Marine Climate Change in Australia
Impacts and Adaptation Responses 2009 REPORT CARD

Macroalgae and Temperate Rocky Reefs

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Summary: Australia has one of the most species rich and endemic temperate algal floras in the world, and it contributes substantially to the unique biodiversity of the Australian continent. Climatic stability over geological time has been one of the key conditions underpinning the evolution of this unique algal flora, and given the current rate of global climate change there is now serious concern for its continued existence.

There are several international examples of climate change impacts on rocky reef ecosystems, but only very few examples from Australia because of a lack of long-term and broad-scale data sets. Moreover, the current evidence has a strong bias towards invertebrates and fisheries resources. Still, it is clear that organisms on temperate rocky reefs are vulnerable to the direct and indirect impacts of climate change, and it seems inevitable that currently projected environmental changes will continue to impact temperate reef communities. Recorded responses are largely consistent with increasing ocean temperature, and it appears that global warming (i.e., increasing temperatures) is the primary climate factor that marine species have responded to so far. To our knowledge there have been no reported changes directly attributable to other climate change related factors such as increasing ocean acidification and altered storm patterns.

In Australia, the altered flow of the East Australian Current and increasing water temperatures have caused a poleward range shift for sea urchins (leading to overgrazing and loss of algal habitat; high confidence), habitat forming algae (low confidence) and invasive species (low confidence) on the east coast and in Tasmania. Recruitment and

migration patterns of rock lobster may have changed on the west coast (low confidence). No changes attributable to climate change have been recorded on the south coast.

In the future, rising temperatures will result in further range-shifts of both macroalgae and invertebrates (high confidence), with local extinction of species that have northern range limits along the southern coastline (i.e., no poleward range shift possible; medium confidence). Rising temperatures will also result in changes in species phenology (high confidence). Ocean acidification will result in negative effects on calcareous algae and other calcifying organisms (high confidence). The combined effects of climate change and non-climate stresses (pollution, reduced water quality) will reduce the resilience of temperate reef communities to perturbations (e.g. storms, diseases, invasive species) (high confidence), many of which may also increase in frequency and/or severity in response to climate change. These changes will lead to loss of, or greatly altered, algal habitats and associated ecological function (medium confidence). These changes will happen progressively through 2030 to 2100.

Possible adaptation measures includes reducing the impacts of regional and local stressors (improve water quality, reduce fishing of predators) and restoration of degraded habitats, for example by re-seeding reefs with habitat-forming algae where these have been lost.

Introduction

A characteristic feature of the Australian continent is that it is bound to the south by the longest east-west facing coastline in the world. Together with the east and west coasts south of ~27^{o}S this coast constitutes a temperate coastline which covers a distance over double the length of the Great Barrier Reef (4000 km compared to 2000 km). It straddles three biogeographic provinces (Waters et al. 2010) and includes some of the most pristine temperate coast in the world, as well as areas which are heavily populated. Rocky reefs dominated by macroalgae (seaweeds) are a defining feature across the coast (e.g., Underwood et al. 1991, O'Hara 2001, Wernberg et al. 2003, Connell and Irving 2008, Smale et al. 2010).

Figure 1. Kelp beds (top) dominated by the laminarian alga *Ecklonia radiata* are a dominant feature of many subtidal rocky reefs across temperate Australia. These kelp beds are highly productive and provide food, habitat and specific environmental conditions for a range of different taxa. Myriads of animals and algae live among the kelp fronds or in the canopy gaps regularly created by the dislodgment of kelps by storms. The influence of reefs extends far into adjacent habitats where, for example, dislodged kelps exported from reefs can be an important trophic subsidy in less productive or palatable habitats (bottom left: drifting kelp in *Amphibolis* seagrass meadow). Kelps also provide a unique habitat via their holdfasts (bottom right), which provide 3-dimensional habitat to hundreds of associated taxa (all photos: T. Wernberg).

