available at beaches	High
c. Increased monitoring, surveillance	Monitoring and surveillance programs	Monitoring programs to detect range-shifting species (e.g., scientific surveys, Reef Life Survey, REDMAP)	High

Adapted from Salafsky et al. (2002).

are adapted from Salafsky et al. (2002), and one of their categories was subdivided (protection and management), with one added regarding infrastructure and operational change.

Spatial management is a relevant strategy for managing range-shifting species two reasons. First, spatial protection in the form of no-take and multiple-use protected areas is a common tool to reduce direct stressors (primarily fishing), thereby potentially increasing the resilience of an ecosystem to additional stressors. Second, management strategies for areas outside of protected areas (i.e., fisheries management tools; species recovery plans) similarly reduce or manage some stressors. Many of these spatial and species-focused management strategies are highly relevant to managing range-shifting species (Table 3). In particular, fishing gear that is highly selective could be used to promote or suppress key process, for example by targeting removal of specific species. Such a strategy has been suggested as a climate change response for coral reef systems to maintain herbivorous fishes (Cinner et al., 2009; McClanahan and Cinner, 2008).

Non-spatial management (i.e., law and policy, education and awareness, incentives, and infrastructure) could also be important for range-shifting species. Elements of law and policy relevant to the marine environment have a somewhat lower relevance for being potentially applied to range-shifting species. For example, general compliance, litigation, and enforcement are likely to be more effective if these are adapted to include range-shifting species. Similarly, education and awareness of range-shifting species can potentially play an important role both in contributing to anecdotal evidence of system changes, as well as in providing a context for individuals to comply with norms and self-regulation (e.g., in the case where a range-shifting species requires protection). Education and awareness can also reduce potential deleterious effects to individuals, in the case of a range expansion of a species that is harmful to humans (e.g., jellyfish or algal blooms), but also form a basis for adaptive strategies (e.g., where fishers may switch species or fishing locations based on an understanding of how species' ranges are changing). Changing incentives can lead to improved management, although this may be less directly applicable to range-shifting species. Finally, changes to infrastructure and operational procedures can help prepare society for adapting to shifts in species' ranges (e.g., the installation of jellyfish nets to protect bathing beaches).

Many, if not all, of the management strategies identified in Table 3 rely on effective monitoring. If wholesale relocations of multiple species result in the formation of new species assemblages and/or novel taxa (e.g., through hybridization, as has been

predicted for Australia's black bream (Hutchinson, 2011)), knowledge of these changes as soon as possible after they occur is essential to maximize opportunities and minimize damage – whether ecological or socio-economic. Large-scale, long-term monitoring is the only viable means of detecting and rigorously quantifying changes in biodiversity over relevant scales.

Despite evidence of range-shifting species in Australia, there have been few management responses to range-shifting species. Reasons for this may be: (1) shifts in species' ranges have been too recent to elicit a management response, particularly given the different temporal scales of change in ecological versus political systems, (2) policy makers are largely unaware of the phenomenon of range-shifting species, and/or (3) the majority of species documented to have shifted range (Table 1; Appendix 1) are viewed as having limited socio-economic consequences and therefore are not viewed as necessitating management response. Increased monitoring efforts with rapid information dissemination aimed at detecting species' range shifts would help address issues (1) and (2).

Our review of the published literature on species' range shifts in Australia and overseas also revealed that the scientific reporting of these events seldom provide a broader socio-economic or management context. A notable example is the study of Ling et al. (2009a), where the range expansion of *C. rodgersii* into Tasmanian waters has resulted in the decimation of some kelp (*Macrocystis pyrifera*) beds. The lower survivorship of urchins in no-take MPAs due to greater abundance and larger size-structure of predators suggests that one potential management strategy is to increase the resilience of subtidal rocky reef systems to effects of overgrazing from *C. rodgersii* (Ling et al., 2009a) by further protecting their predators (e.g., lobsters and large invertivorous fishes).

The ability of relevant management tools to respond to shifts in species' ranges depends on the temporal and spatial scale of the tool. For example, implementation of no-take MPAs in Australia involves a protracted process of community and stakeholder involvement, often taking years – and, in some instances, decades – to implement. This time scale may be different from the time scale over which range-shifting populations' (e.g., *C. rodgersii*) boundaries are changing. In addition, resulting coastal MPAs tend to enclose relatively small areas (i.e., 1s to 10s of km²) compared with the potential range shift distance of species such as *C. rodgersii* (i.e., 100s of km²; Appendix 1). This highlights a potential mismatch between available management tools and the relative temporal and spatial scale of range shifts. In contrast to no-take MPAs, some

fisheries management tools (e.g., total allowable catch; size restrictions) tend to be reviewed on monthly to yearly time scales and are often applied across entire statistical management areas, covering 10s to 100s of km. Species-level protection tools, such as the Environment Protection and Biodiversity Conservation (EPBC) Act in Australia, often apply across entire marine jurisdictions at provincial or national levels (i.e., 10s to 1000s of km) and can take years to implement. Clearly, some of these tools are better suited to respond to changing ranges of marine taxa than others, and this suitability will vary based on the spatial and/or temporal scales of species' range shifts.

