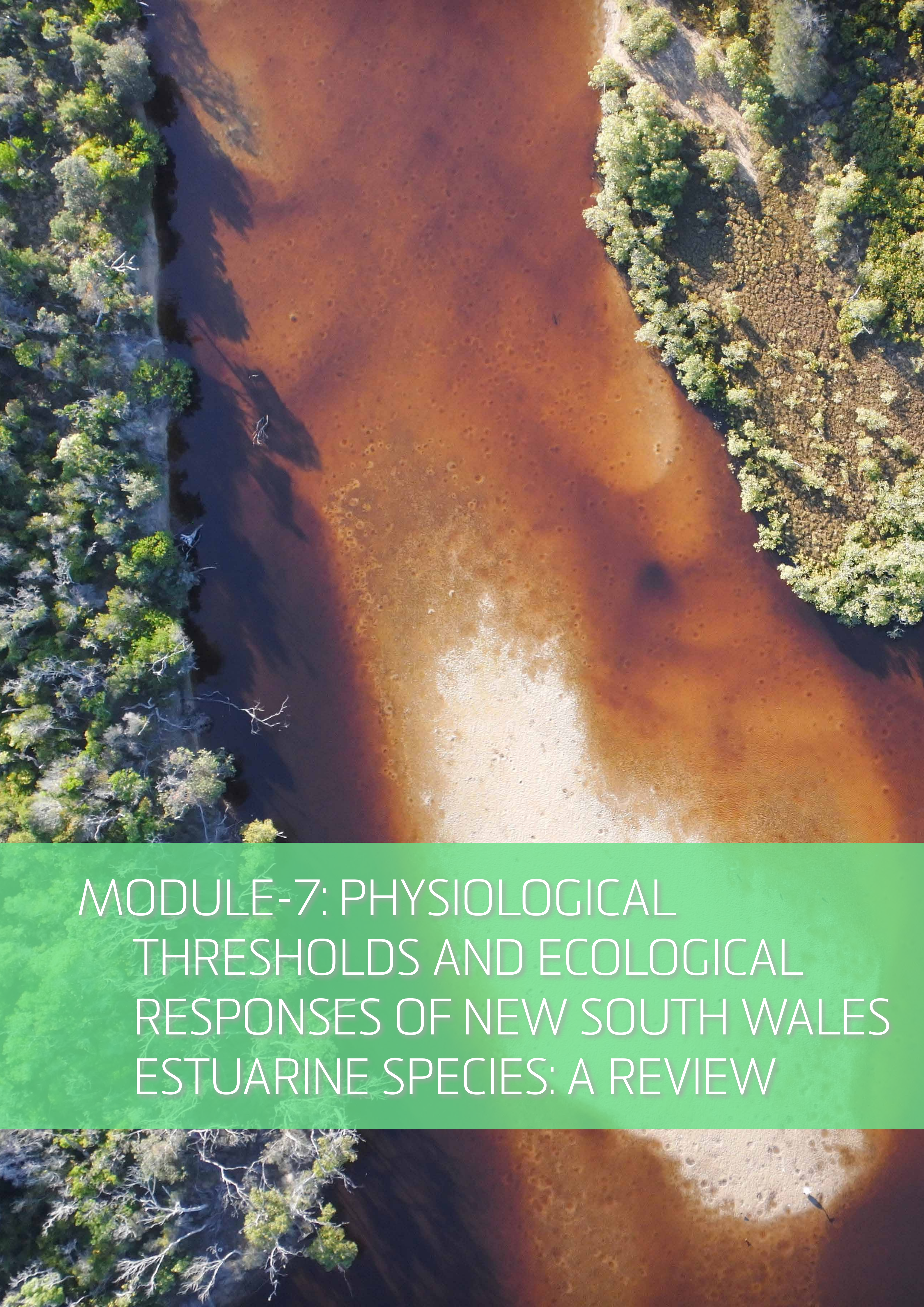

MODULE-7: PHYSIOLOGICAL THRESHOLDS AND ECOLOGICAL RESPONSES OF NEW SOUTH WALES ESTUARINE SPECIES: A REVIEW

Understanding how specific ecological communities respond to environmental changes is critical for an accurate climate change risk assessment.

Drone image of mangroves and saltmarsh in the Hunter River Wetlands, photo: Chris Drummond, WRL, UNSW

MODULE OUTLINE

Preface

This guide is the result of five years of research and close collaboration between project partners. The guidelines and information reproduced in this guide have been agreed by the project partners based on their extensive knowledge and experience in the field of estuaries and climate change with advice from the scientific community. The guide has been published as a series of modules. Each module is a stand-alone document addressing an important aspect of climate change risks in estuaries. The following modules are available in the series (titles are abbreviated here):

1. Introduction
2. Changes in climate
3. Physical responses
4. Ecological responses
5. Managing local stressors
6. Application of the framework
7. **Review of ecological thresholds (this module)**
8. Knowledge gaps and research needs

Summary of Module-7

This module is a supporting document for modules 4 and 6, and complements the Eco-thresholds database. It is a comprehensive review of published literature on the physiological tolerances and ecological responses of NSW estuarine species to environmental variables that are being modified by climate change. Species within the functional groups, mangroves, seagrasses, saltmarshes, shellfish, estuarine invertebrates and estuarine fish, are considered. Coastal freshwater ecosystems are also included as these may become salinized under climate change. The environmental variables under modification from climate change are temperature, salinity, sea level, CO_2, ocean acidification and dissolved oxygen. For each functional group and for each environmental variable, physiological tolerances and ecological responses are synthesised to determine a sensitivity to climate change, which is used in modules 4 and 6.

Questions addressed by Module-7

1. How much is known about the sensitivity of NSW estuarine species to environmental stressors that are being modified by climate change pressures?
2. How are NSW estuarine ecological communities anticipated to respond to climate change?

Cover photo

Drone view of the Belongil Creek ICOLL, Byron Bay, NSW; Photo: Chris Drummond, WRL, UNSW

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Tip for readers:

The modules in this series are designed to be read as double page booklets. To benefit from the double page sized figures and illustrations, it is recommended to read the modules in double page view, which is possible with most pdf readers. The first page is the booklet cover and should be in single page view.

1 INTRODUCTION

Estuaries, and the habitats that they support, are highly productive ecosystems that serve as spawning, nursery and feeding grounds for several economically and ecologically important species and provide a range of essential ecological services like coastal protection, water filtration and blue carbon sequestration (see Module-4 for more detail). These ecosystems, found at the boundary between land and sea, are highly vulnerable to changes in both atmospheric and oceanic climate conditions.

Anthropogenic emissions of greenhouse gasses (mainly CO_2) into the atmosphere have not only produced a rapid increase in atmospheric and oceanic temperatures around the world,[13] but have also produced a cascade of other environmental changes that may positively or negatively influence the abundance and distribution of estuarine species. Altered rainfall patterns and evaporative water loss coupled with sea-level rise are altering estuarine salinity gradients and the timing and duration of flood events. The thermal expansion of water coupled with the melting of ice caps and glaciers is producing sea-level rise that alters the availability of intertidal and shallow water habitats for species, particularly in urban areas (see Module-5). Rising concentrations of pCO_2 in the water are acidifying waters. Finally, climate warming is expected to exacerbate the frequency and duration of low-oxygen events because (1) rising temperatures decrease the solubility of oxygen in water and (2) warming of surface waters can lead to stratification of water bodies, reducing turnover of surface and bottom waters, which oxygenate the latter.[14] The physical basis of these changes of relevance to estuarine ecosystems is covered in greater detail in Module-3.

Understanding how specific ecological communities respond to environmental changes is critical for an accurate climate change risk assessment. A scarcity of information for many species and its inaccessibility presently limits ecological risk assessments for estuaries. This module presents a comprehensive review of available data on the physiological tolerances and ecological responses of NSW estuarine species to environmental variables that are being modified by climate change. Information is provided for 49 species, across five key environmental variables: temperature, salinity, CO_2, dissolved O_2, and sea level. Species were selected on the basis that they were either habitat-forming, commercially important, invasive or threatened.

Saltmarsh in the Hunter River Wetlands, photo: Valentin Heimhuber, WRL, UNSW

The module collates information from 292 resources, including peer-reviewed journals and grey literature. These data sources include observational studies documenting the range of conditions across which a species is found, laboratory and field experiments that test for cause-effect relationships between specific environmental variables and the growth, survival and/or reproduction of species, as well as modelling studies. The pros and cons of these various data types are discussed in greater detail in Module-4. Briefly, observational studies span ecologically relevant scales but, due to their correlative nature, cannot directly attribute species distributions to specific environmental variables. Experimental studies explicitly test for causal relationships between environmental and ecological variables, but may fail to adequately represent the complexity of the natural world, may fail to provide species with ample opportunity to adapt to new environmental conditions, and may only investigate relationships across a narrow range of values, such that they cannot identify thresholds outside of which species cannot survive. Modelling studies are simplifications of natural systems. Where possible, the data sources span the full range of life-history stages (e.g. larvae vs. adults) of a species as these may vary markedly in their environmental requirements and tolerances.

The literature sources on physiological tolerances that are reviewed in this module, are collated into an interactive online database (Eco-thresholds database) that is publicly available at:

http://estuaries.wrl.unsw.edu.au/index.php/climate-change/eco-thresholds-database/

The meta-data included in this database can be used to conduct customised climate change risk assessments in NSW estuaries and will be updated as new information comes to hand. The review also considers how ecological interactions (e.g. changes in competitive, predatory, and facilitative interactions) and organismal behaviour can modify climate impacts. Together, information sources are synthesised to provide a qualitative assessment of functional group sensitivity to climate change variables.

2 Physiological tolerances and ecological responses of NSW estuarine communities

2.1 Mangroves

While there are more than 40 species of mangrove in tropical Australia, only two species dominate the temperate estuaries of NSW: The Grey mangrove *Avicennia marina* (grey mangrove) and the River mangrove *Aegiceras corniculatum* (river mangrove). The geographical distribution in Australia of both species is extensive, ranging from tropical Queensland (and beyond to Indonesia and Papua New Guinea) in the north to Corner Inlet Victoria (Vic) for *A. marina* and Merimbula Lake in southern New South Wales (NSW) for A. *corniculatum* in the south.[15] Apart from these two dominant species, some tropical species can also be found in the northern estuaries of NSW. Perhaps most notably, *Rizophora stylosa* (red mangrove) has extended its southern latitudinal limit by about 400 km in the last couple of decades, to South West Rocks NSW.[7]

Temperature tolerance

The poleward limit of mangrove species is, in many instances, set by their physiological tolerance to low temperature. Consequently, in many cases mangroves are expected to display poleward range expansion under climate warming.[16] In the temperate estuaries of NSW, this may result in a change in species composition, and an increase in mangrove species richness, due to the migration of tropical species southward.[17] The two temperate species that presently dominant NSW estuaries are expected to be relatively resilient to warming temperatures, and may, in fact, increase in productivity.