The temperate algal flora contributes significantly to the unique biodiversity of Australia in that it is one of the most species rich algal floras in the world, and has one of the highest rates of endemism (Bolton 1994, Kerswell 2006). The evolution of this globally unique biodiversity has been attributed to a combination of the extensive rocky reef systems, the unique oceanography associated with the East Australia Current and the Leeuwin Current, and climatic stability over geological time scales (Phillips 2001, Kerswell 2006). A substantial part of the temperate coastline is found within a narrow latitudinal band where a small increase in temperature will affect a very large area. Given the lack of landmasses to the south, most species have limited opportunity to shift further pole-ward, and there is now great concern for the continued existence of Australia's marine biodiversity under the current rates of global climate change. However, it is not only the biodiversity of the algae themselves that is under threat; macroalgae, and large canopy-forming species in particular, are foundation species which provide and modify resources available to other organisms both in terms of environmental conditions (Connell 2003, Wernberg et al. 2005), three-dimensional habitat structure (Wernberg et al. 2004, Coleman et al. 2007, Tuya et al. 2008a) and food (Robertson and Lucas 1983, Steinberg 1995, Wernberg et al. 2006, Crawley et al. 2009, Vanderklift et al. 2009). Because of their central role in a range of ecological processes on temperate reefs and adjacent habitats, loss of canopy-forming algae is likely to be associated with significant loss of associated species and ecological function (Steneck et al. 2002, Graham 2004, Kendall et al. 2004, Schiel et al. 2004, Ling 2008).

Figure 2. Temperate Australia has one of the most diverse and unique macroalgal floras in the world, and the species richness of seaweeds rivals that of reef forming corals. Many species are small delicate red algae (top left: *Pterocladia rectangularis*, bottom right: *Rhodymenia sonderi*), but articulated calcareous algae (bottom left: *Rhodopeltis australis*) and green algae (top right: *Caulerpa scalpelliformis*) are also both common and abundant. Note the pink crusts (encrusting calcareous algae) covering the reef surface in the background of all photos (All photos: T. Wernberg).

Observed Impacts

The southern hemisphere is particularly under-represented in terms of documented impacts of climate change in marine ecosystems (Poloczanska et al. 2007). In Australia, the only well documented example from temperate rocky reefs is the range expansion of the herbivorous sea urchin *Centrostephanus rodgersii*, observed in Tasmania (Ling et al.

2009). There is strong evidence to suggest that a strengthening of the East Australia Current (Ridgway 2007) and warming ocean temperatures, resulting in ocean temperatures now exceeding, the 12^{o}C threshold for successful *C. rodgersii* reproduction, has facilitated the poleward population expansion of the urchin (Ling et al. 2008). As a result, subtidal reefs that formerly supported dense stands of macroalgae have been intensively grazed and transformed into urchin barrens, with considerable loss of biological diversity (Johnson et al. 2005, Ling 2008, Ling and Johnson 2009). It is also evident that historical fishing pressure has exacerbated this effect, as populations of top predators (i.e. lobsters) have been insufficient to curb the population expansion of *C. rodgersii*.

The distribution of large temperate macroalgae in Australia may also have been affected by the warming over the past ~50 years. Anecdotal evidence from herbarium records suggest that the distribution of the three habitat-forming species *Ecklonia radiata, Phyllospora comosa* and *Durvillaea potatorum* have shifted southwards on the east coast over recent decades (A.J. Millar pers. obs.). Massive declines of large algae have also been recorded around urban centres, such as for *P. comosa* around Sydney (Coleman et al. 2008a) and *E. radiata* around Adelaide (Connell et al. 2008). The processes responsible for these changes are currently under study but are likely to be directly or indirectly driven by climate and local anthropogenic stressors such as reduced water quality (Connell 2007, Connell et al. 2008).

There are currently no studies that quantitatively demonstrate effects of climate change on dispersal and gene flow in macroalgae, but given that many species of macroalgae have limited dispersal ranges (e.g., Kendrick 1991) effects are likely to be large, particularly where peak pressures around urban centres causes local extinction of large populations, (cf. Sydney and Adelaide) and when ocean currents change over broad scales. New research has shown that dispersal and gene flow in important habitat-forming marine algae are specific to different coastlines (Coleman et al. 2008b, Coleman et al in review, Coleman and Kelaher 2009). Populations of the common kelp, *Ecklonia radiata*, on the east coast of Australia show less genetic structure than those on the coast of WA or SA and this is likely a consequence of reproductive seasonality relative to the peak strengths of currents. As genetic diversity has been linked to habitat resilience to extreme events (Reusch et al. 2005), such potential changes to population connectivity could have important implications.

