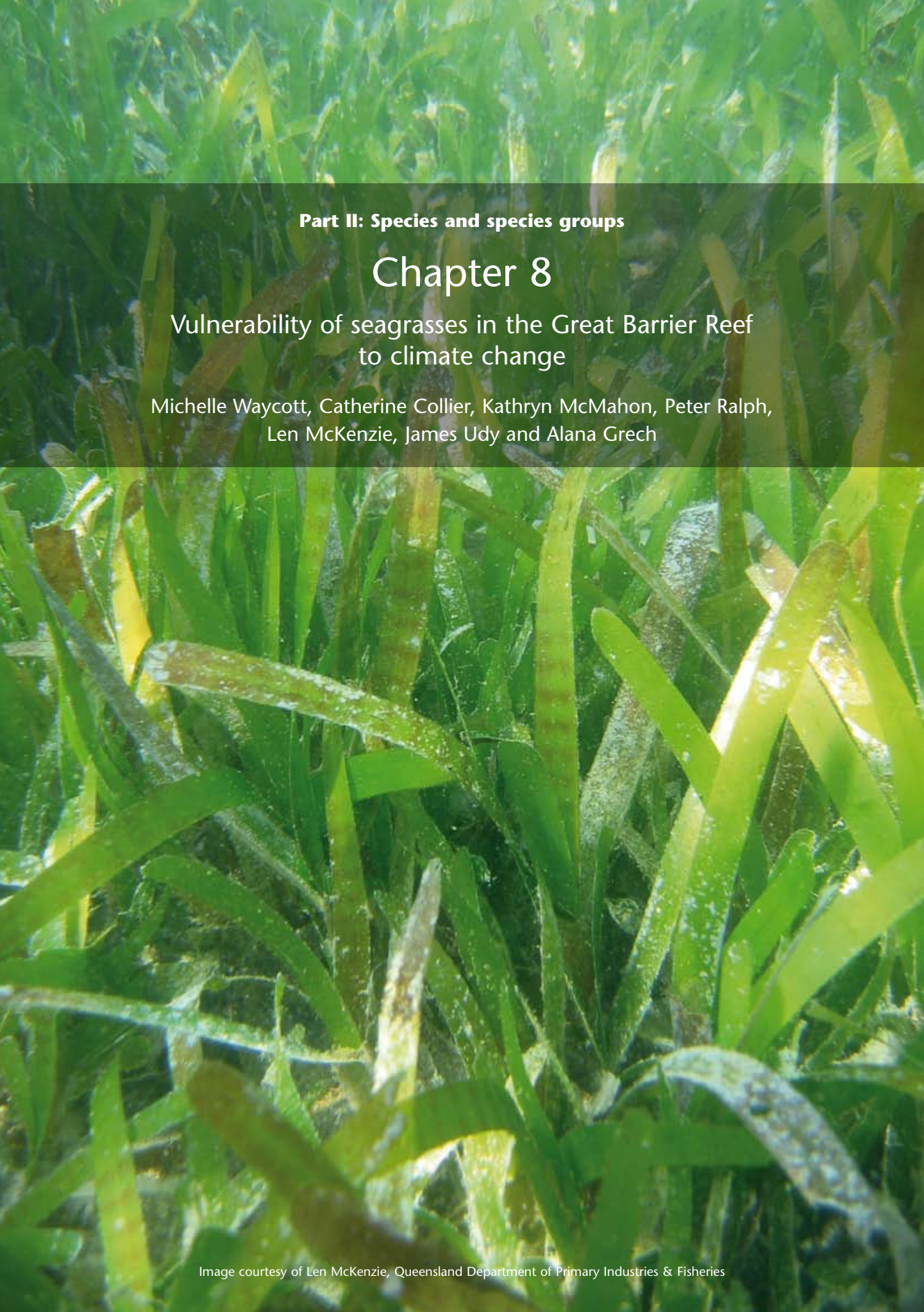


Part II: Species and species groups

Chapter 8

Vulnerability of seagrasses in the Great Barrier Reef to climate change

Michelle Waycott, Catherine Collier, Kathryn McMahon, Peter Ralph, Len McKenzie, James Udy and Alana Grech

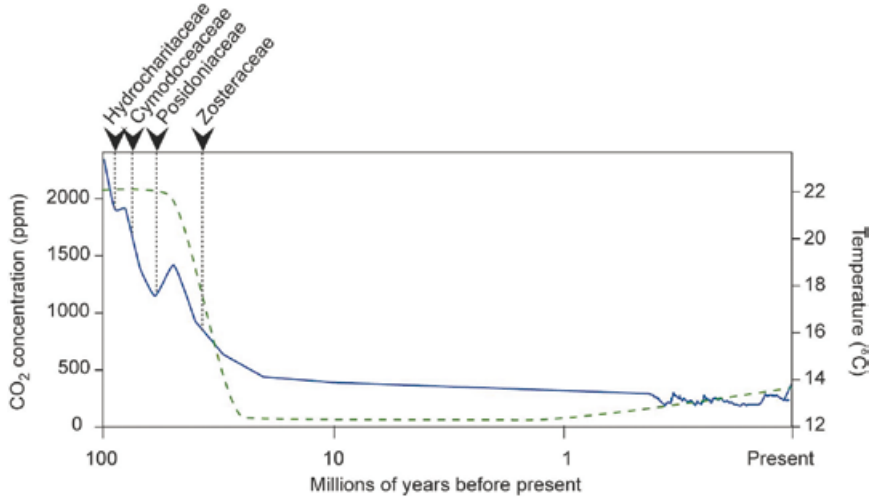
Image courtesy of Len McKenzie, Queensland Department of Primary Industries & Fisheries

8.1 Introduction

Seagrasses are flowering plants and, along with mangroves, have greater affinities to terrestrial plants than other marine macrophytes such as algae. Approximately 55 species of seagrass occur in five different plant families and represent at least three independent evolutionary lineages[85,149]. Thus, seagrasses are not a taxonomically unified group but a 'biological' or 'ecological' group[85,149]. The evolutionary adaptations required for survival in the marine environment have led to convergence in morphology[149]. Seagrasses evolved under differing ambient CO_2 and temperature conditions (Figure 8.1) so may have different tolerances to changing environmental conditions. A wide range of tolerances across marine environments exist amongst the extant diversity of seagrasses, reflecting their substantial adaptive capacity as a group.