For the majority of documented range shifts in Australia, the spatial scale of range shifts exceeds 100s of km over 10s of years (Appendix 1), suggesting that the current suite of available management tools only partially covers this domain. There are, however, potential artifacts in the documentation of species' range shifts where studies are limited by a relevant baseline (e.g., surveys conducted in 1950 and repeated in 2008; Pitt et al., 2010). Because the majority of Australian range shifts have been documented in Tasmania, the ~100 km gap from mainland Australia across Bass Strait may inflate the average range extension estimate. This shortcoming in our knowledge of range shifts highlights one key difficulty in designing adaptive management responses to these range shifts: our knowledge is currently limited by the frequency and spatial scale of studies, limiting our ability to detect changes over monthly to yearly time scales and distances of 1s to 10s of km. Additionally, baselines from which species' range shifts are measured may already be compromised due to the 'shifting baseline' syndrome (Pauly, 1995), whereby the evaluation of changes is based on data from a previously altered system.

Documented examples of marine range shifts in Australia (Table 1; Appendix 1) and globally (Perry et al., 2005; Sorte et al., 2010) show a predominance of range extensions as opposed to range contractions. Whether this pattern reflects the ratio of actual range expansions to contractions is unknown. Regardless, while our understanding of what constitutes an appropriate management response to expanding species' ranges is limited, the lack of documented examples of range contractions renders our knowledge of how to respond to these changes even less well developed. For example, in the southern Gulf of Carpentaria in northern Australia, sea temperature rises or changes in rainfall patterns affect coastal salinity regimes. The ability of species in this region to shift their range in response to sea temperature rises or rainfall-driven salinity changes in order to remain within their physiological tolerances may be limited by the geography of this region. As the Gulf of Carpentaria is relatively shallow (i.e., generally <30 m depth), the opportunity for finding refuge at depth may also be restricted. How best to address this possibility through management actions is not clear. Another example of a possible range contraction is the giant kelp (*M. pyrifera*) in Tasmania (Johnson et al., 2011). This cold water species is at the southern limit of its geographic range in Australia. Its requirement for rocky habitat in temperate waters, combined with lack of suitable habitat south of Tasmania, constrains its ability to shift its range southward (Edyvane, 2003). These two examples would require different management responses. In the first instance, translocation of vulnerable species to other, similar habitats southward could potentially be a viable option, whereas in the latter case mitigation measures to diminish socio-economic repercussions of kelp forest loss may be necessary given the lack of suitable habitat refugia within Australia. Importantly, management responses may ultimately need to be species-, as opposed to region-specific, in order to effectively capture the diversity of changes that different species within the same location may exhibit (Genner et al., 2004).

Shifting of commercially important species' ranges that are likely to occur in future years to decades (Cheung et al., 2010) will

face environmental managers with decisions requiring complex ethical decisions. For example, is it more important to maintain ecosystems in their present form irrespective of lost possibilities, or should we aim to protect the novel ecosystems (or taxa) that emerge as a result of range shifts (e.g., see discussion in Low, 2002)? Such determinations must be guided by carefully considered policy directives. Making such decisions on an ad-hoc basis could result in conflicting decisions being made in different jurisdictions (at local, regional and/or global scales), potentially leaving some species and/or habitats at risk of degradation and/or eradication. In some instances where human health or welfare may be affected by a range shift (e.g., box jellyfish; the small and deadly irukandji jellyfish), the management response and tools to enable an appropriate response may be clear-cut. In other cases, where novel interactions may be diffuse or poorly understood, the appropriate management response may be less obvious. Better knowledge of species' population dynamics and processes which translate into shifting geographic ranges is likely to become increasingly valuable in assessing whether (and how) a species should be protected in its new range. Importantly, building adaptive capacity (e.g., investing in management activities, educating the public) to respond to range shifts to include the full complement of relevant management tools will become necessary as climate change continues to facilitate such shifts.

6. Synthesis

Given recent reports of diverse marine taxa from diverse locations shifting their ranges apparently as a function of climate change (Sorte et al., 2010; Perry et al., 2005; Genner et al., 2004), our synthesis presents a timely approach to understanding the subsequent socio-economic and managerial consequences of observed and future range shifts. This exercise has highlighted a broad range of possible consequences in both of these areas, and it offers insight into which management approaches may be more or less appropriate for addressing the likely challenges posed by these shifts (Table 3). With a current focus on describing the extent and drivers of species range shifts, discussion of subsequent socio-economic and management implications in the literature is necessarily less well developed. Nonetheless, forward thinking about these consequences, even at this early stage, will better prepare us to face the inevitable challenges posed by range shifts in marine taxa when they ultimately occur.