There have been no explicit reports of the ecological effects of recent climate change on temperate reef systems in Western Australia. The longest dataset in WA concerns the distribution, abundance and recruitment of the western rock lobster, *Panulirus cygnus*, an ecologically important species on WA's temperate reefs. Historical recruitment data for *P. cygnus* has shown a strong correlation between the strength of the Leeuwin Current and the extent of puerulus larval settlement. However, very low recruitment of *P. cyngus* has been recorded in the last two years, despite seemingly favourable conditions. Whether this is due to a reduced broodstock or changes in environmental factors (i.e. ocean currents and eddies, temperature) is currently unknown, but recent analyses indicate that recruitment and migration patterns of rock lobster may have changed in response to rising temperature over the last 35 years (Caputi et al. 2010). Rock lobsters are conspicuous consumers of small invertebrates and calcareous algae, and it is possible (but unknown) that they influence algal assemblage structure indirectly.

Invasive species are one of the great contemporary threats to global biodiversity. While the threat from invasive species is not directly climate related, climate has often been proposed to facilitate the establishment, further spread and impact on invasive species on temperate reefs (e.g., Thresher et al. 2003, Scheibling and Gagnon 2009). In Australia, for example, it was suggested that the spread of the shore crab *Carcinus maenas* from Victoria into Tasmania was facilitated by increasing ocean temperatures in response to a strengthening of the EAC (Thresher et al. 2003). *C. maenas* is voracious predator in intertidal and shallow subtidal reef habitats, and exerts strong top down control of reef communities (Bertness et al. 2002). Although currently undocumented, it seems likely that this predator has affected algal dominated reef habitats. Increasing temperatures have allowed invasive invertebrates to cause direct impacts on kelp beds elsewhere. In Nova Scotia (Canada), warmer water increased fouling of kelp fronds by an invasive bryozoa, causing reduced reproductive output and defoliation of the kelps, which led to a switch in reef community structure (Scheibling and Gagnon 2009, and referenced herein).

Despite remarkably consistent range-shifts to higher latitudes across global ecosystems and taxa (Parmesan and Yohe 2003), there are several examples from temperate rocky reefs where shifts in species distributions or communities were ambiguous or not detectable (intertidal invertebrates: Rivadeneira and Fernández 2005, macroalgae: Lima et al. 2007, rocky reef communities: Stuart-Smith et al. 2009). This suggests that either range-shift responses are not universal, they are more delayed in marine systems (because of more stable conditions), or may not be progressive and so are less detectable in the early stages. For example, despite evidence for concurrent warming and major ecological changes prior to their study, Stuart-Smith et al. (2009) found relatively few changes in Tasmanian rocky reef communities over the 10-15 year period of their study, and suggested that this reflected a period of relative stability following a major abrupt community reorganisation. Indeed, a number of studies have emphasised non-linear responses and the importance of interactions with other non-climate perturbations such as fishing pressure (Beaugrand et al. 2008) or disturbances (Harley and Paine 2009) as triggers of impact.

Physiological acclimatisation may be the process that offsets the immediate translation of environmental change into distributional change. For example, the dominant habitat-forming macroalga in temperate Australasia, kelp *E. radiata*, is known to exhibit substantial physiological adjustment to seasonal (Fairhead and Cheshire 2004) and latitudinal (Stæhr and Wernberg 2009) changes in environmental conditions (primarily temperature and light conditions). While these adjustments enable the alga to maintain a positive metabolic balance, the cost appears to be reduced recruitment success and recruit performance with subsequent suppressed ability to recover from physical disturbances in relatively warm conditions (Wernberg et al. in review-b). In other words, increasing temperatures *per se* may not topple the algae, but rather gradually reduce their resilience to natural perturbations such that impacts manifests either abruptly when the physiological threshold of existence is finally exceeded or progressively as the cumulative effect of localised failure to recover. In addition, range shifts may be obscured by habitat buffering, where complex interactions between geomorphology and environmental conditions create benign micro habitats maintaining the latitudinal extent of a species in a mosaic of micro-refugia (Helmuth et al. 2002, Helmuth et al. 2006).

A common feature of virtually all examples of impacts of climate change is the potential for a host of other mechanisms to co-explain the observed patterns e.g. non-climate change related changes in oceanic circulation patterns or El Nino events. Therefore we cannot unambiguously link observed changes to anthropogenic climate change. The number of cases where climate can be reasonably linked to the pattern is however conspicuous.