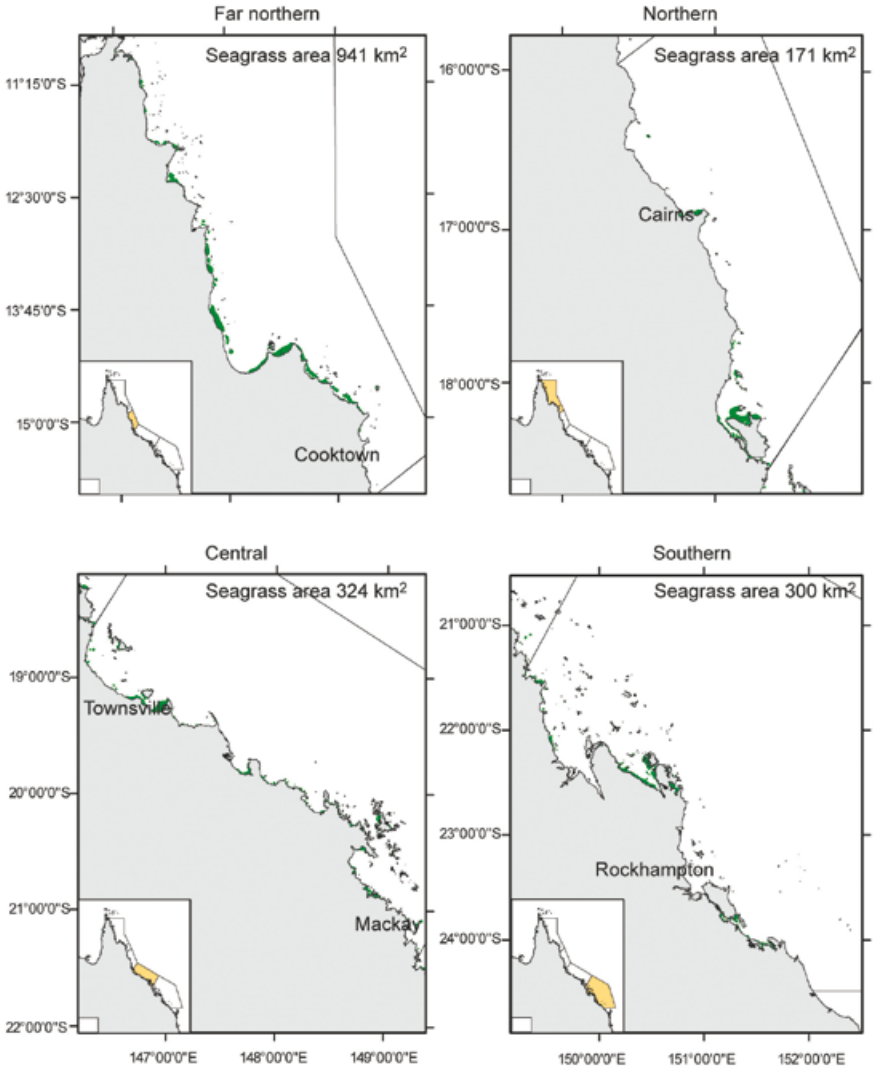
Seagrass diversity in Australia is amongst the highest in the world, in part due to the overlap of already diverse tropical and temperate floras[141,31]. The bays, estuaries, lagoons and reef platforms of the Great Barrier Reef (GBR) region provide habitat for 12 seagrasses including one endemic species, *Halophila tricostata*. The seagrasses of this region are typically found growing in waters less than ten metres below mean sea level. However, some species of the genus *Halophila* can be found to depths of 56 metres[82,25]. Shallow and intertidal seagrass meadows are influenced by coastal topography and shelter, as a result, most larger seagrass meadows are found in north facing bays and estuaries that are protected from the dominant south-easterly winds. The highest densities of seagrass occur between Princess Charlotte Bay and Cairns (13.5 to 17 °S) and below Rockhampton (23 °S). Seagrass meadows are sparse north of Princess Charlotte Bay and south of Mackay in the area where tidal velocities are high. The total area of seagrass habitat along the Queensland coast has remained relatively stable during the past 5 to 10 years.

Figure 8.1 *Timeline of seagrass evolution showing the current estimated time of origin of major seagrass lineages, estimated and measured atmospheric CO_2 concentration (solid line) and mean global ambient temperature (dashed line) (adapted from Orth et al. 2006)*



The mapped area of seagrass is approximately 1741 km² (Figure 8.2), while best estimates of total area of seagrass meadows along the east coast are 5668 km² of intertidal and shallow subtidal habitat (down to 15 metres water depth)[66,4,83,84,91,26,27,28,29,30,92,93] (Queensland Department of Primary Industries and Fisheries unpublished data) (Figure 8.2). The area of seagrass meadows in reef lagoon waters of the GBR deeper than 15 metres may be as high as 40,000 km² [25], however these seagrasses are little studied. We present the seagrass areas of the GBR in four regions to facilitate discussion regarding the different general environments seagrass occur.

Figure 8.2 *Four regions of the GBR with total mapped seagrass distributions plotted (green). Calculated area of mapped seagrass within each zone is nominated. Data is sourced from all mapping studies available and integrated over time (1981 to 2004)*



As productive coastal habitats that typically connect terrestrial, estuarine, saltmarsh and mangrove habitats, seagrass communities are recognised as having a high value globally (reviewed in Orth et al.[109]). Seagrasses act as the foundation of a diverse community with numerous ecological roles; primary production, habitat for other species of plants and animals, food for micro, meso and mega herbivores (including turtles and dugongs), sediment stabilisation, biochemical modification of their local environment and hydrodynamic modifiers. Another highly valued ecosystem service is their role in nutrient cycling[35].