Experimental studies assessing the effect of temperature on the survival of temperate mangroves are scarce. Nevertheless, based on latitudinal distributions, it appears *A. marina* can tolerate atmospheric temperatures (AT) of at least 4.7 – 32.1°C and sea surface temperatures (SST) of 11.7 – 28.1°C and A. *corniculatum,* ATs of 4.1 – 30.8°C and SSTs of 14.4 – 29.5°C.[15,18,19] At its southern-most distribution of South West Rocks, NSW, *R. stylosa* is exposed to a mean minimum AT in the coldest month of 11.3°C and SST is 18.5°C.[18,19] Laboratory experiments have shown that seedlings of both *A. marina* and A. *corniculatum* can survive chilling temperatures (5°C), with *A. corniculatum* more resilient to these conditions with 100 % survival compared to 65 % for *A. marina.*[20] Peng et al. (1994)[21] found that the lethal chilling temperature for seedlings of *A. corniculatum* (-2°C) was slightly lower than for *A. marina* (0°C).

In situ measurements suggest that optimal temperatures for leaf production vary among the species, consistent with their distributions. Whereas *A. marina* displayed optimal leaf production at 20.0°C, for *R. stylosa* it occurred between 27.0 – 28.0°C and for *A. corniculatum*, 25 - 27°C.[22] *In situ* photosynthetic rates of *R. stylosa* revealed a maximum photosynthetic efficiency for this species at temperatures of around 29°C.[23] Ball (1988)[24] found that seeds of *A. marina* ceased germination at 8.1°C and reached high mortalities at 40°C. She also found that photosynthesis in this species stopped at 35°C, achieving a maximum efficiency at 29°C.

In general, mangrove survival is limited by minimum, not maximum temperatures. Consequently, a direct negative impact of warming on NSW mangrove communities is unlikely. Nevertheless, southward range expansion of tropical species may occur, resulting in a reorganization of mangrove community structure.

Salinity tolerance

Although individual mangrove species can tolerate a wide range of salinities, mangroves are generally considered obligate halophytes, which means that they require sodium carbonate (salt) for successful development.[25] High salinities can also be detrimental for growth and productivity. Ball (1980)[26] suggested that salinity gradients and species salinity tolerances are the two most crucial factors in determining the structure of mangrove forests. For that reason, potential changes in salinity related to climate change are expected to have a substantial impact on the structure and distribution of these estuarine communities.

Of the two mangrove species that are most common in NSW estuaries, *A. marina* lives at higher salinities than *A. corniculatum.*[27] Most studies on the effect of salinity on mangroves have focused on early life history stages, quantifying germination and growth rates. These have found that the optimal salinity for germination of *A. marina* propagules is between 7 and 17.5 PSU and for *A. corniculatum*, between 0 and 15 PSU.[28,29] Propagules of both species can germinate in freshwater or seawater conditions, but only *A. marina* survived after germination at 35 PSU while *A. corniculatum* settlement and seedling survival failed in salinities above 25 PSU.[29,30]

Ball (1988)[24,31] found that the optimal salinity for propagule growth of *A. marina* was around 17.5 PSU while, propagules of *A. corniculatum* grew better in almost freshwater conditions (3.5 PSU). However, biomass production in both species was negatively affected by salinities around 35 PSU, with this effect stronger in *A. corniculatum* with a reduction of about 70 % in growth while in *A. marina* growth reduction was around 40 %.[24] In a similar study, Burchett et al. (1998)[32] also found that fully marine salinity conditions (35 PSU) were detrimental for the growth rates of both species with 70 % growth reduction in *A. corniculatum* and 50 % in *A. marina*, however, they also found that freshwater conditions reduced growth rates in both species, resulting in a 50 % growth reduction for *A. marina* and a 30 % growth reduction for *A. corniculatum*. Both species displayed an optimal salinity for growth of 8.7 PSU. Other studies on *A. marina*, also found that this species grows better in intermediate salinities (between 8.7 to 28 PSU), with freshwater or full marine conditions detrimental.[33-37] Additionally, an observational study in the Sundarbans area in Sri Lanka found that *A. marina* trees are naturally distributed in areas with salinities between 9 to 23 PSU avoiding areas with extremely high or low salinities.[38]

Unfortunately, there are few studies examining salinity tolerances of *R. stylosa*, but the limited literature available suggests that *R. stylosa,* which lacks salt-secreting glands on its leaves, is not as tolerant to changes in salinity as *A. marina*. Three separate studies [25, 39, 40] found that *R. stylosa* had an optimal growth rate at 8.7 PSU, with growth rates decreasing sharply at higher salinities.

> Despite the generally broad salinity tolerances of mangrove species, altered salinity gradients may produce changes in community structure due to variation among species in salinity optima. The most common NSW species, *A. marina*, survives at higher salinities than some other mangrove species present along the east Australian coast. Hence, at locations where the cascading effects of climate change include an increase in salinity, *A. marina* may increase its dominance.

Sea level rise responses

Unlike most intertidal species, mangroves have the capacity to respond to sea-level rise through vertical accretion.[41] Fine sediments and organic material are trapped and incorporated into the sediment (sediment accretion) by mangrove roots, increasing the surface elevation (SE).[42] Palaeoecological evidence shows that during periods of slow sea level rise (SLR) mangroves have kept pace and even expanded in many locations.[43] However, in periods when SLR had exceeded their accretion capability, large mangrove areas were lost.[44]

SE is influenced by mangrove vertical accretion capability, but it is also affected by physical processes like inorganic sedimentation rates, groundwater influx and underground land movements.[41] Rogers et al. (2006)[45] measured mangrove accretion and SE rates in several NSW estuaries from 2000 to 2003. They found that while accretion rates on average are high (5.1 mm/year) these do not necessarily reflect net SE rates (averaging only 0.62 mm/year), which are strongly influenced by local groundwater movement and sediment compaction processes. Lovelock et al. (2011)[46] similarly found differences in SE rates between the east (5.9 mm/year) and west (1.4 mm/year) of Moreton Bay, Qld, despite similar accretion rates in both areas (around 8.5 mm/year).

Due to the complexity of variables involved in SE and their high spatial variation, modelling the mangrove's response to SLR is challenging. Some models like the Sea Level Affecting Marshes Model (SLAMM) have integrated accretion rates across wetlands generally[47] and applied these to mangrove systems.[48] However, the available information on SE and accretion rates is insufficient for adequately accounting for spatial variation.[42]

Several studies have used empirical measurements of SE change to model changes in the area of specific NSW mangrove forests under SLR scenarios. Models utilising long-term measures of SE and accretion rates at Kooragang Island projected that under the relatively high rate of SLR (3.65 mm/year) predicted for the NSW region, the loss of wetland by submersion would be negligible and an increase in the wetland area of 16 % is instead expected by 2050.[49] Similarly models utilising measurements of SE change at Ukerebagh Island, NSW, between 2000 to 2012 found that although over this period local SLR rates (4.24 mm/year) were significantly higher than mangrove SE rates (1.4 mm/year) there was no evidence of mangrove stress or submersion in this area.[1] However, the dominant mangrove species on this island (*A. marina*) expanded landward gaining about 1 ha over saltmarsh areas.[1] Despite lower SE rates and SLR in the Minnamurra River estuary (0.63 mm/year and 1.8 mm/year respectively) between 2001 to 2011, Oliver et al. (2012)[2] predicted that mangroves will increase in area until 2050, replacing saltmarsh.

The existing models do not give information about different responses to SLR among mangrove species. However, the differential tidal elevations at which the three species are found may influence their responses. *R. stylosa* and *A. corniculatum* are usually found seaward of *A. marina*.[30,42] Palaeoecological studies in the Van Diemen Gulf, Northern Territory, showed that in the last 7000 years when there are periods of SLR, *R. stylosa* migrate landwards replacing *A. marina* forests and, at the same time, *A. marina* encroaches into saltmarsh areas.

> Overall, most studies have found that mangroves are highly resilient to moderate SLR and that even when SLR is higher than SE rates, mangroves can expand landward encroaching into saltmarsh areas. This phenomenon has already been reported in several regions along the south-east Australian coast.[1-4] However, under the worst case scenarios of rapid SLR (see Module-3), mangroves may be lost by 2100.[2]

CO_2 increase and ocean acidification responses

Increased concentrations of CO_2 in the atmosphere can enhance the growth of plant species that use C3 photosynthesis, by increasing photosynthetic efficiency.[50] Although there are few studies specifically focused on mangroves (which are C3 plants), most of them support the idea that increasing atmospheric CO_2 will have a positive effect on net photosynthesis, growth rates and water use efficiency (for a review see Gilman et al. (2008)[16]). For example, a comparative study between *R. stylosa* and the less salinity tolerant *R. apiculata* showed that doubling CO_2 concentrations increased growth rates in both species, although the effect was stronger in *R. apiculata*.[40] However, when combined with an increase in salinity, the effect of increasing CO_2 disappeared, while increasing humidity boosted it.[40] In another study, Farnsworth et al. (1996)[51] reported a positive effect of increasing CO_2 on the growth of *R. mangle* seedlings; however, this effect disappeared over time during the one-year long experiment. In a recent study, Jacotot et al. (2018)[52] found increased photosynthetic rates and water use efficiency of *A. marina* and *R. stylosa* seedlings at high CO_2 concentrations, with effects significantly stronger in *R. stylosa*. Finally, experiments on *Avicennia germinans* seedlings demonstrated that in this species CO_2 increase also enhanced growth rates, however, when grown under competitive conditions with saltmarsh species this effect is less noticeable.[53,54]

In summary, increasing atmospheric concentrations of CO_2 will likely have a positive impact on mangrove growth rates, and this effect will be stronger in fast-growing, less salinity tolerant species like *A. corniculatum* or *R. stylosa* than A. marina. However, whether the "positive" effect of CO_2 on growth rates translates to increased biomass will be influenced by interspecific competition and changes in salinity.

2.2 Seagrasses

These marine flowering plants are adapted to living fully submerged and inhabit intertidal and shallow subtidal estuarine areas.[55] In south-east Australia, there are three main seagrass species: *Halophila ovalis* (paddle weed), *Zostera muelleri* (eelgrass) *and Posidonia australis* (tape weed). The first two of these are broadly distributed across the Pacific and Indian Ocean, from tropical to temperate latitudes while, *P. australis* is endemic to temperate Australian waters.