In summing up, there are several international examples of observed climate change impacts on rocky reef ecosystems, but very few examples from Australia because long-term and broad-scale data sets are lacking. Still, it is clear that temperate rocky reefs are vulnerable to the direct and indirect impacts of climate change even if they are naturally highly dynamic environments. The current evidence has a strong bias towards a limited number of invertebrates and commercially important species. Anecdotal evidence suggests that ecologically important canopy-forming algae have been affected, but more studies are needed to confirm the extent of this impact. Nevertheless, recorded responses are largely consistent with increasing ocean temperature, and it would thus appear that global warming (i.e., increasing temperatures) is the primary climate factor to which algae and rocky reef species are responding. To our knowledge, there have been no reported changes directly attributable to other climate change related factors such as altered storm patterns, sea-level rise or ocean acidification.

Potential impacts by the 2030s and 2100s

Documented impacts of climate change in Australia are very sparse. It is therefore difficult to make predictions on how macroalgae and temperate rocky reef communities will respond to climate change with any confidence. What little evidence exists for temperate rocky reefs of Australia, and from elsewhere in the world, strongly suggests that the physical changes taking place in response to anthropogenic climate change do impact natural ecosystems. In addition, there is an abundant literature of small-scale experimental studies to suggest that several factors directly or indirectly associated with climate change may impact temperate rocky reefs and macroalgae in the future.

Temperature

Temperature is one of the strongest drivers of species distributions of marine organisms, including macroalgae (Breeman 1988, Adey and Steneck 2001). The projected temperature increase for temperate Australian marine waters is in the order of 1-3 ^{o}C by 2030 and 2100 respectively (Lough 2009). Given the limited observations of how temperate reef species have responded to recent climate warming in Australia, the consistent latitudinal gradients in ocean temperature along the east and west coast of Australia can provide valuable insights into how species might respond to future climate warming (Smale and Wernberg 2009). In Australia, temperature gradients of in the order of the projected change for 2030 and 2100 are associated with considerable differences in physiology (Stæhr and Wernberg 2009), species distribution (O'Hara and Poore 2000, Wernberg et al. 2003, Tuya et al. 2008b, Smale et al. 2010, Wernberg et al. in review-a), population structure and dynamics (Ling et al. 2008, Wernberg et al. 2008), habitat structure (Connell and Irving 2008) and community structure of rocky reef organisms (Wernberg et al. in review-a). It therefore seems very likely that the impending temperature increase will cause some redistribution of flora and fauna equivalent to these patterns.

A recent study of broad scale benthic community structure along a latitudinal gradient in WA, showed that some algal taxa exhibit clear trends with latitude (Smale et al. 2010, Wernberg et al. in review-a), and these patterns are probably largely driven by water temperature. For example, the canopy-forming brown alga *Scytothalia dorycarpa* predictably increases in abundance with increasing latitude (Smale et al. 2010). *S dorycarpa* is a cool water species and may undergo a range contraction as coastal waters of WA warm and it becomes physiologically stressed and out-competed by lower-latitude species in warmer waters. Conversely, the relative abundance of a diverse ‘brown foliose algae’ group, which primarily comprised of tropical or warm temperate species such as *Padina* spp. *and Dictyota* spp., was inversely related to latitude. It seems likely that

Increasing water temperatures will result in a decreased cover and competitive ability of cool-water canopy forming algae, and allow the brown (and red) foliose algae to dominate subtidal reefs. Such changes in macroalgal assemblage structure would have major implications for ecosystem structure and coastal biodiversity.

The successful recruitment of prominent reef organisms may be suppressed in a warmer future. In Western Australia, there is a clearly negative relationship between reproductive and recruitment success of *Ecklonia radiata*, and water temperature along the west coast (Wernberg et al. in review-b). The growth and productivity of *E. radiata* has also been shown to decline above 18.5^{o}C (Kirkman 1984). Similarly, populations of the prominent turbinid gastropod *Turbo torquatus*, currently show signs that elevated temperatures may affect recruitment succcess - populations in warmer waters are strongly dominated by one cohort, which recruited during a period of relatively cool ocean conditions (Wernberg et al. 2008), whereas populations in cooler waters have multiple cohorts representing continuous recruitment. Increasing temperatures may put these populations under further pressure and eventually collapse.