Tropical seagrass meadows have been documented to create habitat complexity compared with unvegetated areas – providing up to 27 times more habitable substrate[115] – as well as providing refuge and food for a range of animals. At least 20 species of prawns (mostly commercially important juveniles) can be found in seagrasses of the GBR in densities eight times that of adjacent bare areas[23,80,24]. Seagrass meadows are also crucial habitat for at least 134 species of fish, predominantly gobies, leatherjackets, pony fish and trumpeters[23,80,24].

In the GBR, the abundance of fauna occupying seagrass meadows correlates strongly with seagrass biomass or living space (leaf area)[103,61,74]. The fish and prawns occupying these seagrass meadows are predominantly carnivorous, feeding not directly on the seagrass but on a range of fauna occupying the meadows including amphipods, isopods, gastropods and copepods[145,74]. These smaller invertebrates form an important trophic link between seagrasses, epiphytes and the carnivorous fauna[68]. In contrast, as much as 99 percent of dugong and 97 percent of adult green turtle diets consist of seagrass[75] with the remainder comprising invertebrates and algae that are usually, though not always, incidental foods[50,116].

Seagrasses may significantly influence the physical, chemical and biological environments in which they grow by acting as 'ecological engineers'[153]. The roles of different seagrass species in their communities vary depending on their stature and life history. The often sparse meadows typical of the GBR are probably less important for sediment trapping than in other regions due to their smaller size[105,70], often being less than 10 cm in height[22,90,56]. Seagrasses can attain high productivity rates comparable to the highest production occurring in terrestrial ecosystems[64,35], although this is mostly based on information from regions other than the GBR. Known leaf growth rates of coastal seagrasses in the GBR range from 0.3 grams dry weight (DW) per metre squared per day for *Syringodium isoetifolium* to 2.0 grams DW per metre squared per day for *Halodule uninervis*[87,139]. These are well below the global average of 3.8 grams DW per metre squared per day[45], but growth rates can increase significantly following intense grazing by dugongs[117,94]. Some GBR seagrass tissues are often less than two percent nitrogen but in some locations attain extremely high nitrogen concentrations of greater than six percent, becoming a dominant nutrient sink in those areas[106]. Seagrass material typically decomposes rapidly and may contribute to a more rapid cycling of nutrients than adjacent habitats such as mangroves[65].

8.1.1 Seagrass habitats in the Great Barrier Reef

There is a perception that seagrasses inhabit a limited range of environments within the GBR. Compared with Caribbean ecosystems, the GBR has limited areas of year-round, dense, highly visible seagrass meadows, yet the extensive inter-reef[25] and inshore seagrass beds[81] result in a diverse assemblage of seagrass habitats[21] (Figure 8.3). In an undisturbed state, the different habitats would have been characterised by low nutrient concentrations, with seagrass growth being primarily

nitrogen limited[11,139]. It is also probable that some variation in biomass occurs seasonally in response to summer rainfall, tropical storms and cyclones that result in large flows of sediment-laden fresh water. These have the dual impact of reducing available light (temporarily) and increasing the availability of nutrients. Large grazers, eg dugongs (*Dugong dugon*) and green sea turtles (*Chelonia mydas*) are also an important and unique feature in structuring tropical Australian seagrass communities in the region[21,100].

Variation in morphology, ecology and ecosystem functioning of different species leads to structural and ecological differences among seagrass species and their associated communities[144] (Figure 8.4). Carruthers et al.[21] refined this inherent variability into functional groups for tropical habitats of northeast Australia including the GBR. These authors defined four broad categories of seagrass habitat as 'rivers and inlets', 'coastal', 'reef' and 'deep water'; each has one dominant controlling factor. Coastal and reef habitats are further separated into subtidal and intertidal, and key drivers of structure and function in these communities described[21].

The 12 seagrass species that occur in the GBR represent a range of capacities to respond to differing environmental conditions (Figure 8.4). Short lived, structurally small species such as *Halophila* contrast with robust, long-lived, structurally large species such as *Enhalus acoroides*. Growth form of each species has consequences for their recovery strategies and adaptability to disturbances. The smaller,

Figure 8.3 *Seagrass habitats of the GBR. Dominant seagrass species associated with each habitat are indicated*