Additionally, in NSW there are two species of salt-resistant macrophytes (*Ruppia megacarpa* and *R. polycarpa*)[56,57] which, although not true seagrasses, are considered here due to their capacity to outcompete seagrass under future climate scenarios.. *Ruppia* spp. inhabit a variety of environments from brackish lagoons and temporary salt lakes to shallow estuarine waters.[55,58] *Ruppia* species display an opportunistic life history, producing large numbers of resistant seeds which can survive extreme conditions, including desiccation, and recolonize areas faster than 'true' seagrasses.[59] Studies in America have shown that *R. marina* has replaced seagrass species in several locations after extreme climate events.[60-62]

Seagrass meadows are declining rapidly around the world, mainly due to direct human impact through pollution, eutrophication and dredging, as well as climate change related stressors like increasing water temperature and frequency of hurricanes, and storms.[63] *P. australis* has been catalogued as endangered in six estuaries under the New South Wales Fisheries Management Act 1994[64] and as globally near threatened by the IUCN.[65] *P. australis* has an unusually long lifespan (~2000 years) and a slow recovery rate following disturbance due to its low success recruiting from seed, and its inability to establish lateral runners following damage to rhizomal growing tips.[64] *Z. muelleri* and *H. ovalis,* which display much faster rates of growth, tend to outcompete *P. australis* in recovering seagrass meadows.[66]

Temperature tolerance

Seagrasses, in general, are highly sensitive to increasing temperatures, with many species already experiencing thermal stress.[67] Of the three main species of seagrass found in NSW, *H. ovalis* has the broadest latitudinal distribution, extending from south Asia to the south of Victoria in Australia.[15,65] Mean monthly SSTs across this latitudinal range are between 12.1 to 27.3°C.[19] *Z. muelleri* also covers a wide latitudinal range, extending from the northern tip of Australia to the south of New Zealand,[15,65] across which mean monthly temperature range between 8.5 to 29.7°C.[19] Of the three species, *P. australis* has the most restricted distribution, extending from the central coast of NSW and Western Australia (WA) to Tasmania,[15,65] across which mean monthly SST varies between 10.3 to 26.1°C.[19]

Laboratory experiments have shown that photosynthetic activity in *H. ovalis* ceases at water temperatures below 10 - 12.5°C and above 35 - 37°C, with optimal rates around 25 - 30°C,[68-71] although varying between tropical (28°C) and temperate (23°C) populations.[72] Similar experiments have revealed that the maximum temperature at which photosynthesis of *Z. muelleri* can occur is slightly lower than *H. ovalis* (between 30 - 35°C) and the optimal temperature slightly higher at about 27°C.[69,73,74] The temperature below which the photosynthetic activity of *Z. muelleri* ceases is variable between studies, with Campbell et al. (2006)[69] reporting a lower thermal limit of 10°C but Kerr and Strother (1985)[73] reporting a limit of 3°C. This variability likely reflects genetic and phenotypic differences among populations, associated with adaptation to local conditions, with the first study[69] focusing on a north Queensland (Latitude 16.75° S) population, and the second on a southern Victorian

(Latitude 38.22° S) population. A growth experiment on *Z. muelleri* plants collected from Lake Macquarie, NSW, yielded similar optimal and upper thermal limits to those for photosynthetic rates, with maximum growth at 27°C and high mortalities at temperatures over 32°C.[75] In comparison, Collier et al. (2017)[76] found a significantly higher optimal photosynthetic temperature for *Z. muelleri* of 31°C and a higher upper thermal threshold of 44°C. However, in the same study, the optimal temperature and upper thermal limit for biomass production were notably lower (24 and 36°C respectively).

Germination rates for *Z. muelleri* seem to peak at lower temperatures than photosynthesis; two different studies in South Queensland found optima of 15 to 20°C[77,78] and Brenchley and Probert (1998)[77] found germination more or less ceased above 26 °C.

There is surprisingly little information on the thermal tolerances of *P. australis*. In the only manipulative study that we are aware of, Masini et al. (1997)[79] grew seedlings of *P. australis* at 13, 18 and 23°C finding that growth and photosynthetic rates were greatest at 23°C. In an observational study in Shark Bay, WA, Walker and McComb(1988)[80] found that *P. australis* meadows display optimal biomass production at 19°C.

Unfortunately, there is no information about temperature thresholds for the *Ruppia* species found in NSW, but a closely related American species (*R. maritima*) displays high thermal tolerance, surviving annual temperatures from 7 to 35°C in Tampa, Florida.[81] In a laboratory experiment, Koch and Dawes (1991)[57] also showed that *R. maritima* grows optimally in a broad range of temperatures between 13 to 29°C.

Overall, *P. australis* is anticipated to be negatively affected by climate warming, with the other species potentially benefiting by outcompeting the temperate species.

Salinity tolerance

In general, most seagrasses are highly tolerant to high salinities.[82] Tolerance to low salinity is, however, one of the main factors shaping seagrass distributions, varying from species to species and among life history stages.

Adult plants of *Z. muelleri* can tolerate salinities from 8.7 PSU up to 140 PSU, with optimal growth at seawater conditions (35 PSU).[73] Germination of this species, by contrast, requires significantly lower salinities, with optimal rates between 0 to 8.7 PSU and will not progress above 35 PSU.[78]

Studies of salinity tolerance in *H. ovalis* have focused only on adult plants. Hillman et al. (1988)[83] observed that meadows of this species in the Swan River in Western Australia, reached maximum productivity at salinities between 15 to 35 PSU and stopped growing when salinity fell below 10 PSU. These results are consistent with experimental studies that found optimal growth of *H. ovalis* between salinities of 14 to 35 PSU and cessation of growth at salinities below 10 PSU.[70,84] Photosynthesis in *H. ovalis* showed slightly broader salinity tolerances, occurring between 0 to 70 PSU, with optimal rates at 35 PSU.[85]

Information on *P. australis* salinity tolerance is poor; Cambridge et al. (2017)[86] investigated the upper salinity tolerance of *P. australis* propagules, and found that at salinities around 54 PSU growth stopped and survival reduced to 31 %. In a different experiment, Tyerman et al. (1984)[87] concluded that salinities between 17.5 to 35 PSU are optimal for growth and photosynthesis of this species.

Both *R. megacarpa* and *R. polycarpa* have board salinity tolerances, surviving in estuaries and ephemeral salt lakes ranging in salinity from freshwater to more than 210 PSU.[58] However, manipulative experiments[88, 89] found that *R. megacarpa* seeds displayed greatest germination under freshwater conditions (between 0 to 6 PSU), remaining dormant at salinities over 29 PSU and ceasing to grow above 45 PSU.

In summary, “true” seagrasses (i.e. excluding *Ruppia* species) require salinities exceeding 8.7 PSU for survival and development. Consequently, where climate change results in an increased frequency and/or duration of freshets (rush of fresh water from rainfall events), a contraction in seagrass distribution and expansion in *Ruppia spp*. distribution may be seen.

Sea level rise responses

Seagrasses need a minimum of around 10 % of the irradiance received on the surface of the water in order to photosynthesise. For that reason, in most locations they are confined to the upper 10 m of the water column.[90] Reductions in water clarity due to anthropogenic and natural processes have been identified as one of the leading causes of the decrease of seagrass meadows around the world.[91] SLR will increase water depth and, consequently, it will reduce further the light available for seagrasses, increasing the already high levels of stress on these communities.[92]

In NSW, *Z. muelleri*, *P. australis* and *H. ovalis* coexist and are found to depths of 8-10 m in the clear waters of Jervis Bay and outer Sydney Harbour,[93-98] but are limited to depths of 2-3 m in the more turbid waters of urbanized estuaries such as Botany Bay, Port Hacking and Pittwater. Changes in SLR will have a particularly large impact on the distribution and survival of seagrasses in urbanized NSW estuaries where high turbidity already limits the depth to which seagrasses can extend.

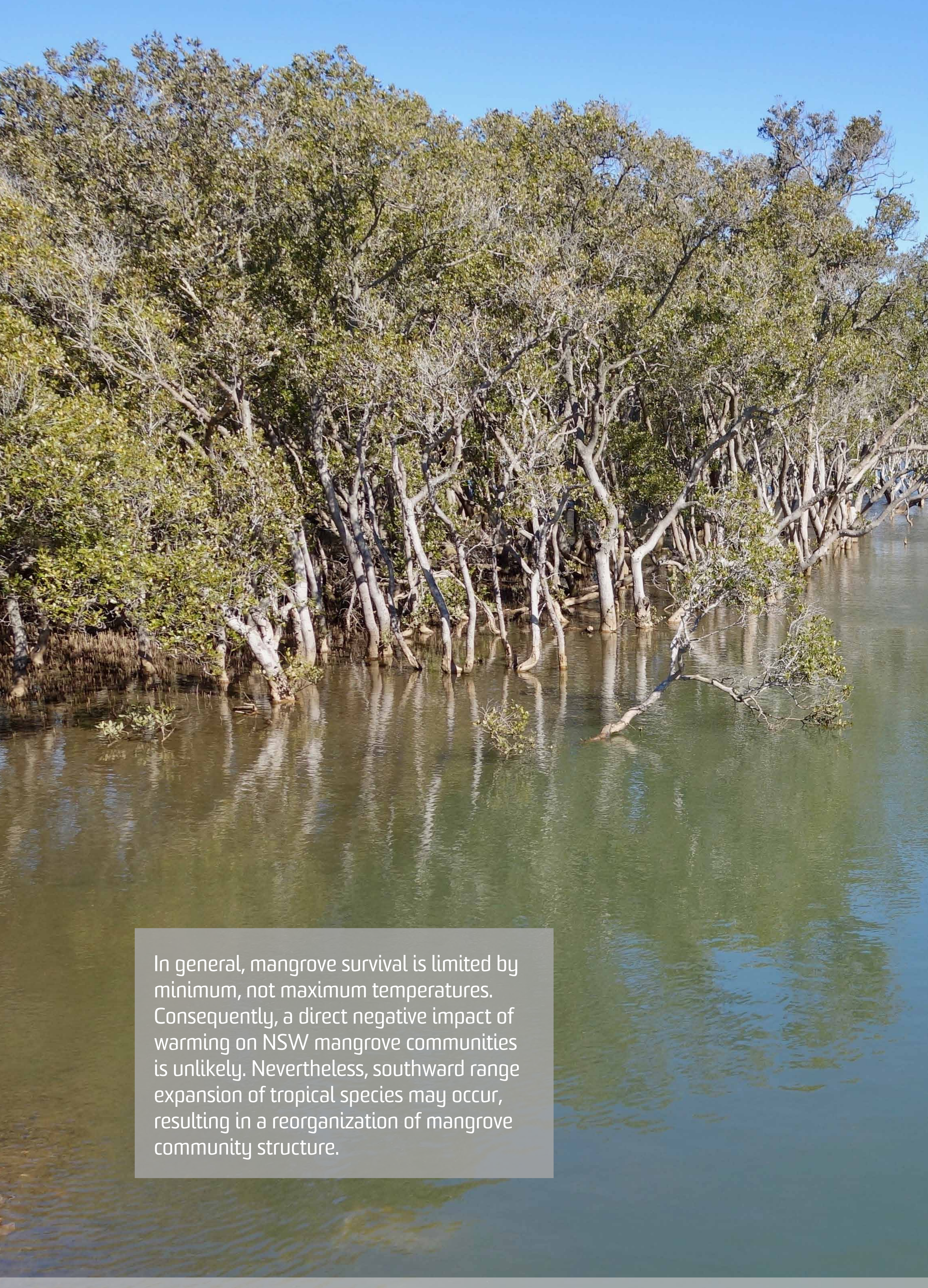
A model of the impact of SLR on NSW seagrass meadows predicted a loss in area of between 6 to 32 % for *P. australis* and 4 to 44 % for *Z. muelleri* by 2100.[99] In a similar SLR model, Saunders et al. (2013)[92] predicted a loss of 17 % of *Z. muelleri* cover in Moreton Bay, Qld, by 2100. In this model, the impact of SLR was notably higher in areas with high turbidity and shallow seagrass distributions.[92] There are few studies on the depth distribution of *Ruppia* species in NSW. However, in Victoria *R. polycarpa* and *R. megacarpa* are restricted to shallow areas of less than 3 m depth. Consequently, these species may also be sensitive to sea level rise.[58,100]

In general, seagrass distribution is mainly limited by the depth of light penetration into the water column. For that reason, these species are extremely sensitive to changes in SLR especially in areas where water turbidity is elevated (as in many estuarine areas).