Although there is compelling evidence to suggest that temperate reef systems will respond to future climate change it is important to acknowledge that temperate organisms live in a seasonally variable environment, where annual (or even diurnal) variation in temperature is several times greater than the projected temperature increase caused by climate change (e.g., Wernberg and Goldberg 2008, Smale and Wernberg 2009). With the possible exception of populations at the edge of their ranges, impacts from increasing temperatures are most likely to be indirect, either through suppressing the resilience of species to other perturbations (Wernberg et al. in review-b), by increasing growth and activity of competitors and invasive species (Scheibling and Gagnon 2009) or by shifting the window for reproductive and recruitment success (Thresher et al. 2003, Ling et al. 2008). However, based on the limited number of observational studies and more extensive, but spatially or temporally limited experimental data, it is anticipated that by 2050 a number of important macroalgal and rocky reef species will have responded to increased warming by altering their ranges, experiencing changes in their population structure or the timing of key events.

Ocean Acidification

The direct effects of ocean acidification on temperate marine ecosystems are unlikely to be realised for the next 40-100 years. Recent research has emphasized that significant changes in ocean pH are occurring and future changes may occur much more rapidly than originally anticipated (Wootton et al. 2008). Under future climate change scenarios, ocean pH is predicted to drop by a further 0.3-0.4 units by 2100. Although most experimental studies to date have focused on tropical assemblages, recent research in Australia has shown that effects of ocean acidification on temperate reef systems may be equally complex and deleterious (Russell et al. 2009).

Calcifying algae such as encrusting or articulated coralline algae are among the most abundant and widespread organisms on subtidal rocky reefs (Steneck 1986). On the temperate coast of southern Australia, crusts occupy up to 80% of hard substrate, dominating space beneath canopies . Recent experimental work in Australia has shown that acidification associated with conservative projections of future CO_2 concentrations (550 ppm) will have negative effects on the growth and recruitment of coralline algae (Russell et al. 2009). Furthermore, increased [CO_2] and temperature have greater negative effects in combination (~ 700 ppm and 3°C, respectively) than in isolation (Mediterranean coralline algae; Martin and Gattuso 2009). Therefore, while there has been no work on predicting the spatial extent of the effects of climate change on calcareous algae, moderate predicted levels can have large negative effects, so it is likely that greenhouse gas emissions in scenarios A2, A1B and A1F1 will have large negative effects across the geographic range of these algae by 2050.

In contrast to coralline algae, elevated [CO_2] may have little negative or even positive effects on non-calcareous algae (Beardall et al. 1998, Russell et al. 2009, Russell and Connell unpubl. data). There is still debate on whether increasing [CO_2] will enhance productivity in marine algae. Most marine algae have carbon concentrating mechanisms (CCMs) which allow them to use bicarbonate for photosynthesis, meaning that photosynthesis is carbon saturated at current concentrations . Experiments have so far been inconclusive, and general consensus within the literature seems to be that algae with CCMs will not increase productivity under future conditions (see review by Beardall et al. 1998). Because global stressors will manifest at local scales, however, the effects of CO_2 will interact with local stressors such as elevated nutrients. Therefore, while increased CO_2 may not affect algal turfs, there could be synergistic positive effect when combined with elevated nutrients (Russell et al. 2009).

There is compelling evidence to suggest that ocean acidification will have direct negative effects on calcareous species, particularly coralline algae due to their skeletons being composed of magnesium-calcite that has a higher solubility compared to aragonite. There is, however, a need to expand this area of research towards the direct and indirect (competition, facilitation) effects of ocean acidification on calcifying and non-calcifying species on Australian temperate rocky reefs. As with changes in temperature, ocean acidification is likely to result in sublethal effects (e.g. changes in induced defences, susceptibility to disease, changes in behaviour and reproductive capabilities) on a wide range of species and/or have differential effects depending on an organism's life history stage. In addition, multiple stresses are likely to lead to complex and synergistic effects. Further experimental research is required to fully understand the consequences of ocean acidification for Australian temperate rocky reef ecosystems.