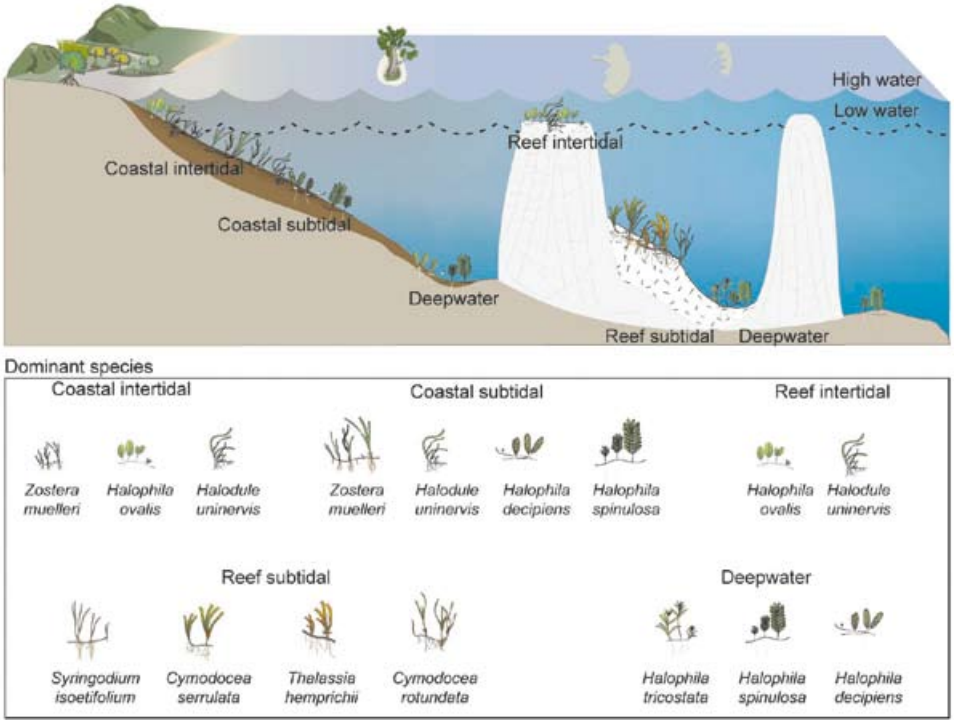
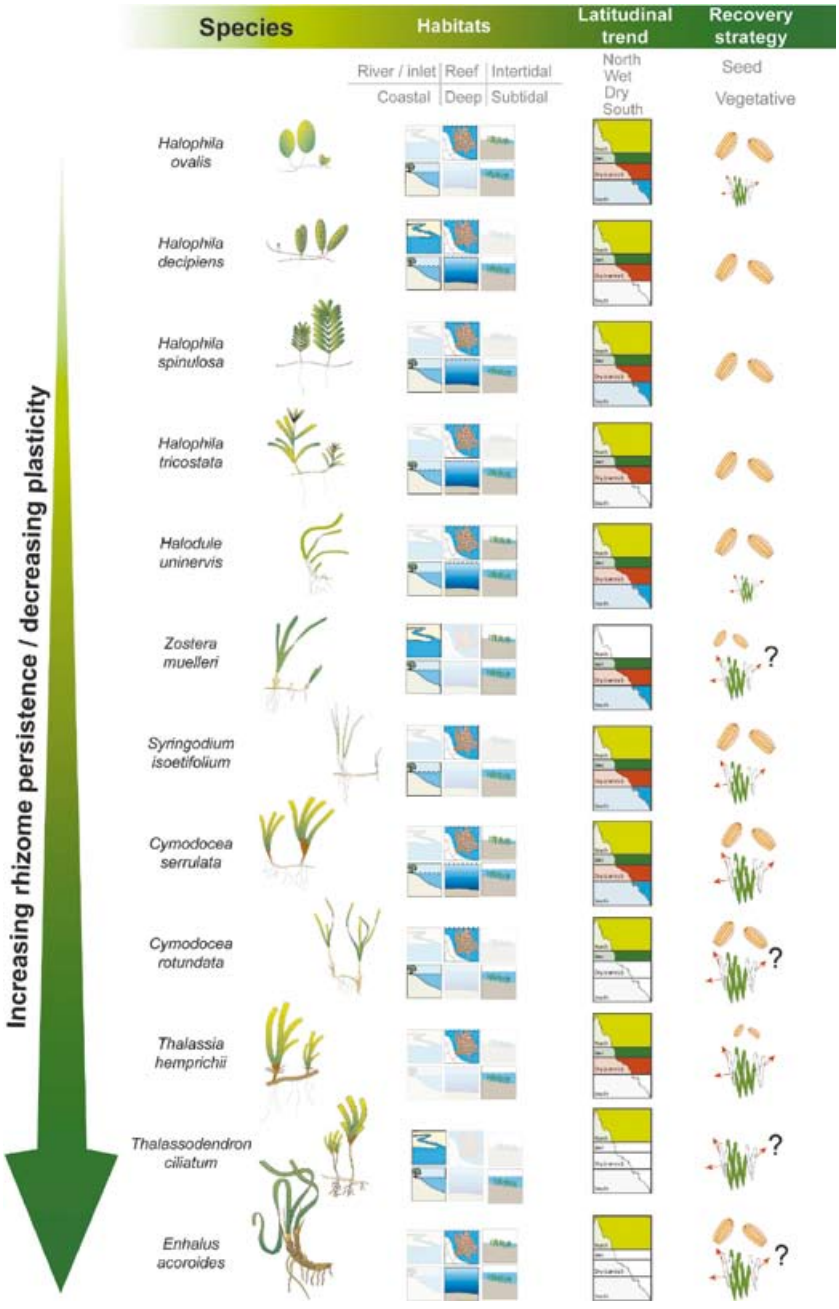


Figure 8.4 *Seagrasses of the GBR, arranged from top to bottom in order of structural size, rhizome persistence and reverse order of morphological plasticity. Habitats and regions where they occur commonly within the GBR region, and their main mechanism of recovery to disturbance are shown using icons named at the top of each column*



faster-growing species may respond to changing conditions more rapidly, and as a result are already dominant in highly disturbed ecosystems such as intertidal and heavily grazed habitats. In contrast, the more persistent species, such as *Enhalus* and *Thalassia*, may take a longer period to be impacted due to enhanced resistance in the short-term but in the longer-term have limited capacity to recover.

8.1.2 Critical factors for seagrass survival

Seagrasses require light, nutrients, carbon dioxide, substrate for anchoring and tolerable salinity, temperature and pH to survive; limitations to these basic requirements result in seagrass loss and lead to declines in ecosystem services. Different seagrasses vary in their specific requirements for these resources reflecting diversity in growth strategies, resource utilisation requirements and as a result adaptability, all of which are important determinants of community composition.

8.1.2.1 Light

Light availability dictates the depth to which seagrasses may grow. Species with the ability to survive on lower levels of incident light, mostly from the genus *Halophila*[147], are those found in deeper water and highly turbid waters. However, as seagrasses generally have high minimum light requirements compared to other marine primary producers, they are particularly sensitive to low light availability[40]. There are numerous cases of seagrass loss associated with the reduction of light, some of the most dramatic examples occurring in Australia[17,54,143,40,132,120].

Light-related seagrass loss can follow several cause-effect pathways. For example, meadow loss can be triggered by rapid and ongoing increases in available nutrients promoting the development of algal growth in the water column or epiphytic algae growing on seagrasses[40]. Both types of algal bloom reduce the amount of light reaching the seagrass plants[17,18,132]. To date, this is a phenomenon more commonly observed in temperate environments.