CO$_2$ increase and ocean acidification responses

Like mangroves, seagrass species are C3 plants so may experience enhanced growth rates under elevated CO$_2$ conditions.[101] Although there are no studies specifically examining the effect of elevated CO$_2$ on NSW seagrass species, experiments on similar species (e.g. *Zostera marina*) elsewhere have found elevated CO$_2$ to increase growth and photosynthetic rates.[102,103] The physiological responses of seagrasses to enriched CO$_2$ are however contingent on adequate nutrients and light, and are also affected by temperature.[67] Additionally there is some evidence that the enhancement by elevated pCO_2 of photosynthetic rates may reduce seagrass’ daily light requirements, lessening the adverse effects of SLR.[67]

Overall, the predicted increase in seawater pCO2 is likely to have a positive impact on seagrasses, boosting growth, productivity and resilience to other environmental stressors associated with SLR.



In general, mangrove survival is limited by minimum, not maximum temperatures. Consequently, a direct negative impact of warming on NSW mangrove communities is unlikely. Nevertheless, southward range expansion of tropical species may occur, resulting in a reorganization of mangrove community structure.

Mangroves in the Hunter River Wetlands, Newcastle, NSW; photo: Valentin Heimhuber, WRL, UNSW

2.3 Saltmarshes

In contrast to mangroves, saltmarsh diversity increases in moving from tropical to temperate latitudes.[104] More than 90 % of the 100 plant species that live in Australian saltmarshes are found at temperate latitudes. This is despite the fact that 97 % of intertidal area available to saltmarsh is located in tropical regions.[105]

Temperature tolerance

In a comprehensive biogeographical study, Saintilan [105] found a strong inverse relationship between mean minimum daily temperatures and saltmarsh diversity, suggesting that for many species germination and growth rates are inhibited at high temperatures. However, experimental studies that explore this hypothesis are rare: Greenwood and McFarlane (2006)[106] found that germination rates of *Phragmites australis* (common reed), *Juncus kraussi* (sea rush) and *Juncus acutus* (spiny rush) were lower at temperatures between 15 to 30°C than between 10 to 15°C, with this difference insignificant at salinities below 17.5 PSU.

Most information on temperature tolerances of saltmarsh species comes from studies on their latitudinal distribution. Some of the most common Australian saltmarsh species like *P. australis*, *Sporobolus virginicus* (sand couch) or *Sarcocornia quinqueflora* (beaded samphire) are broadly distributed from subpolar to tropical zones[15] ranging in AT from 2.1 to 31.4°C and SST from 8.3 to 30.4°C.[18,19] However, other common species like *J. kraussi* or the invasive *J. acutus* do not extend into tropical zones, and are instead limited to locations where maximum mean monthly AT do not surpass 30.5°C.[15,18,19]

> Two main factors make saltmarsh species highly sensitive to increasing temperatures: (1) their seemingly low physiological tolerance (based on their latitudinal distributions) of high temperatures and (2) the indirect effect arising from poleward extension of mangrove species. Mangroves are better adapted to higher temperatures and likely will out-compete saltmarshes at several NSW locations. This phenomenon already has been reported elsewhere in the world.[11,12]

Salinity tolerance

Saltmarsh plants vary in the range of salinities they can tolerate.[107,108] For example, the common species *S. quinqueflora* has been experimentally shown to tolerate up to 36 PSU, with optimal growth rates at 17.5 PSU.[109] On the other hand, *S. virginicus,* a grass that co-occurs with *S. quinqueflora* in many NSW estuaries, cannot grow in salinities over 28 PSU and grows optimally under freshwater conditions.[30] Marked differences in salinity tolerance can also occur between species of the same genus. For example, in NSW the indigenous species *J. kraussi* experiences greatest germination and grows most rapidly in freshwater conditions (salinities lower than 5 PSU) but can tolerate salinities of up to 28 PSU.[30,106,110] In contrast, the invasive congener, *J. acutus*, which has spread along the NSW coast, struggles to grow at salinities above 17.5 PSU.[106,111,112]

The variable salinity tolerance of saltmarsh plants influences interspecific interactions and intertidal zonation.[108] At low salinities (less than 10 PSU) *J. acutus* outcompetes *J. kraussi*, however at higher salinities *J. kraussi* inhibits the expansion of the invasive *J. acutus.*[106] Good competitors (i.e. with high colonisation and growth rates) typically occupy less stressful areas of low salinity, with poorer competitors “forced” to adapt to high salinities.[113] For example, the grass *P. australis* dominates the low salinity environments of freshwater marshes and the high elevations of tidal saltmarshes, that are infrequently inundated by seawater.[114,115] A poor salinity tolerance has, however, historically limited proliferation of *P. australis* at regularly inundated lower intertidal elevations of saltmarshes. Salt tolerance does, however, vary among populations. Populations at Kooragang Island, NSW[106] and Shandong, China[116] can germinate and grow at salinities close to 30 PSU, but populations in Europe and America do not grow above 22 PSU.[117-119] Expansion of *P. australis* into saltmarshes has recently been seen following translocation of salt tolerant varietals[120] or reductions in salinity due to human activities.[121]

> In summary, changes in salinity are likely to result in altered saltmarsh species composition, benefiting some species and negatively affecting others depending on their salinity tolerances and competitive abilities.

Sea level rise responses

Saltmarshes have historically kept pace with SLR through vertical accretion and landward migration.[122] The capacity of saltmarsh to vertically accrete, however, depends on local sedimentation processes, with studies in NSW estuaries finding that even moderate rates of SLR rates will significantly out-pace saltmarsh vertical accretion. Oliver et al. (2012)[2] found that in the Minnamurra River, NSW the average SE change between 2001-2011 of 0.29 mm/year was notably lower than the SLR of 1.8 mm/year, suggesting a potential loss of saltmarsh areas. In an analysis spanning 2000-2012, Rogers et al. (2014)[1] similarly found the average SE change in Tweed River saltmarshes of 0.17 mm/year was considerably lower than the mean SLR of 4.24 mm/year, resulting in about 1 ha of saltmarsh loss.

Saltmarsh species vary in their capacity to vertical accrete, and hence adapt to SLR. In Botany Bay, NSW, Kelleway et al. (2017)[123] recorded rates of vertical accretion by *J. kraussi*, *S. quinqueflora*, and *S. virginicus* of 1.2, 0.8, 0.9 mm/year, respectively. These species also differ in their vertical distribution, with *S. quinqueflora*, the most salinity tolerant of the three species, found between 0.2 to 0.4 m above mean sea level, *S. virginicus* 0.4 to 0.8m above mean sea level, and J. *kraussi* 0.5 to 1.2 m above mean sea level.[124] Consequently, due to its lower rate of accretion and lower position on the shoreline, *S. quinqueflora* will be significantly more sensitive to SLR than *J. kraussi* which is more efficient at accreting and is found higher in the shore.

> In general, the main risk for saltmarshes is encroachment by mangroves, which are more resilient to SLR and are already replacing saltmarsh communities in several locations along south-east Australia.[1-3]

CO_2 increase and ocean acidification responses

Although elevated atmospheric CO_2 increases the growth and photosynthetic rates of C3 plants, it does not have a significant effect on C4 plants,[7] such that C4 plants may be outcompeted by C3 plants under high CO_2 conditions.[125-127] In NSW, estuarine saltmarshes are mainly dominated by *S. virginicus* (C4 plant) and *J. kraussi* (C3 plant) in the upper intertidal, and *S. virginicus* and *S. quinqueflora* (C3) in the lower intertidal.[123] Under high CO_2 conditions, decreases in the relative abundance of *S. virginicus* might therefore be expected.

> Because pCO_2 acts as a fertilizer for C3 but not C4 plants, mangroves, which are C3 plants, are likely to outcompete C4 saltmarsh plants.[7]

2.4 Shellfish ecosystems

There are three oyster species that are cultivated in NSW estuaries: two indigenous species, *Saccostrea glomerata* (Sydney rock oyster), which has been cultivated since the 1870s[128] and *Ostrea angasi* (flat oyster); and the introduced species *Crassotrea gigas* (Pacific oyster). Wild populations of all three species are also found, fouling artificial (e.g. concrete pilings, seawalls) and natural (rocky shores, mangroves) substrates and in some instances contributing to oyster reefs.

Unlike *S. glomerata* and *C. gigas,* which are broadcast spawners, *O. angasi* are brooders, holding eggs in the female mantle cavity where they are fertilised.[129] Larvae are incubated for 7-10 days before release, with a relatively short pelagic larval phase of 14-21 days. Such differences in biology may result in differences in the sensitivity of the three species to climate pressures. Whereas the larvae of brooders are more protected from short term disturbances and extreme events than broadcast spawners, the latter will potentially be more resilient to long term changes due to their higher capability for long distance dispersal.[130-132]

Temperature tolerance

The divergent latitudinal distributions of the three species are suggestive of differences in thermal tolerance. *S. glomerata* has the broadest latitudinal distribution extending from Victoria to tropical Australia, across which mean monthly AT ranges between 3.5 to 30.5°C and SST between 11.9 to 28.2°C.[15,18,19] The other native species, *O. angasi,* has a more temperate distribution, ranging from Tasmania to the sub-tropical south Queensland, across which mean monthly AT range between 2.6 to 28.6°C and SST between 10.5 to 26.4°C.[15,18,19] Finally, the introduced species, *C. gigas*, is limited to temperate water extending from Tasmania to the central coast of NSW, tolerating a more restricted range of mean monthly AT between 2.1 to 34.8°C and SST between 10.3 to 30°C.[18,19,133]

Several studies have found that the optimal water temperature for the larval development and growth of *S. glomerata* is between 22 and 26°C,[134-139] with a minimum of 19°C required for normal larval development. Parker et al. (2009)[136,139] studied the synergic effect of pCO_2 and water temperature on the early development of *S. glomerata*, finding that under high pCO_2 conditions of 856 µatm (concentration predicted for 2050), the upper thermal maximum for this species was about 30°C. However, under normal pCO_2 conditions (currently around 390 µatm) oyster larvae were able to develop at and survive the maximum experimental temperature of 33°C.[138] In a field experiment, McAfee et al. (2018)[140] found that adults of *S. glomerata* were able to survive substrate temperatures of up to 34°C but 50 % mortality was experienced over 37°C. Thermal tolerance varied among oyster populations, with those bred for fast growth and disease resistance less tolerant to high temperatures than wild populations.[140]

In contrast to the Sydney rock oyster industry, flat oyster aquaculture is relatively new,[128] and reflecting this, there is relatively little information available on its thermal tolerances. O'Connor et al. (2015)[141] found that the optimal temperature for *O. angasi* larval development is between 26 to 29°C with a thermal maximum of 31.5°C. Other studies on this species reported successful larval incubation at 15 and 17°C, however, these were short-term experiments where survival rates were not assessed across subsequent life history stages and only a small set of temperatures were examined.[142,143]

Temperature effects on *C. gigas* have been extensively studied due to its global importance in aquaculture and as an invasive species. The temperature at which this species displays greatest larval growth varies among populations, from 23 to 32°C,[144-147] with a high percentage of abnormal larvae observed when development occurs below 16-20°C or above 30°C.[145,146] For NSW populations, Parker et al. (2010)[137] reported optimal fertilisation and larval development at water temperatures between 26 to 30°C. Adults of this species seem to have a broader thermal range of tolerance between 3 to 35°C with optimal growth between 11 to 34°C (for a review see Mann et al. (1994)[148]).