Our analysis of the evidence of marine range shifts in Australia revealed that the overwhelming majority of studies documenting range shifts cite temperature as the predominant presumed driver (Appendix 1). It is worth noting that while climate change is often cited in these studies as the presumed ultimate driver of oceanic temperature variability, this temperature variability may also be due to high and low frequency variability in oceanic circulation patterns (e.g., multi-decadal El Niño – Southern Oscillation (ENSO), which is likely responsible at least in part for changes in the East Australian Current (Holbrook et al., 2010; Table 1)). It is also important to note that even with clear evidence of range shifts, definitive attribution of specific anthropogenic cause(s) is generally difficult (e.g., Holbrook et al., 2009). We therefore suggest that a moderate degree of evidence exists that range shifts in marine taxa – specifically in Australia – are occurring due to changes in climate (both changes due to low frequency variability and possible trends). However, a high degree of both evidence and consensus suggests that factors that play a role in physiologically mediating species' distributions (e.g., temperature) will continue to vary in the future, suggesting that we should assign a high corresponding degree of confidence that species' ranges will continue to be affected (Fig. 2).

Degree of consensus	High		Socio-economic & management impacts (projected)	Ecological impacts (projected)
	Moderate		Ecological impacts (current)	
	Low	Socio-economic & management impacts (current)		
		Low	Moderate	High
		Amount of evidence		

Fig. 2. Confidence assessment of the likelihood of ecological, socio-economic and management impacts of range-shifting taxa. Darker shading indicates greater degree of confidence. Adapted from IPCC “Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties”.

Our exploration of the realized and potential socio-economic consequences of range-shifting species in Australia highlights that many of these will be negative impacts on human society, but that in some cases different stakeholder groups will view these changes in opposing lights. Importantly, these changes predominantly affect three interlinked aspects of human societies: economic activities, human health, and ecosystem services (Table 2). However, because few studies to date have explored the socio-economic consequences of marine range shifts, very little evidence exists as to the likelihood or nature of these consequences. Likewise, the degree of consensus as to what kinds of changes we can expect is correspondingly low, leading to a low level of confidence in this area overall (Fig. 2). Nevertheless, we present this forward-looking analysis as a necessary first step in understanding, and therefore developing the capacity to respond effectively to, the socio-economic repercussions of climate-induced range shifts.

Examination of these socio-economic implications has enabled us to explore potential for using various management tools available for marine systems in Australia. In particular, spatial protection in the form of no-take and multiple-use protected areas, as well as management strategies for areas outside of protected areas such as standard fisheries management tools (e.g., catch controls) and species recovery plans, can be highly relevant to managing range-shifting species (Table 3). However, in each of these cases, adaptive capacity will be a prerequisite for effectively coping with range shifts due to the inherently dynamic nature of this problem. Because few management actions have yet been initiated in response to range-shifting species in Australia, evidence for the ideas presented in Table 3 is scarce, and thus no consensus exists as to which management actions will ultimately prove most effective in addressing this challenge. Confidence is therefore low in this regard, urgently necessitating further analyses as new information becomes available. Perhaps one of the most important policy decisions that must be addressed is the approach that managers should take in protecting species and ecosystems under changing range boundaries – for example, which species and ecosystems merit greater protection, new or old?

One of the key limitations underlying the various approaches to exploring implications of range-shifting species, such as the approach presented here, is the relative paucity of evidence for

both definitive accounts of climate-induced range shifts and for the diverse consequences of such changes (Booth et al., 2011). It is important to realize that a large portion of the evidence of range-shifting taxa within Australia (and globally) come from a handful of examples. Specifically, much of the available Australian-based evidence comes from the urchin *C. rodgersii* (Box 1), a habitat modifier through its ability to consume large amounts of macroalgae (e.g., *Ecklonia radiata*, *Phyllospora comosa*, and occasionally *Macrocystis pyrifera*) that function as important ecosystem engineers. While this species' range shift has clear ecological and socio-economic consequences, not all range-shifting taxa will likely have such dramatic repercussions. It is important to remember, therefore, that while the conclusions and predictions set forth here are based on the best available evidence of range-shifting taxa, this evidence is still quite limited and our conclusions should be treated with corresponding caution. Irrespective of causality, environmental managers must strengthen efforts to build resilience and the adaptive capacity to deal with a changing climate and the changing species range boundaries that it brings. As these changes in species distributions and abundances become more common, managers will increasingly face the challenge of managing novel ecosystems and interactions with emerging properties. Forward-thinking consideration of the ecological, socio-economic and management challenges these changes will pose is a critical first step in this process.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.gloenvcha.2011.10.008](https://doi.org/10.1016/j.gloenvcha.2011.10.008).

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