A phenomenon more common in tropical regions is the ongoing introduction or resuspension of sediments and other particles into the water column, which leads to increased turbidity and reduced light availability[143,118,87]. Experimental assessments of seagrass tolerance to reductions in light availability have revealed species-specific relationships. Structurally small, higher turnover *Halophila* species, common throughout the GBR and Australia-wide in dynamic habitats such as estuaries[147], die rapidly under complete shading after approximately 40 days[88]. In contrast, structurally large seagrasses such as *Posidonia* species (temperate) can survive for extended periods (more than 140 days of shading)[54,32].

8.1.2.2 Nutrients

Seagrass productivity is often nutrient limited or co-limited[45]. As a result, increases in nutrient availability may increase seagrass growth. This has been observed in the GBR[138,102]. For example, the expansion of seagrass meadows around Green Island off Cairns since the 1970s is associated with an increase in nutrient availability and may be a consequence of increased nutrient delivery to the GBR lagoon[139]. While elevated nutrients may enhance seagrass growth, they can also stimulate algal blooms resulting in light limitation[132,120], although stated previously, this has not been observed in the GBR. At present, the relationship between seagrass growth and nutrient availability in the GBR appears to be that of nutrient limitation in outer reef locations to the point where seagrasses are

often absent. However, coastal regions along the GBR have significant terrestrial sediment inputs and seagrasses appear to be only secondarily limited by nutrients, although experimental evidence does indicate enhanced growth under enhanced nutrient concentrations[138,102].

To date no observation of a direct impact of nutrients causing seagrass decline in the GBR has been reported[127]. However, in north-eastern Australia nutrient input rates are often associated with the mobilisation of terrestrial sediments and their subsequent runoff. Based on this, Abal and Dennison[1] predicted that detectable nutrient-related impacts on seagrass meadows might result from higher sediment loads associated with river flood events. This is supported by research on seagrasses in subtropical Moreton Bay that found tissue nutrient content of seagrass close to river mouths were higher than those more distant[138]. These observations suggest that nutrient inputs do influence seagrasses in the GBR, although nutrients *per se* have not been the cause of any declines observed to date.

8.1.2.3 Physical disturbance

Disturbance regimes are particularly important to local seagrass meadow survival and community composition. In tropical Australia grazing by dugongs, which are obligate seagrass feeders, controls the species within a community when grazing pressure is high[117,94]. Sediment movement and fresh water due to flooding during storm and cyclonic events are also known to affect seagrass communities[118,19]. The resilience of seagrass communities to these events will vary greatly depending on community type. For example, species that are structurally smaller and rapidly growing are typically adapted to higher disturbance regimes (eg *Halophila* and *Halodule*), or higher energy environments on rocky substrates (eg *Thalassodendron*)[144]. In contrast, species which occur in lower disturbance environments such as sheltered bays and estuaries are higher biomass, slower colonising seagrasses such as *Thalassia* species. Disturbance can also affect seed bank reserves and long-term adaptability of seagrasses[118,67,148].

8.1.2.4 Salinity, temperature, CO_2 and pH

Typically, seagrasses grow best in salinities of 35 parts per thousand, although they have been observed in salinities from 4 to 65 parts per thousand[62]. It is clear that some seagrasses are more tolerant of wide fluctuations in salinity with the widespread seagrass *Halophila ovalis* being among the most tolerant[38]. Temperature is a critical factor in plant survival, and in the marine environment, also controls the range of pH and dissolved carbon dioxide (CO_2) concentrations in the water column. Temperature-pH-carbon concentration optimums in seagrass are species-specific and partially constrain the current spatial distribution that represents the long-term histories of species[5]. In addition to affecting water column chemical composition, temperature influences the rate of growth and the health of organisms, particularly at the extremes. In the GBR, temperature tolerance experiments suggest upper temperature limits to seagrass survival in this region[20]. Limited research has been conducted into the specific responses of seagrasses to the potential influence of environmental parameters that may affect plant physiological status under climate change impacts[131].

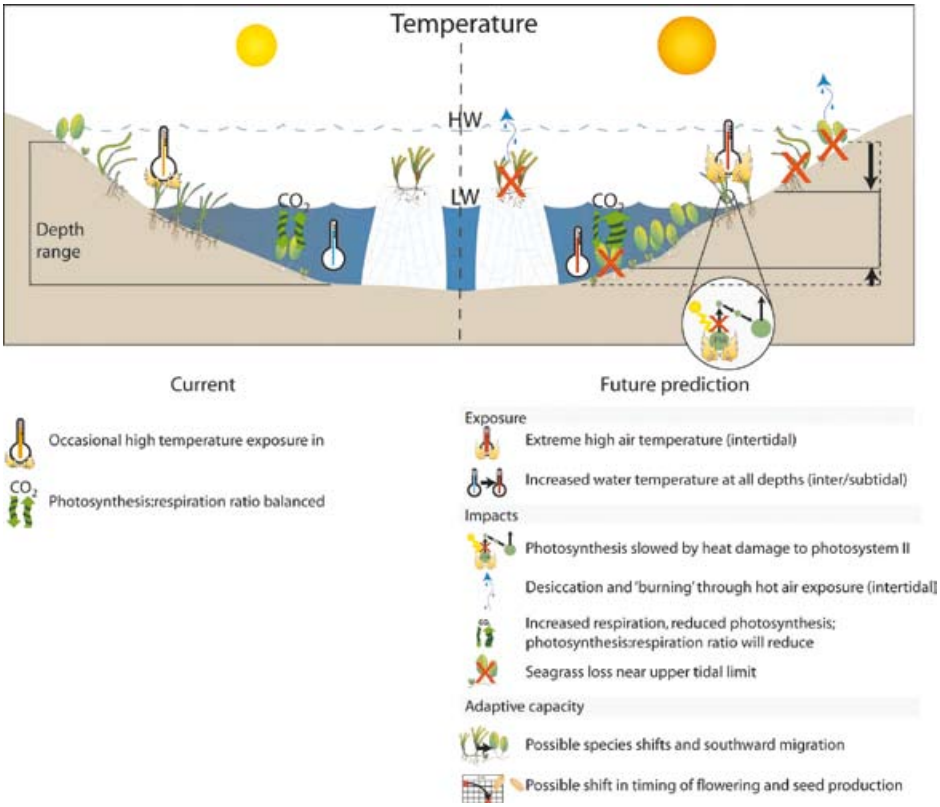
8.2 Vulnerability of seagrasses to climate change

Different species and habitats will vary in their tolerances to climate change and these have been considered in this assessment of their vulnerability. We categorise seagrass community responses to climate change as either changes to seagrass community structure or abundance. Based on the scenarios outlined in this volume, we predict that the greatest impact of climate change on seagrasses will be caused by increases in temperature, particularly in shallower habitats where seagrasses are present. In turn, sea level rise, disturbance regimes, flooding and the other changes will limit the survival capacity of seagrasses throughout the GBR.