Several studies have also found that *C. gigas* adults can withstand short-term extreme heat shocks of 1 to 2 hours exposure to temperatures between 37 to 39°C.[149,150] Moreover, Carvalho-Saucedo[151] found that critical maximum temperatures for *C. gigas* adults were reached after four days exposure to 32°C, but this thermal threshold can be increased to 37°C after gradual acclimation.

Based on extant literature on direct temperature effects, it appears *S. glomerata* is likely to tolerate levels of warming predicted for NSW estuaries. In the case of the other two common species, *O. angasi* and *C. gigas*, chronic exposure to temperatures over 32°C will likely have a negative impact, especially on early development. Nevertheless, it is possible that warming may have strong negative indirect effects on *S. glomerata*, arising from an increased incidence of disease and/or predation. For example, QX disease which is a leading cause of mortality in wild and farmed populations,[128] arises from infection of a parasite first identified in the sub-tropical waters of Queensland.[128] It is expected that increasing seawater temperatures will facilitate poleward extension of QX disease and possibly also other tropical parasitic diseases that affect oysters. Increasing water temperatures may also increase predation rates of crabs and sea snails on oyster beds, as a result of their increased metabolic rates.[152-154]

In summary, *S. glomerata* will be more resilient to direct temperature increase than the other two species present in NSW estuaries. However, indirect effects like disease migration and increasing predation rates may have a critical negative impact on all NSW oyster communities in general.

Salinity tolerance

Oysters are euryhaline organisms adapted to living in environments with variable salinity conditions. Nevertheless, salinity is a key factor defining the distribution of oysters within estuaries, with tolerances varying with developmental stage. In *S. glomerata* optimal salinities increase from 20 PSU for embryos to 35 PSU for spat.[135] Once settled, *S. glomerata* and *O. angasi* grow optimally at salinities of 25 to 39 PSU.[155,156] When all life history stages are considered, the minimum salinity required for survival for *S. glomerata* is about 15 PSU,[135,157] while for *O. angasi* it is a little higher at 20 PSU.[141,158]

In comparison to the two native species, *C. gigas* tolerates lower salinities. In France and Italy, optimal larval development occurs between 24 to 30 PSU with a minimum threshold for larval development around 25 PSU.[146,147] In the Chesapeake Bay, USA translocated spat of *C. gigas* displayed greatest growth in a section of the bay with average salinities of 25 PSU and tolerate salinities as low as 10 PSU.[159] In Port Stephens NSW, larval development is optimised at salinities of 19 to 27 PSU.[159] Adults of *C. gigas* can tolerate and grow in an impressive range of salinities from almost freshwater conditions to hypersaline environments. In a review, Mann et al. (1994)[148] reported a salinity tolerance of 10 to 42 PSU for this species. However, Nell and Gibbs (1986)[158] proposed a significantly broader range of 5 to 55 PSU.

Saltwater intrusion into estuaries as a result of SLR may favor native species of oyster, over *C. gigas* which has larvae sensitive to high salinity. By contrast, freshwater pulses may negatively impact *S. glomerata* and *O. angasi,* both directly, and also indirectly by compromising their immune system such that they are more vulnerable to parasitic and viral infection, for example by the QX disease-causing parasite.[5,6]

Sea level rise responses

As discussed elsewhere in this module, the capacity of estuarine biogenic habitats such as mangroves and saltmarsh to persist under scenarios of SLR rests largely on their capability to vertically accrete. Unfortunately, there is a notable lack of studies on response of Australian shellfish ecosystems to SLR. However, recent studies on the American oyster *Crassostrea virginicus* have concluded that vertical growth of oyster reef has the potential to outpace SLR even under the more severe climate change scenarios.[8,160] In one of these studies, Rodriguez et al. (2014)[160] found vertical accretion rates of up to 11.5 cm/year in an experimental reef, and calculated that older natural reefs have vertical accretion rates between 0.6 to 2 cm/year, which has allowed them to keep pace with the local mean sea level rise of the past 15 years. In a more recent study, Ridge et al. (2008)[8] reported accretion rates for young *C. gigas* reefs of 6.7 cm/year and older reefs of 2 to 4.3 cm/year, depending on variations in the local mean sea level in the last five years. SLR also may affect the availability of areas for new natural oyster population settling as well as for farming. However, these factors depend entirely on the local geomorphological characteristics and the level of urban development in each estuary, which makes this risk difficult to generalise.

> Overall, due to their relatively high resilience to SLR, oyster reefs are likely to play an essential role as refuges for many species in a changing climate, and provide important coastal protection.[8] Unfortunately, in Australia, only 8 % of *S. glomerata* and 1 % of *O. angasi* reefs present at the time of European settlement remain, largely due to historic overharvest.[10]

CO_2 increase and ocean acidification responses

Ocean acidification is predicted to have a negative impact on shelled molluscs like oysters, increasing carbonate shell dissolution, and negatively affecting biomineralization (shell production).[161]

In NSW, several studies have experimentally examined the effect of predicted increases in pCO_2 on the fertilisation, development and survival rates of *S. glomerata*. Watson and colleagues found that *S. glomerata* larvae exposed to pHs of 7.8 and 7.6 reduced their size considerably, and empty shells from dead individuals were almost completely dissolved after seven days indicating that the pH of 7.6 is close to the acidity threshold that this species can tolerate.[162] Parker et al. (2009)[136] found that there are strong synergic effects of temperature and pCO_2 on *S. glomerata* fertilisation and early development. Increasing pCO_2 reduced fertilisation success, larval development, and growth rates, with these effects worsening at high temperatures.[136] In this study, there was no larval development at temperatures close to 30°C and pCO_2 higher than 750 µatm, and almost 100 % of larvae experienced abnormalities at this temperature and pCO_2 exceeding 600 µatm.

Such experiments, however, ignore the possibility of cross-generational adaptation and Parker et al. (2017)[163] found that larvae from *S. glomerata* exposed to higher pCO_2 displayed greater growth under high pCO_2 than larvae from individuals exposed to ambient pCO_2, however, these "more adapted" larvae could not survive exposure to moderately elevated temperatures (28°C). Parental exposure to high pCO_2 (856 µatm), also increased the ratio of females by 16 % and reduced fertility by 57 % in the next generation.[139]

The sensitivity of *S. glomerata* to elevated pCO_2 also displays marked variation among populations of *S. glomerata*. A wild population displayed greater reductions in growth and slowing of development than a population selectively bred for fast growth and disease resistance.[164,165] In a recent study, Stapp et al. (2018)[166] found that the primary mechanism responsible for the higher tolerance of selectively bred oysters to elevated pCO_2 is related to more efficient filtration rates which increase their ability for CO_2 release. Additionally, oysters growing at high intertidal elevations are more sensitive to elevated pCO_2 than those growing at low intertidal elevations because they experience a longer period of aerial exposure, over which internal acidosis develops.[167]

Only one study, by contrast, has addressed effects of ocean acidification on *O. angasi*. Cole et al. (2016)[168] exposed *O. angasi* larvae to a pH of 7.8 finding a slight reduction of 3 % in size but no other adverse effects. More studies on this species are required to build a strong predictive understanding of its sensitivity to elevated pCO_2 but based on the available data it appears *O. angasi* may be more resilient to acidification than *S. glomerata.*

C. gigas also appears more resilient to ocean acidification than *S. glomerata*. *C. gigas* larvae can survive pCO_2 concentrations of up to 1000 µatm (or pHs of around 7.8), although larval development is slowed and size is reduced by around a third at the upper end of this range.[169-171] In a comparative study, Parker et al. (2010)[137] found that *C. gigas* survived pCO_2 of 395 to 1000 µatm, at temperatures of 18 to 30°C. By contrast *S. glomerata*, suffered high mortalities under elevated pCO_2 conditions at 18 and 30°C. Nevertheless, a pCO_2 of over 2000 µatm (i.e. pH around 7.4), is lethal after a few days of exposure.[170,172]

Despite the apparent adverse effects of ocean acidification on the rate of early development of oysters, effects on survivorship at optimal salinity and temperature conditions are rare. However, most of the studies reported here were done under controlled hatchery conditions that lack predators. Smaller, weaker oysters produced at high pCO_2 conditions will be less resilient to predators in field settings. *S. glomerata* with shells weakened by acid sulphate soil acidification (another critical source of acidification in estuaries) were more susceptible to predation by *Morula marginalba* than control oysters, unaffected by acidification.[173] In another study, Wright et al. (2014)[174,175] found that exposure to elevated pCO_2 not only made *C. gigas* more vulnerable to predation by reducing its size and shell strength, but also increased the predatory behaviour of whelks.

Overall, there is growing evidence that oysters may be able to physiologically adapt to increasing pCO_2 levels, such that direct effects of this stressor are smaller than initially anticipated. However, large indirect effects of ocean acidification could result if the cumulative effect of a reduction in oyster shell size and strength and increased rates of gastropod predation leads to enhanced rates of predatory mortality.

2.5 Estuarine clams and cockles

Bivalves are a diverse group that includes different orders, families and thousands of species. This section focuses on two species: (1) the clam *Donax deltoides* (pipi), which represents about 1.6 % of the annual NSW Estuary General Fishery (EGF) with an annual value of 0.6 million AUD in 2014[176] and (2) the cockle *Anadara trapezia* (Sydney cockle), which is among the most common species on NSW mudflats and is an important pollutant bioindicator for mudflat ecosystems.[177-179] These two species dominate the unvegetated intertidal and shallow sub-tidal zones, with *D. deltoides* more common in sandy sediments while *A. trapezia* is more common on mudflats and in seagrass meadows.[180,181]

Temperature tolerance

Both species have a broad latitudinal distribution from Tasmania to tropical Australia, with *A. trapezia* extending further northwards. Based on their latitudinal distribution, *D. deltoides* and *A. trapezia* share similar minimum mean monthly limits of AT 4.6°C and SST 10.8°C,[15,18,19] while the upper latitudinal thermal limits of *D. deltoides* are slightly lower (AT 30.9°C and SST 27.7°C) than *A. trapezia* (AT 32°C and 30.3°C).[15,18,19] Unfortunately, there are not manipulative studies determining thermal thresholds of *D. deltoides*. Hatchery trials, however, suggest optimal development of *D. deltoides* at temperatures between 19 to 23°C.[182,183] These trials found that *D. deltoides* grow faster at higher temperatures around 28°C but survival is lower compared with temperatures around 23°C.[183] Taylor et al. (2017)[181] studied the synergistic effects of temperature and salinity on *A. trapezia* survival, finding that this species suffered high mortalities at sub-optimal salinities at temperatures lower than 10°C and higher than 30°C, with optimal survival rates at 20°C.