Disturbance and perturbation

Changes in storm tracks

Significant changes in the direction and intensity of storm tracks have been observed in temperate Australia over the last few decades. Recent projections suggest that long-range swell systems that originate from the Southern Ocean are likely to increase. This will cause increased frequency and extent of canopy loss (Seymour et al. 1989, Thomsen et al. 2004) and as such, physical disturbance from more frequent storm events and stronger, persistent winds could be of great ecological significance. Physical disturbance regulates species richness and community structure in many marine environments, and disturbance regime plays an important role in maintaining diversity and driving patch dynamics in the kelp forests of temperate Australia (Kendrick et al. 1999, Kendrick et al. 2004, Toohey et al. 2007, Wernberg and Connell 2008, Wernberg and Goldberg 2008). Studies have shown that increased wave energy correlates strongly with larger gaps in the seaweed canopy (Kennelly 1987, Farrell 1989, Wernberg and Connell 2008), which will have implications for local diversity, productivity and overall community structure (Kennelly 1987, Kendrick et al. 1999, Wernberg 2006, Wernberg and Connell 2008). Exactly how rocky reef community structure will be affected by increasing frequency and/or intensity of physical disturbance remains uncertain, but evidence from elsewhere suggests that chronically disturbed habitats generally support species poor assemblages (Sousa 1979, Hughes and Connell 1999, Barnes and Conlan 2007). In addition, a recent study from WA has shown that increasing disturbance regimes will interact with, and compound, the negative effects of elevated ocean temperature on the recruitment and recruit performance of kelps, compromising the ability of kelp canopies to withstand and recover from disturbances (Wernberg et al. in review-b).

Figure 3. Diver working in an experimental seaweed canopy clearing, in an experiment testing the interaction between extent and intensity of physical disturbance (canopy loss) and ocean temperature along the west coast of Australia (Photo: T. Wernberg).

Rainfall and nutrients

Intensity of rainfall can substantially alter the load of terrestrially derived nutrients entering near-shore marine systems (Gorman et al. 2009). Climate change is predicted to change rainfall patterns, but these changes will differ regionally; regions of low rainfall will have reduced rainfall, and therefore less nutrient runoff, while areas of higher annual rainfall will typically receive greater rainfall and increased nutrient inputs.

While increased nutrient inputs may cause small increases in the growth of some habitat forming species of algae, experience from urbanised coasts shows that elevated nutrients benefit smaller, more opportunistic species to a larger extent (Pedersen and Borum 1996, Worm et al. 1999, Russell and Connell 2005), leading to shifts from habitat to turf-forming algae dominated systems (e.g., Worm et al. 1999, Eriksson et al. 2002, Connell et al. 2008). Therefore, increases in nutrient inputs would generally be predicted to have a negative impact on reef assemblages. However, these effects will also interact with the regional biological context. For example, increasing nutrients have disproportionately large negative effects in regions of oligotrophic waters, such as those in southern Australia (Russell et al. 2005), but it is these dry regions which are predicted to receive less rainfall under climate change. Further, eastern Australia has greater grazing pressure that may counter any negative effects of nutrients by consuming bloom forming algae (Connell and Vanderklift 2007, Connell and Irving 2008), whereas control by grazers on the southern coast is likely to be short-term and largely ineffective (Russell and Connell 2007, Connell and Irving

2008). Therefore, while rainfall is likely to increase in areas of eastern Australia, these regions are less likely to be impacted than the southern coast.

Herbivores

Altered consumer pressure, for example caused by disease or over-fishing, has long been one of the main concerns regarding the future of macroalgal communities on temperate rocky reefs (Steneck et al. 2002). The extensive changes that inceasing herbivore populations can cause is well illustrated by the southward expansion of the urchin *Centrostephanus rodgersii* in Tasmania (Ling 2008). Evidence from urchin population studies in the expansion zone, indicate that *C. rodgersii* will continue to its spread in Tasmania as temperatures continue to increase (Ling et al. 2008, Ling and Johnson 2009), with continuing devastating effects on local algal habitats. The incidence of urchin barrens in Tasmania, and the loss of kelp forests, is therefore expected to continue. While the spread of *C. rodgersii*, and its impacts on Tasmanian algal assemblages, ultimately is caused by increased larval transport and survival under warmer conditions, increasing temperatures may also affect herbivores and their foraging activities indirectly. Studies from WA indicate that physiological adaptation and acclimatisation of *Ecklonia radiata* to warmer environments is associated with substantial changes in tissue nutrients and pigments such that the nutritional content of kelp tissue decrease by ~15% $^{o}C^{-1}$ increase (Stæhr and Wernberg 2009). The nutritional status of their algal food sources are known to influence the performance of fecundity of algal associated invertebrates (Foster et al. 1999, Kraufvelin et al. 2006), and these may have to consume increasingly large amounts of algal material to maintain current ecological performance.