8.2.1 Changes in air and sea surface temperature

Current sea surface temperatures in the Great Barrier Reef are warmer than they have been over at least the past 250 years (Lough chapter 2). Climate change scenarios suggest elevated temperature extreme ranges are projected to rise between 1.2°C and 4.1°C by 2100. Within this framework, the impacts of increasing temperature on seagrasses will be particularly significant for coastal intertidal and shallow subtidal seagrasses (Figure 8.5).

Figure 8.5 *Expected impacts of increased sea surface and air temperature on seagrasses based on climate change predictions for the GBR*



8.2.1.1 Exposure – temperature

All seagrass habitats will be affected by elevated sea temperatures. In the relatively shallow waters of the GBR lagoon, the northerly flowing coastal current mixes down to approximately 20 metres, due to persistent south-easterly trade winds[53]. As there is currently no evidence of a persistent thermocline across the GBR lagoon, it can be assumed than in waters shallower than 20 metres, temperature at depth will reflect surface temperature. Seagrass in deeper waters, ie greater than 20 metres, would be impacted to a lesser extent from short-term changes in air and sea temperature due to the buffering effect of water depth.

Intertidal habitats will be the most severely impacted by increases in air temperature as exposure and desiccation are significant factors limiting the upper distributional limits of seagrass meadows. In shallow pools seagrasses are exposed to desiccation during low tidal periods due to exposure to air, high incident solar radiation and increased salinities due to higher evaporation rates[37,47].

8.2.1.2 Sensitivity – temperature

Water temperature is a major factor controlling seagrass photosynthesis and elevated temperatures generally increase photosynthesis in tropical species over a wide range of temperatures[110,133]. The thermal tolerance of seagrasses depends on the individual species and their optimum temperature for photosynthesis, respiration and growth. Generalisations on the sensitivity of photosynthesis to temperature increases can be drawn from terrestrial plants. As temperatures increase (up to an estimated 38°C based on land plants) the rate of photorespiration increases reducing the efficiency of photosynthesis at a given CO_2 concentration. The cause of thermal stress at higher but moderate temperatures (38 to 42°C) is the disruption of electron transport activity via inactivation of the oxygen producing enzymes of photosystem II[126]. Above these temperatures many proteins are simply destroyed in most plants.

Experimental studies on tropical seagrasses demonstrated that the sensitivity of photosynthesis is species specific as *Cymodocea rotundata*, *Cymodocea serrulata*, *Halodule uninervis* and *Thalassia hemprichii* are more tolerant to short term (1 to 4 hour) exposures of thermal stress (35 to 45°C) than *Halophila ovalis*, *Zostera muelleri* (syn. *capricorni*) and *Syringodium isoetifolium*[20]. Where mean sea surface temperature increases up to 2°C we predict a significant impact on species of seagrass that survive at the upper limit of their thermal tolerance[119]. Fong and Harwell[52] suggested that the productivity of tropical seagrass species starts to decline above 30°C. Thorhaug et al.[134] reported that at temperatures elevated 3 to 4°C above ambient, *Thalassia testudinum* showed evidence of reduced standing crop and productivity, and that tropical plants were more tolerant than subtropical plants to elevated temperature. However, some species (eg *Halophila ovalis*) with a wide geographical range have a broad temperature tolerance[119]. However, tolerance of tropical seagrass species to sustained periods of high temperature exposure is largely unstudied.

The sensitivity of seagrass to elevated temperature will also be related to their ability to cope with other impacts. For example, light requirements for carbon production are greater at higher temperatures because of increased compensation irradiance (eg Bulthuis[16]). So species that can tolerate a wider range of light levels, in particular lower levels, would be less sensitive to the impact of increasing temperature on productivity. In addition, as water temperature increases the solubility of gases such as CO_2 decreases, a disadvantage for species that are dependent on CO_2, although this may be offset

by decreasing pH associated with elevated absorbed CO_2 concentrations. Other plant growth factors subject to temperature regulation, including enzyme-mediated processes such as nutrient uptake, are expected to differ between species but remain unstudied.

8.2.1.3 Impacts – temperature

The main impact of elevated sea temperature on seagrasses will be the change in growth rates and general physiological processes of the plants themselves (Figure 8.5). Seawater temperature directly affects seagrass metabolism and the maintenance of a positive carbon balance described above[51,16,155]. These factors influence the seasonal and geographic patterns of species abundance and distribution[17,63,97,119]. At a broad scale, the distribution of seagrass species in the GBR is expected to shift south. For example, species more prevalent in tropical and equatorial waters north of the GBR (eg *Enhalus acoroides* and *Thalassodendron ciliatum*) could expand south. The scale and rate of such change is uncertain as water currents and delivery of suitable recruits via seeds, plant fragments, and other propagules is an important determinant.

Elevated temperatures may also influence the growth of deep water seagrasses although the mechanism and scale of impact is unknown. *Halophila ovalis* has a broad water temperature tolerance and deep water (greater than 15 metres) plants have been found adjacent to submarine hot springs (28.6°C) in the northern hemisphere[73]. Although localised adaptations acquired over evolutionary time scales, exposure to these conditions may explain the wide tolerances observed. The presence of *Halophila tricostata*, an ephemeral deep water seagrass endemic to Queensland, correlates with warmer sea temperatures possibly due to the requirement for greater than 26°C water temperature to affect germination[72]. *Halophila tricostata* may have a broader distribution with increasing water temperatures.