The available information, although poor in quality, suggests that upper thermal thresholds are highly affected by salinity conditions; however, based on their broad geographical distribution it is likely that at optimal salinities these species are highly tolerant to thermal changes.

Salinity tolerance

Like oysters, estuarine clams and cockles are generally tolerant of high salinities, with their sensitivity to low salinities instead determining their distributions. Both, *D. deltoides* and *A. trapezia* share similar optimal developmental salinities between 22 to 30 PSU and upper thresholds between 45 to 50 PSU.[158,181,182] However, *D. deltoides* is less tolerant to low salinities with limits close to 20 PSU than *A. trapezia*, which can tolerate salinities of 15 PSU.[158] Bivalves can survive salinities out of their tolerance range for a short time period closing tightly their valves; for these species this period is up to 7 days for *D. deltoides* and 11 days for *A. trapezia*.[158]

Each species may be each expected to display similar responses to climate change induced changes in salinity: where sea-level rise increases the distance up estuaries that saltwater intrudes, expansions in the distributions of these species may be seen; however where altered rainfall patterns lead to freshwater pulses, particularly those of protracted duration, populations may be negatively impacted.

> Although, these bivalves are tolerant to high salinities, increase in freshwater inputs may impact them negatively in some areas.

Sea level rise responses

There are no studies specifically focused on the impact of SLR on *D. deltoides* or *A. trapezia*. However, there have been some efforts to model the effect of SLR on intertidal flats (the primary habitat for *D. deltoides* and *A. trapezia*) around the world.[184,185] Modelled predictions are highly variable depending on the geomorphology of the area of study; however, a shared conclusion is that the degree of impact will depend on the availability of space for their landward migration which is influenced by seawalls and other urban structures that armour the shoreline. In some NSW estuaries in excess of 50 % of the shoreline is armoured by seawalls and other structures, making their intertidal communities highly vulnerable to SLR.[186] Although the subtidal distribution of *D. deltoides* or *A. trapezia* has not been mapped in Australia, closely related species (*Donax trinculus*, *Donax vittatus*, *Anadara granosa*) can live down to 20 m depth.[187,188] Hence, populations of *D. deltoides* and *A. trapezia* may not be as sensitive to SLR as species that are limited to the intertidal.

> Information on the vertical distribution of *D. deltoides* and *A. trapezia* is poor; however, close related cockle and clam species can survive in depth subtidal areas which make them less vulnerable to changes in SLR than intertidal species.

CO_2 increase and ocean acidification responses

As calcified molluscs, clams and cockles are potentially susceptible to the effects of ocean acidification, arising from an increased pCO_2 of seawater. Like oysters (see also “shellfish ecosystems”), clams and cockles may experience decreased shell hardness, fertilisation success, and growth rates and increased developmental time. Additionally, acidification may also affect the burrowing behaviour of clams and cockles. A study on the razor clam *Sinonovacula constricta* found that acidification reduced energy production affecting the clam’s ability to burrow efficiently and increasing exposure to predators.[189]

> Although predicted pH levels for seawater are generally sub-lethal for bivalves, indirect effects such as reduced shell formation, which render bivalves more susceptible to predation, make these species highly sensitive to ocean acidification.

Dissolved oxygen tolerance

Although intertidal habitats, which are exposed to air at low tide, and have sediments that are well mixed by waves, rarely suffer from the effects of low dissolved oxygen, subtidal clam and cockle populations may be negatively impacted by reductions in the dissolved oxygen of seawater.

Dissolved oxygen thresholds for *D. deltoides* or *A. trapezia* have not been published, however, studies on two closely related species, *Donax serra* and *A. granosa*, found that these can tolerate short periods of exposure to very low levels of oxygen (under 2ppm) by changing to anaerobic based energy production, but that low dissolved oxygen events persisting for a few days are lethal.[190,191] Hence, whether climate change induced hypoxic and anoxic events result in mortality are likely to depend on their duration. The probability of low oxygen events is greatest for deeper water bodies, that have a greater propensity for stratification.

> Although bivalves may be highly tolerant of short-term low levels of oxygen, mortalities may result from longer-duration hypoxic events.

2.6 Estuarine crabs

Crabs are also an important fishery resource in NSW estuaries; these crustaceans represent around 12 % of the EFG annual landings.[176] The main two commercially exploited species in NSW are *Scylla serrata* (mud crab) and *Portunus pelagicus* (blue swimmer crab). Another estuarine crab species of interest in NSW estuaries is *Carcinus maenas* (European green crab). This is an invasive species, that poses a threat to native shellfish.

Temperature tolerance

Both the native species, *S. serrata* and *P. pelagicus,* have extensive latitudinal ranges, with thermal limits slightly warmer for *S. serrata* (AT 6.2 to 32°C and SST 13.3 to 30.4°C) than for *P. pelagicus* (AT 3.3 to 32°C and SST 12 to 29.1°C).[15,18,19] Studies on thermal tolerances of *S. serrata* provide variable results and Ruscoe et al. (2004)[192] suggest that due to the broad latitudinal distribution of this species, different populations have developed different thermal tolerances. For example, experimental trials in South Africa found optimal *S. serrata* larval development between 15 to 20°C and minimum thresholds around 10°C,[193] while in tropical Australia and Japan similar trials in local populations found optimal temperatures between 28 to 30°C and minimum thresholds between 17 to 20°C.[194,195] Furthermore, studies on *S. serrata* populations from South Africa and tropical Australia found similar upper thresholds around 35°C for both; however, optimal temperatures were notably different (15 to 20°C in South Africa compared with 30°C in tropical Australia).[192,193]

On the other hand, Ikhwanuddin et al. (2012)[196] found that the optimal temperature for *P. pelagicus* larval development was 30°C, irrespective of salinity, but two other studies concluded that thermal tolerances of *P. pelagicus* are influenced by acclimation temperatures. These latter two studies found that depending on acclimation temperatures, critical minimum and maximum temperatures may vary up to 5°C in this species (CTmin varied between 12 to 19°C and CTmax about 38 to 44°C).[197,198] Based on the available information, it appears that *S. serrata* and *P. pelagicus* have broad temperature tolerances and their distributions, in NSW at least, are likely to be unaffected by warming.

In Australia, the non-native *C. maenas* is restricted to temperate waters between Tasmania and Batemans Bay in NSW south-east coast , where mean monthly AT are between 10.9 to 24.3°C and SST between 11 to 24.3°.[15,18,19,199] Worldwide, the latitudinal distribution of this species extends from subpolar regions with minimum monthly SST to -1°C to subtropical areas with SST between 22 and 26°C.[200-202] Manipulative experiments on *C. maenas* breeding and larval development support similar upper thermal thresholds around 26°C with optimal temperatures significantly lower around 12°C.[203,204] Acclimation temperatures also have a strong influence on the thermal tolerance of this species; adults of *C. maenas* can increase their upper thermal thresholds around 6°C after slow acclimation, surviving water temperatures up to 36°C.[205,206] Nevertheless, the northward extent of *C. maenas* along the east Australian coast is consistent with temperature control.

> Crabs have high thermal plasticity with large differences in thermal tolerance among populations. In NSW, native populations will likely be unaffected by warming conditions, while populations of the invasive *C. maenas* will likely contract.

Salinity tolerance

Salinity tolerance in *S. serrata* varies notably during its life cycle; adult females migrate from estuaries to offshore to spawn, and larvae develop pelagically mostly under fully marine conditions around 35 PSU.[207] Consequently, adults in this species have extremely broad salinity tolerances ranging from almost freshwater conditions (2 to 5 PSU) up to 60 PSU[190,192,208] and optimal growth conditions between 10 to 20 PSU.[209] In contrast, larvae need higher salinity conditions over 17.5 PSU for successful development, with an optimal range between 25 to 35 PSU.[193,195] Like *S. serrata*, *P. pelagicus* migrates to deeper offshore waters to spawn, however, the adults of this species are not as efficient at osmoregulation as *S. serrata* and cannot tolerate salinities lower than 15 PSU.[209] Adults of *P. pelagicus* tend to migrate out of estuarine systems in winter when freshwater inputs are higher.[210] *P. pelagicus* larvae also have a relatively narrow low salinity tolerance of 15 to 20 PSU and a higher salinity tolerance up to 45 PSU.[196,211,212]

The life cycle of *C. maenas* differs from the two natives crab species discussed here. *C. maenas* spawn inside the estuary and the larvae are transported offshore by tidal currents "re-invading" the estuary in the late larval stages.[213] *C. maenas* is not a good osmoregulator and is generally only found at salinities above 17 PSU, with optimal growth at 35 PSU.[214-216] In an experimental study, Legeay and Massabuau (2000)[217] found that this species can survive salinities as low as 10 PSU but nevertheless behaviourally avoid them by leaving the water. Like other crab species, *C. maenas* larvae cannot tolerate salinities under 17.5 PSU and develop optimally at salinities between 22 to 40 PSU.[218,219]

Impacts of salinity changes will vary among species according to their ability to osmoregulate. *P. pelagicus* and *C. maenas*, which are poor osmoregulators, unable to tolerate low salinities, may benefit from incidences of saltwater intrusion caused by sea-level rise extending their distributions up estuaries. However, these species may experience mortality where altered rainfall patterns lead to freshwater pulses, particularly those of protracted duration.

Sea level rise responses

As crabs are highly mobile organisms, direct impacts of SLR are unlikely. However, these species may be indirectly affected if estuarine habitats which they require for completing certain phases of their life cycle are negatively impacted by SLR. For example, *P. pelagicus* almost exclusively uses seagrass meadows as nursery and feeding grounds,[220] and seagrass meadows are highly sensitive to SLR. *C. maenas*, which is most abundant on intertidal rocky shores, may be negatively affected in estuaries where shoreline modification prevents landward migration of its habitat. Possibly, the least sensitive species to SLR is *S. serrata*, which lives in mudflats of mangroves[221] – a habitat which is highly resilient to SLR (see section on mangroves, above).

In general, the impact of SLR on crabs will depend on their habitat requirements. Species, such as *P. pelagicus* and *C. maenas* that depend on habitats such as seagrass and intertidal rocky reef may be more affected than the mangrove species *S. serrata* due to differences in habitat vulnerability to SLR.

CO_2 increase and ocean acidification responses

Crabs, and crustaceans more generally, are highly tolerant to changes in pCO_2 and to the effects of ocean acidification.[222-224] This is due to their capacity to maintain an internal acid-base equilibrium through ion-transport[225] and their possession of an exoskeleton that is more resistant to dissolution at low pH than that of molluscs.[224] For example, *C. maenas* can survive a pH of 6.3 and pCO_2 concentration up to 4000 without showing evidence of extreme stress.[226,227] *P. pelagicus* can tolerate pHs greater than 5.5.[228] These pH minima represent acidification levels significantly higher than those predicted by climate change models.