Disease

There is considerable concern globally that predicted warming and other anthropogenic stressors may increase the spread of pathogens and enhance their virulence as well as decrease the resilience of host organisms including macroalgae (Jackson 2001, Lafferty et al. 2004).

It has been argued that climate change may increase the rate of infections. Moreover, disease has sometimes been cited as the cause of large-scale die-offs of macroalgae but the suggestions are rarely confirmed or investigated further. For example, diseases have been suggested to have caused massive declines (40-100%) in the habitat-forming kelp *Ecklonia radiata* in New Zealand (Cole and Babcock 1996, Cole and Syms 1999) and in *Laminaria religiosa* from Japan (Vairappan *et al.* 2001). Recent research, however, indicates complex interactions between bacterial pathogens, seaweed chemical defences and environmental factors, such as temperature, in determining the extent to which a common red alga in southeastern Australia (*Delisea pulchra*) suffers from bacterial disease which can result in death or damage to the alga (Case *et al.* in preparation). In particular, elevated seawater temperatures reduce levels of chemical defences (furanones) in *D. pulchra* allowing surface biofilm formation and cellular invasion by the bacterial pathogen *Ruegeria* sp. R11 (Case *et al.* in preparation).

Key Points

- There are few observed direct impacts of climate change for temperate macroalgae and rocky reefs due to a paucity of long-term data sets.
- Increasing temperature has been linked with changes in the distributional range of a small number of macroalgal species and invertebrates.

- The interaction of local stresses and climate change are likely to lead to complex and synergistic effects for temperate rocky reef assemblages.

Confidence Assessments

	Amount of evidence	Degree of concensus	Confidence level
Observed changes			
Warming and EAC has caused a southward range shift of a sea urchin (*Centrostephanus rodgersii*), and this led to over-grazing and loss of kelp habitat in Tasmania	High	High	High
Warming has caused a southward range shift of canopy-forming algae (*Ecklonia radiata*, *Phyllospora comosa* and *Durvillaea potatorum*) in eastern Australia	Low	Low	Low
Changes in the recruitment and migration patterns of western rock lobster (*Panulirus cygnus*) in response to warming.	Low	Low	Low
Expected changes			
Multiple stresses at regional and local scales will interact with climate change to reduce resilience and accelerate susceptible species responses to climate change e.g. loss of canopy in areas of pollution susceptibility.	High	High	High
Although there are limited observed effects of climate change on temperate Australian rocky reefs, there are significant experimental data suggesting that future climate change will lead to changes in species distributions, abundance and phenology, which may in turn lead to local extinction, particularly for species whose northern range limits are on the south coast of Australia.	Medium	Medium	Medium

Adaptation Responses

The stress of climate change is unlikely to have homogeneous influences across the temperate coast of Australia. A broad spectrum of climate through local land and marine-based processes operating at regional (e.g. over-fishing, eutrophication, non-native species) and local (coastal development, point-source pollution, aquaculture) scales are driving unprecedented and complex changes in marine systems. The impacts of global climate change and regional and local scale stresses are likely to interact synergistically (Harley et al. 2006, Crain et al. 2008), causing species and systems to respond idiosyncratically. The combined effect of climate change and non-climate stresses reduces the resilience of marine systems (Wernberg et al. in review-b), however, by managing local and regional scale processes marine systems may be better placed to adapt to the stress of climate change (Russell et al. 2009). Recognition of this, in combination with the greater attention paid to the anticipation and prevention of socially-unacceptable regime shifts, has lead to more proactive management of local stressors in some regions. For example in South Australia, local government has encouraged research into the processes that either increase support or weaken resilience, and of the socio-economic drivers and governance that regulate modification of the physical environment (e.g. water quality) and their biota (e.g. fisheries). South Australian managers now recognise global-local connections of future change, recently implementing long-term policy solutions for the sea (policy on reducing wastewater discharge) that also act as solutions for the land (policy on establishing new sources of water that do not rely entirely on rainfall). Upgrades to wastewater treatment plants, to produce recycled water for residential and industrial use, not only reduces reliance on rainfall for fresh water supplies, but also reduces the nutrient rich discharge that has primarily contributed to phase shifts on metropolitan reefs from kelp to turf-dominated (Connell et al. 2008).