High air and water temperatures and desiccation through direct exposure to air are probably the most important factors limiting upper intertidal distribution of seagrasses. Recent *in situ* monitoring of tropical intertidal seagrass canopy seawater temperatures[a] reported seagrass 'burning' when temperatures up to 10°C above the seasonal average occurred, especially during low spring tides and midday solar exposure[20]. During these events seagrasses may be exposed to elevated seawater temperatures for periods of 3 to 4 hours. High seawater temperatures and desiccation have negatively affected seagrass meadows in a number of areas worldwide[142,49] with one episode of temperature-related seagrass loss linked to an El Niño event[129].

Intertidal seagrass communities (both coastal and reef) are exposed to a certain level of desiccation during tidal cycles. Typically, desiccation risk will limit the extent of seagrass in the upper intertidal[10]. Periodic leaf burn-off can be associated with the changing lunar cycle which results in different timing of tides. Exposure during the middle of the day in full sun is more damaging than exposure during the middle of the night. As the expected increases in sea and air temperatures occur, so will the frequency of desiccation events due to the higher intensity of exposure. Such an increase in frequency of desiccation events is expected to favour a species composition dominated by *Halodule/Halophila* due to their faster recovery times and smaller stature limiting their exposure during low tide.

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Increased temperature may also alter seagrass distribution and abundance through direct effects on flowering[96,48] and seed germination[58,111]. Temperature plays an important role in flower development, flowering induction and controlling the flowering process[2]. For example, the initiation of flowering in *Zostera* is related to a rapid rise in ambient temperature, from the annual low, and associated increase in day length[89]. Similarly, anthesis (the opening of flowers) has been observed in southern Queensland during late spring/early summer before temperatures reach their summer peak[34,90,122].

The impact of elevated temperature on seagrass sexual reproduction and flowering is unclear. Some species may increase the duration of their flowering period, while for other species the initiation of flowering may be altered. *Halophila ovalis*, possibly the most ubiquitous seagrass species in the GBR, flowers throughout the year with ambient temperature between 15 and 27°C (peak flowering 23 to 26°C in Moreton Bay)[94]. Changes in temperature may have a negligible effect on this unusually tolerant species. However, the environmental factors that initiate sexual reproduction remain unexplored, and for most species, changes in temperature are expected to exert a significant effect on flowering.

8.2.1.4 Adaptive capacity – temperature

Seagrasses that persist in coastal and reef intertidal habitats of the GBR are adapted to a wide range of environmental extremes. Seagrass communities that dominate along the northern intertidal coastal fringe of the GBR, are generally comprised of species that are adapted to tolerating extremes in temperature (eg *Halodule uninervis* and *Thalassia hemprichii*), or alternatively have the ability to recolonise after an extreme event (eg *Halophila ovalis*). This is in contrast to communities that dominate the southern intertidal coastal fringe of the GBR, which are generally composed of more persistent and stable species such as *Zostera muelleri* and it is unlikely that species such as these will be able to successfully adapt. Elevated sea surface and air temperature are likely to cause intertidal seagrass communities to contract – the shallow edge will move seaward due to desiccation and elevated temperatures.

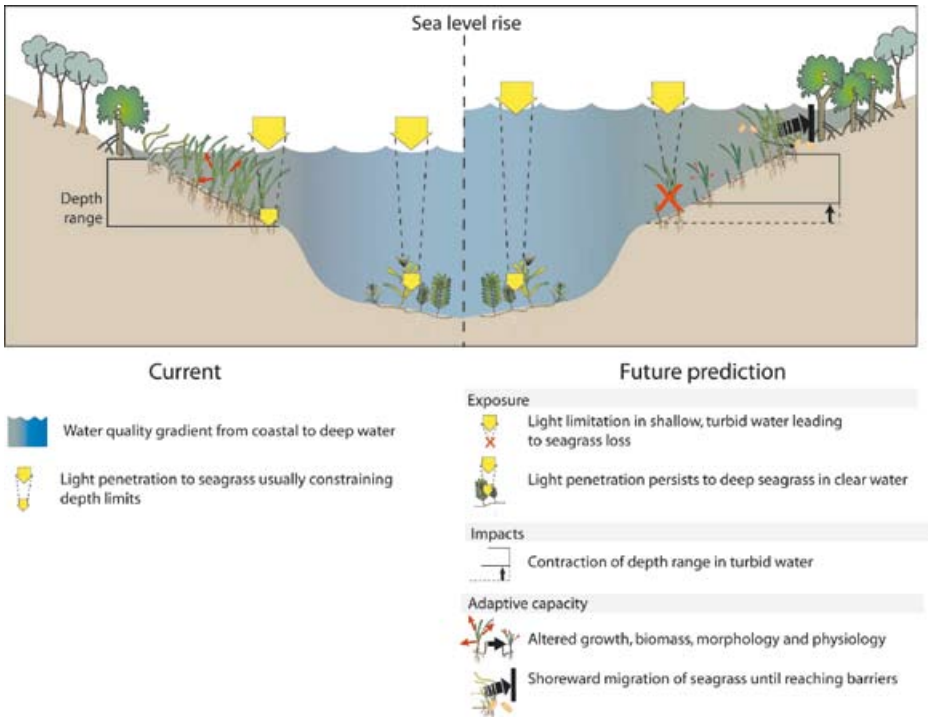
8.2.1.5 Vulnerability and thresholds – temperature

The vulnerability of seagrasses to elevated air and sea temperature will be species dependent, and in some cases may be significant. At present the inherent variability of seagrasses responses to changing temperature *in situ* is virtually unmeasured (cf. Thorhaug et al.[134]) making the identification of thresholds vague. However, it is expected an elevated temperature of 5°C, even if experienced for just a few hours during low tide, will result in significant loss of seagrass in shallow or intertidal seagrass meadows. Vulnerability may be further exacerbated by other indirect temperature associated impacts such as increased algal epiphyte growth and the intensity of extreme weather events, which will be discussed in following sections.