While most studies are focused on adults of these species, one study on the larval development of *P. pelagicus* showed that pH values around 7.5 could negatively affect larval development, resulting in high mortalities.[211]

> Although crab species in general seem to be highly resistant to acidification and high levels of pCO2, more studies on the impact of these variables on the early life stage of these species are necessary.

Dissolved oxygen tolerance

Crabs can survive several hours of hypoxia, by modifying their behaviour and metabolic processes.[217] For example, *S. serrata* will climb out of the water to oxygenate if dissolved oxygen is reduced below 2 ppm and can survive several hours at a dissolved oxygen concentration of less than 1 ppm.[229] Similarly, *C. maenas* can tolerate oxygen levels below 2 ppm, climbs out of water at levels close to 1 ppm, and can survive up to 18 hours of hypoxia (i.e. no oxygen).[214,230] On the other hand, larvae of *P. pelagicus* experience more than 50 % mortality after just three hours without aeration and 100 % mortality after 7 hours of dissolved oxygen levels below 1 ppm.[211] Consequently, protracted hypoxic events, of large spatial scale may pose a threat to crabs as behavioural and physiological mechanisms of minimising exposure will be ineffectual.

> Adult crabs are highly tolerant to low oxygen levels, exhibiting not only physiological but behavioural responses. However, larval stages are more sensitive, especially to extensive periods of hypoxic conditions.

2.7 Estuarine prawns

NSW estuary prawn trawling represented 3 % of the total NSW marine fisheries production in 2014, with an annual value around 3.3 million AUD.[176] There are three dominant prawn species in NSW estuaries: *Metapenaeus macleaya* (school prawn), *Penaeus plebejus* (Easter king prawn) and *Metapenaeus bennettae* (greasyback prawn). The first two species are actively targeted by the commercial fishery while *M. bennettae* is considered a by-product.[231]

Temperature tolerance

The three species differ in their latitudinal distributions: *M. macleaya* is restricted to temperate waters from Bemm River in southern Victoria to the Sunshine Coast in southern Queensland, tolerating a mean monthly SST between 13.7 to 26.7°C. *P. plebejus* has a broader latitudinal distribution from Tasmania to Torres Strait Islands in tropical Australia, surviving monthly SST between 12.5 to 30.3°C. *M. bennettae* shares its southern limit with *M. macleaya* in Victoria but extends to tropical latitudes in North Queensland (mean monthly SST between 13.7 to 30.3°C).[15,18,19] Based on interannual seasonal patterns of variation in abundance, Young (1978)[232] concluded that *M. macleaya* and *P. plebejus* shared similar thermal ranges of 13.7 to 30.3°C, *M. bennettae* had a warmer thermal range of 14 to 32°C, and all three species had a similar optimal temperature of around 22.7°C.

In an experimental study comparing temperature tolerances, Preston (1985)[233] found that the three species of prawn shared similar low thermal thresholds for larval development of around 15°C and could tolerate temperatures above 34°C, although at that temperature hatching success decreased in all species. Spawning in *P. plebejus* was more successful at temperatures between

20 to 24°C, while warmer temperatures between 22 to 29°C were better for the two *Metapenaeus* species.[233] Despite the lower optimal temperature for spawning of *P. plebejus* than *M. macleaya, P. plebejus* had a higher optimal temperature for larval growth than *M. macleaya* (30°C vs 24.1°C).[234] Preston (1985)[233] also found that salinities can have a substantial effect on temperature tolerance. For example,*M. bennettae* larvae hatched in brackish water are more tolerant to lower temperatures than larvae from the same individuals hatched in fully marine conditions.

Like crabs, prawns seem to be highly adaptable to changes in temperature. For example, slow acclimation of *M. bennettae* extended lower thermal limits from 8.1°C to 5°C and upper limits from 32.9 to 36°C.[235] Additionally, the ambient temperature at the time of spawning greatly influenced the thermal tolerances of subsequent life stages.[235]

Highly mobile species of crustaceans such as prawns, can behaviorally adapt to changes in thermal conditions and are likely to be able to cope with the predicted increase in ocean temperatures.

Salinity tolerance

Salinity tolerance in prawns varies significantly among life stages, reflecting the different environments utilised by each. Adults migrate offshore to spawn, larvae migrate to estuaries and settle in mangroves and seagrass areas.[232] In a comparative study, Preston (1985)[233] found that *P. plebejus* and *M. macleaya* required salinities higher than 25 PSU to successfully spawn, while *M. bennettae* could spawn in brackish water down to 10 PSU. The high salinity tolerance of *M. bennettae* explains why it is the only one of the three species which has been recorded spawning inside estuaries.[233] Adults of *M. bennettae* are also stronger osmoregulators than *P. plebejus*, tolerating salinities of less than 3 PSU to more than 50 PSU, with optimal salinities around 27,5 PSU, while *P. plebejus* tolerate a narrower range of 7 to 50 PSU and optimal salinities of 30 PSU.[236] Unfortunately, there are no studies on the osmoregulation capabilities of adult *M. macleaya*.

Juveniles of these species inhabit estuaries and are consequently better osmoregulators than adults, which predominantly live under marine conditions. Young (1978)[232] found that juveniles of *M. macleaya* and *P. plebejus* inhabited areas with salinities of 8.1 to 35.8 PSU), while *M bennettae* juveniles inhabited waters of 2.5 to 36.2 PSU. Furthermore, after acclimation, juveniles of *M. bennettae* can tolerate conditions ranging from freshwater to 60 PSU.[235]

In summary, there are significant interspecific differences in salinity tolerance among NSW prawn species and although the three species are highly tolerant to high salinities, increasing rainfall and freshwater input will affect their distribution favoring the most efficient osmoregulator, *M. bennettae*, over the other two species.

Sea level rise responses

NSW prawn species are highly mobile and salinity tolerant which make them highly resilient to changes in SLR. However, the post-larval stages of these species are common inhabitants of seagrass meadows which provide them with food and protection[232] so may display large negative indirect responses to SLR, if seagrass meadows contract (see *Seagrass* section).

A direct impact of SLR on prawn species is unlikely, but the high sensitivity of prawn nursery habitats like seagrasses may have an indirect negative effect.

CO_2 increase and ocean acidification responses

Like other crustaceans, prawns are highly resilient to ocean acidification and increasing pCO_2 as a result of efficient internal regulation of the base-acid equilibrium and possession of an exoskeleton that is resistant to dissolution by low external pH.[224,225] Although studies specific to NSW species are lacking, studies on other *Penaeus* species have shown that the lethal pH for these species is extremely low, at around 3.7[237] – a threshold that will not be reached due to climate change. However, several studies have found that a moderate reduction in pH to 6 can reduce the body size and survival rates.[238,239] This pH value could potentially be reached in areas with high freshwater influence, which are used by *M. bennettae* use as nursery grounds.

Despite some potential sub-lethal risks, prawns, like most crustaceans, are expected to be remarkably resilient to changes in pCO_2 and ocean acidification.

Dissolved oxygen tolerance

Juvenile prawns that inhabit estuarine areas may be exposed to a reduction in dissolved oxygen due to climate warming (see Module-4). Unfortunately, there are no studies of O_2 tolerance in NSW prawn species; however, studies on other prawn species have shown that these can survive low oxygen conditions of 2 ppm and even total anoxia for 6 hours.[240,241] In an experimental study the prawn *Palaemon elegans* showed a behavioural response to oxygen depletion, swimming to the surface and using its pleopods to oxygenate the water, surviving total anoxia.[240] Despite the capability of prawns to migrate out of low water oxygen levels, prawns, like other aerobic organisms cannot survive in hypoxic areas for long periods.

Various behavioral responses enable prawns to tolerate short duration low oxygen events. However, these responses are ineffectual for longer duration events.

2.8 Estuarine finfish

The NSW General Estuary Fishery is valued at about 25 million AUD per year, and most of this production comes from finfish.[176] Additionally, recreational fishing of estuarine finfish is extremely valuable to NSW coastal communities.

Fish are highly mobile species which can migrate if conditions reach levels close to physiological thresholds; however, these shifts in distribution can also have a strong impact on community structure, especially at temperate latitudes.[242]

Temperature tolerance

In general, thermal tolerance in fish is extremely variable among species, and geographical distribution is closely related to their physiological limits.[243] Most NSW estuarine fish species of commercial importance have broad latitudinal distributions. Indigenous species like *Mugil cephalus* (sea mullet), *Acanthopagrus butcheri* (black bream), *Girella tricuspidata* (luderick) and *Argyrosomus japonicus* (Mulloway) are distributed from tropical and sub-tropical Queensland to the south of Tasmania, tolerating monthly mean SST between 10.2 to around 30.3°C.[15,18,19] Additionally, freshwater species that use estuaries as nursery grounds, such as *Macquaria novemaculeata* (Australia Bass), are broadly distributed between south Victoria to sub-tropical Queensland, tolerating monthly mean SST between 11.8 to 27.9°C.[15,18,19] Despite similarities in their latitudinal distributions, there are differences in optimal thermal requirements among species. For example, Payne et al. (2016)[243] found that adults of *A. japonicus* grow optimally at 22.6°C and stop growing at an upper thermal threshold of 27.5°C, while *G. tricuspidata* have a significantly lower optimal temperature for growth of 19.3°C and an upper thermal threshold of 25.4°C. More noticeable is the differences between the early development of *M. cephalus* and *M. novemaculeata*. Both species use estuaries as nursery grounds but *M. cephalus* is mainly marine and has thermal thresholds between 14 to 30°C,[244,245] while *M. novemaculeata* lives mostly in freshwater and has a thermal limit between 8 to 24°C.[246,247]

There are also differences between geographically distant populations, for example, the optimal thermal condition for *A. japonicus* populations in South Africa was around 25.5°C,[248,249] notably higher than the optimal found for NSW populations around 22.6°C.[243] Acclimation time and temperature have a strong effect on thermal tolerances of estuarine fish. Although studies are lacking in NSW species, Rajaguru (2002)[250] compared seven estuarine species in India finding that acclimation can affect thermal maxima by 4 to 5°C. Understanding the consequences of latitudinal shifts on NSW estuarine fish species requires local studies.[251]

> Overall, finfish tolerance to thermal conditions varies among species and populations. Their high mobility makes it difficult to assess the direct impact of regional warming. However, changes in the NSW estuarine fish community are likely due to potential migrations of species from lower latitudes.