While it is likely that little can be done to directly mitigate the effects of increasing CO_2 on temperate reefs systems, at least in the short-term due to the inertia of the climate system, findings on nutrient and CO_2 driven synergies empower local managers because they show that policy taken to reduce the effects of local stressors (e.g. nutrient pollution) can reduce the effects of global stressors which are not under their governance (e.g. ocean acidification) (Russell and Connell 2009, Russell et al. 2009). Indeed, efforts to reduce the compounding influence of multiple stressors may reduce the frequency and extent to which ecological systems change to unexpected states (Paine et al. 1998, Scheffer and Carpenter 2003). If multiple perturbations reduce the resilience of a system, then local management may be effective in reducing the effects of climate change (Hughes et al. 2007). Further, if local impacts are driving local system shifts (Gorman et al. 2009), once these stressors are removed, resilience of systems may be restored though actions akin to terrestrial re-foresting. For example, it may be possible to reverse observed shifts from kelp to turf dominated systems by re-seeding kelp forests, a technique which has been successful demonstrated on Japanese coastal waters. Mitigation procedures could therefore include re-seeding reefs where canopy algae are lost.

A key outcome of the temperate reef report card is that there are very few observed examples of species responding to climate change. It is, however, very likely that a large number of species have experienced range shifts or changes in their population structure in response to recent warming, but a lack of baseline data for even conspicuous habitat forming species has seen changes go unrecorded (Edgar et al. 2005, Richardson and Poloczanska 2008). Although long-term monitoring is not scientifically “cutting edge”, there is a need to initiate monitoring programs so that impacts on species, assemblages and ecosystem functioning are documented, subsequently allowing appropriate management plans to be designed and implemented. Due to the number of biogeographical provinces in temperate marine systems, and the high levels of biodiversity and endemism, it is not possible to monitor all species. Therefore, efforts should be made to identify climate indicator species as has been done by the MarClim project in the United Kingdom (Mieszkowska et al. 2005) in the UK and proposed by Smale et al. (2010).

Monitoring, however, is not sufficient. Integrated field and laboratory manipulations over broad temporal and spatial scales, coupled with modelling are required to understand the mechanisms driving change. For some species, use of the fossil record may also be applicable (e.g., Greenstein and Pandolfi 2008). 'Natural' experiments using existing gradients of temperature (Pennings and Silliman 2005, Wernberg et al. in review-b) and pH (Hall-Spencer et al. 2008) can provide important insights into how species or systems may respond to future climate change. The Australian coastline, particularly the west coast, is well suited to undertake such 'natural' experiments as there is a 2-3°C temperature change across 6° of latitude, yet nutrients, substrate variability and wave disturbance do not co-vary (Smale and Wernberg 2009). 'Natural' experiments can be particularly valuable in quantifying the sublethal effects of climate change that in turn may reduce the resilience of the system (e.g., Wernberg et al. in review-b). Importantly, by understanding the ways in which species respond to different environments across their geographic range, it may be possible to implement measures and management to increase adaptive capacity.

In conclusion, a combination of monitoring of climate indicator species (or functional groups),and habitats, experimental studies and modelling are required to understand the mechanisms driving responses to climate change in marine systems, which is necessary to provide accurate forecasts for future change. Finally reducing the impact of local and regional stresses will increase the resilience of marine systems to global climate change. Initiatives such as those adopted by local government in South Australia should be promoted and adopted throughout Australia.

Knowledge Gaps

The key knowledge gaps which limit our responses to climate impacts in temperate reef systems are:

- An increased knowledge of current changes to temperate reef assemblages. Current evidence is limited to a small number of invertebrates and conspicuous algae and provides no information on many of the hundreds of species which are endemic to southern Australia;
- Greater knowledge on the response of species to multiple stressors, both global and local. The response of most species to predicted future conditions is mostly limited to temperature, yet it is likely that this response will be altered by other environmental conditions;
- An increase in experiments which alter conditions to predicted future levels, including temperature both temperature and CO_2 (pH). Current predictions based on model outputs are inadequate, because we have no knowledge of the response of species to these factors outside their natural seasonal range. Experimental approaches should include both highly controlled enclosure-based experiments and comparative field experiments;
- A greater knowledge about the links between sub-lethal physiological effects of adaptation and acclimatisation and ecological responses, and, in particular, knowledge about the capacity of ecologically important species for adaptation;
- Increased knowledge of the effects of climate change on sub-tidal species. The current knowledge is biased towards intertidal species, which are likely to be impacted by a different set of conditions (e.g. temperature and salinity *vs*. pH and CO_2 availability).

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