Salinity tolerance

Salinity is the main factor defining the distribution of fish species within an estuary.[252] Salinity tolerances vary markedly among species and, within species, among life-history stages. For example, the cosmopolitan species *M. cephalus* is a marine species which uses estuaries as nursery grounds.[253] Eggs of this species fertilize and start developing optimally at salinities between 26 to 35 PSU, with a minimum salinity of around 14 PSU.[18,19,254] Post-larvae and juveniles of *M. cephalus,* by contrast, inhabit low salinity areas within the estuary,[253] developing optimally at salinities around 17.5 PSU but tolerating a broad range of conditions from freshwater to 35 PSU.[255] Adults of this species are mainly marine and can survive acute exposure to salinities several times higher than seawater around 126 PSU and chronic exposure to salinities up to 50.3 PSU.[256]

Species that live mainly within estuaries like *A. butcheri* and *A. japonicus* have broad salinity tolerances, During very early development *A. butcheri* display greater survivorship at 35 PSU and cannot survive salinities below 10 PSU,[257] while *A. japonicus* larvae display optimal development at salinities between 5 to 12.5 PSU.[258] Juveniles of *A. japonicus* also inhabit low salinity conditions between 5 to 17.5 PSU; however, juveniles of *A. butcheri* can tolerate a broader range of salinities from freshwater to 60 PSU.[259] Like many other marine species, adults of *A. butcheri* can survive at higher salinities, up to 86 PSU.[260,261]

Several freshwater fish species also use estuaries as nursery grounds. The most common in NSW is *M. novemaculeata*, Larvae of this species need salinities higher than 8 PSU for development and can tolerate fully marine conditions.[246,262] However, adults of this species have never been recorded spawning in estuarine areas with salinities higher than 14 PSU, which suggest that this salinity is close to their upper threshold.[262]

> In general, estuarine fish are tolerant to a wide range of salinities, however, the level of tolerance varies notably among species and life stages and, changes in salinity are likely to have a substantial effect on the structure of the fish community.

Sea level rise responses

SLR will modify salinity gradients within estuaries, but its direct impact on the fish community is difficult to assess. Impacts could arise as a consequence of loss of biogenic nursery habitats (i.e. seagrass, saltmarsh); however, these changes will depend on the geomorphology and level of urban development of each estuary.[251]

The impact of SLR on finfish communities is difficult to determine and will depend mainly on the geomorphological characteristics of each estuarine location.

CO_2 increase and ocean acidification responses

Fish are considered highly resilient to pCO_2 increases and ocean acidification due to their ability to regulate their internal acid-base balance.[180,263] The high metabolic cost of maintaining that base-acid balance may, however, produce non-lethal consequences of acidification, including behavioral changes, growth reduction and sensorial impairment, among others.[264] Although adult life history stages are relatively resilient to acidification, early life stages display enhanced mortality at elevated pCO_2.[263] The only study on a NSW estuarine fish species found that *A. japonicus* larvae died after 26 days exposure to a pCO_2 of 910µatm, which is the level predicted for 2100.[265]

Although, compared with other estuarine organisms, fish are highly tolerant to ocean acidification, these species eventually will be severely impacted by chronic exposure to high pCO_2 levels.

Dissolved oxygen tolerance

Perhaps the most critical factor for fish survival is dissolved oxygen; most fish species are highly sensitive to a reduction in dissolved oxygen especially during the early life stages. A moderate decrease of about 50 % (around 4 ppm) of dissolved oxygen is lethal for eggs and early larvae of species like *M. cephalus* and *A. butcheri*.[244,266] High mortality of *A. butcheri* larvae was recorded in the Hopkins River when dissolved oxygen reached levels around 40 % (3.5 ppm).[267] Adults of *A. japonicus* reached lethal oxygen limits at 1.9 ppm.[268] This oxygen level is considered hypoxic (around 2 ppm) and is lethal for most aquatic species.

Fish are highly mobile organisms that can migrate from areas with low oxygen; however, in enclosed estuaries reduction in dissolved oxygen can result in high mortalities of estuarine fish populations.

Drone image of saltmarsh in the Hunter River Wetlands, Newcastle, NSW; photo: Chris Drummond, WRL, UNSW

Changes in salinity are likely to result in altered saltmarsh species composition, benefiting some species and negatively affecting others depending on their salinity tolerances and competitive abilities.

2.9 Coastal freshwater ecosystems

This module includes a brief review of freshwater species common in coastal environments which are likely to be impacted by changes in estuarine ecosystems.

Temperature tolerance

Coastal freshwater bodies in NSW are dominated by macrophytes with broad latitudinal distributions. The four most common species *Aldrovanda vesiculosa*, *Lemna minor*, *Myriophyllum propinguum* and *Potamogeton pectinatus* are distributed from Tasmania to the Northern Territory at temperatures of 2.2 to 31.7 °C.[15,18,19] There is also the invasive species *Hydrilla verticillate* which is impacting several freshwater ecosystems around the world. This species has a lower thermal limit around 14°C, but with increased temperatures it is likely to spread further poleward.[269-271] Important endemic invertebrates like freshwater mussels *Alathyria jacksoni*, *Hyridella australis*, *Hyridella depressa*, *Hyridella drapeta* and *Velesunio ambiguus* are restricted to temperate waters, inhabiting environments of 4.6 to 30.5°C.[15,18,19,272,273] These endangered species are extremely susceptible to increasing temperatures because poleward migration in freshwater species is limited in Australia.

On the other hand, the endemic freshwater crayfish *Cherax cuspidatus* and *Cherax destructor* are less tolerant to low temperatures, with lower thermal limits around 15°C, but can tolerate water temperatures up to 34°C.[274-276] Similar thermal thresholds are exhibited by important NSW freshwater fish species like *Bidyanus bidyanus* (silver perch), *Maccullochella peelii* (Murray cod) and *Macquaria ambigua* (golden perch) with thermal tolerances of 12 to 35 °C.[277-280]

> Rising temperatures increases are unlikely to negatively impact freshwater crustaceans and fish may even increase growth rates.

Salinity tolerance and sea level rise responses

Without a doubt, increased salinity due to higher evaporation rates and saltwater intrusion as a result of SLR is the chief hazard for coastal freshwater ecosystems. Freshwater organisms are highly sensitive to salinity levels; all the NSW freshwater macrophyte species reviewed in this module, *A. vesiculosa*, *L. minor*, *M. propinguum*, *P. pectinatus* and *H. drapeta*, inhabit zones with maximum salinities around 7 PSU and lethal thresholds at salinities between 10 to 15 PSU.[269,281-283] Freshwater mussels are even more sensitive; these species live only under freshwater conditions, and salinities over 6 PSU are lethal for all species.[272,273,284] On the other hand, NSW freshwater crayfish *C. cuspidatus* and *C. destructor* can tolerate short periods of exposure to relatively high salinities between 23 to 29 PSU.[275,285] However, these species attempt to leave the water when salinities increase above 12 PSU.[285] In fish species, salinity tolerance varies among life stages; for example, *B. bidyanus* larvae cannot survive at salinities above 9 PSU,[278, 286-288] however, juveniles can tolerate salinities of 15 PSU[278, 288, 289] and up to 20 PSU after slow acclimation.[157] *M. ambigua* is slightly more tolerant to higher salinities, with larvae surviving salinities up to 12 PSU and juveniles tolerating salinities of 23.9 PSU.[288]

> Freshwater organisms, in general, cannot tolerate salinities above 14 PSU and seawater transgression due to SLR will be lethal for all species unable to migrate upstream. Even for highly mobile species like crustaceans and fish, increasing salinities in estuaries with natural or artificial barriers for upstream migration will result in high mortalities.

CO_2 increase and water acidification responses:

In contrast with ocean acidification due to pCO_2 increase, this phenomenon has been poorly studied in freshwater ecosystems. The reason behind this is the complexity in parameters affecting pCO_2 in freshwater systems.[290] Levels of pCO_2 vary greatly among geographical locations, seasons, water body sizes, and several other factors.[290-292] However, recent studies have shown that like oceans, and despite their complexity, freshwater ecosystems will experience acidification due to increasing atmospheric pCO_2 and this effect will be significantly stronger than that resulting from other sources like acid rain.[291,292]

In general, freshwater organisms are expected to be highly adaptable to changes in water pH and pCO_2 due to the high natural variability to which they are exposed. However, some studies have shown that relatively small reductions in pH (0.5 units) can impair the olfactory capabilities and predator avoidance behavior of several freshwater fish and crustaceans.[9]

Dissolved oxygen tolerance

Decreases in dissolved oxygen related to climate change are expected to strongly affect closed or semi-closed freshwater bodies like lakes and lagoons. There are several studies on the dissolved oxygen requirements for freshwater crayfish and fish of NSW. In general, all the species listed in this section are highly tolerant to low levels of oxygen above 1 or 1.5 ppm. However, long-term exposure to hypoxic conditions eventually becomes lethal for most aquatic animal species. The survival of these species will depend mostly on the capability for migrating out of low oxygen areas.

Despite the high tolerance of freshwater species to hypoxic conditions, long-term exposure will result in high mortalities for population unable to migrate.

Saltmarsh in the Avalon Coastal Reserve, Port Phillips Bay, Victoria, Photo: Valentin Heimhuber, WRL, UNSW

3 Conclusions

The sensitivity of estuarine ecological communities to climate stressors is highly variable among species. Determining the species composition of an estuary and understanding the specific ecological responses of the key species is paramount to an accurate estimation of the potential climate change risk. Here, we have presented a comprehensive review of physiological thresholds and probable ecological responses for several key estuarine species common in NSW. This document can be used as a starting point for the creation of a common baseline for assessing NSW estuarine communities' sensitivity to climate change.

However, most studies reviewed by this module do not consider how inter-species interactions and multi-stressor effects may modify the outcomes of climate change stressors. Interactions such as predation, competition and facilitation may, in some instances, serve to exacerbate and in other instances dampen the effects of climate stressors. Because stressors may have additive, synergistic or antagonistic effects that are not easily predictable from single stressor studies, consideration of how climate change associated, and other anthropogenic pressures interact to influence the growth, survival and reproduction of estuarine organisms is critical to the prediction of impacts. Key synergistic interactions between climate change and other anthropogenic stressors are touched upon in Module-5.

There are significant knowledge gaps regarding the sensitivity of several estuarine species to major climate stressors. For example, experimental data on critical temperature limits for most plant species are rare and thermal tolerances must be derived from latitudinal limits or regional distributions. Furthermore, only a handful of species, have data available on both acute and chronic exposure to climate stressors making inter-specific analyses extremely challenging. Most experimental studies on organismal tolerances come from aquaculture trials, which are mainly focused on finding optimal environmental conditions rather than actual physiological thresholds and are conducted under artificial rather than natural conditions. Additionally, the impact of some significant stressors is highly understudied. For instance for pCO_2 and ocean acidification, studies are primarily limited to calcified organisms. Other data gaps include the effects of SLR on subtidal communities and the impact of low dissolved oxygen on plant species.

Given that meaningful climate change risk assessments require quantitative ecological data, there is need to expand on current knowledge of the environmental tolerances of NSW estuarine species and the impact of climate change stressors on their ecological interactions. With this module and the Eco-threshold database (see link in the introduction) we provide a starting point for conducting a 'whole-of-ecosystem' climate change risk assessment, to be updated and built upon as additional studies become available.

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Back cover photo

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Drone view of the Belongil Creek ICOLL entrance, Byron Bay, NSW; Photo: Chris Drummond, WRL, UNSW