8.2.2 Sea level rise and coastal inundation

Seagrass distribution is usually limited by light penetration. Sea level is predicted to rise between 10 and 90 centimetres within the next century. This increased water depth will further attenuate light penetration to seagrass (Figure 8.6). The process of sea level rise will have an additional impact of inundating massive tracts of coastal land. The degree to which the coastline is regressed will depend

Figure 8.6 *Expected impacts on seagrasses from sea level rise based on climate change predictions for the GBR*



upon the local topography, however as a rule of thumb it has been estimated to be up to ten times the vertical change in sea level, so it is possible to have 10 metres horizontal inundation of the coastal zone[15]. Regression of the coastline will cause erosion of shallow sediments[44] impacting seagrass habitat availability. The hardening of shorelines through coastal development poses a significant risk to seagrass habitat availability as sea levels rise.

8.2.2.1 Exposure – sea level rise

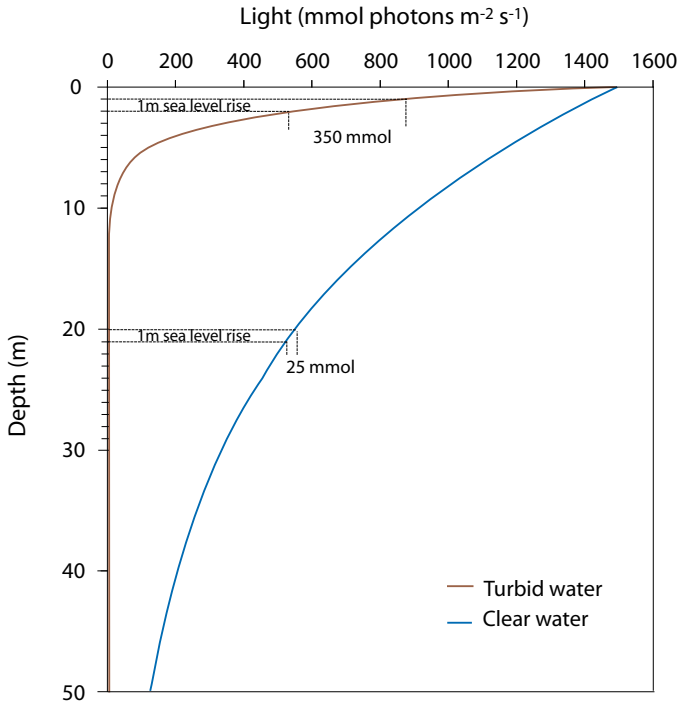
All seagrasses within the GBR will be exposed to changes in sea level and therefore a reduction of light penetration and habitat availability. Topography of the land adjacent to the current shoreline will define the degree of horizontal inundation. The region south of Cooktown has the largest surface area of land one metre above sea level predominantly within river floodplains, while in the northern GBR there will be less inundated land. Inundated areas will be potentially habitable for seagrasses. Furthermore, the lower distribution of current intertidal seagrass meadows will become subtidal and a change in seagrass community composition will follow. One note of caution to this interpretation is that while inundated lands may occur, where substantive mangrove communities, rocky shorelines and coastal developments that create hard surfaces, such as concrete, exist the capacity of seagrasses to colonise will be curtailed.

8.2.2.2 Sensitivity – sea level rise

The sensitivity of seagrasses in the GBR to light reduction from sea level rise is likely to depend on local water quality conditions and the species present. Seagrass depth limits are usually constrained by light availability with the deepest meadows growing at their minimum light requirements[40]. Seagrasses growing at their depth limit will be the most sensitive to sea level rise as increasing water depth reduces light penetration. Assuming minimum light requirements are known for each species of seagrass it would be possible to estimate the spatial extent of impacts of light reduction.

Estimation of impacts of sea level rise also requires knowledge of the light attenuation coefficient, which describes the exponential reduction of light with depth, of clean mid-reef water versus turbid coastal water throughout the GBR. Without this information, it is anticipated that deep seagrasses inhabiting clean water will not be impacted, but those in shallow, highly turbid waters will be heavily impacted. This is due to the small relative change in light availability with depth for the deep water regions, while in shallow, turbid water a small change in depth results in a large change in total light penetration (Figure 8.7). Seagrasses vary in their tolerance to long-term reductions in light availability; *Halophila* species often inhabit a range of high- to low-light regions while *Thalassia* and *Cymodocea* species are often found only in high-light habitats and may be more sensitive to light reductions[21].

Figure 8.7 *Depiction of the impact of light availability with depth to seagrasses for different light penetrations based on a one metre sea level rise*



8.2.2.3 Impacts – sea level rise

There is no experimental data on the impact of sea level rise on seagrass distribution[44]. There has been no documented evidence of seagrass loss due to sea level rise and there have been no experimental manipulations to suggest how rapidly seagrasses could adapt to these conditions. The greatest impact will occur on the deep coastal edge of the meadows where, currently, light availability only just meets minimum light requirements[1] but with elevated sea levels will become limiting to growth. This could result in complete loss of seagrasses at the deeper edge, while for the remainder of the meadow, biomass and growth are likely to reduce as these are known to reduce with increasing depth for many seagrasses[21].

Seagrasses could colonise newly inundated lands; however, inappropriate coastal sediments, rocky shores or other barriers will limit the capacity of seagrasses to colonise. The simplest outcome would be for the meadow to migrate up slope the same distance that the lower edge was lost (no net loss of seagrass habitat or biomass) however we do not believe this is likely in many cases. Species with rapid recruitment capabilities (eg *Halophila, Halodule, Zostera*), however, will occupy new areas more rapidly than slower recruiting species (eg *Thalassia, Cymodocea*)[100,149] and other environmental drivers are likely to influence community composition such as substrate type. Duarte[44] suggested that increased sea level would result in uprooting of seagrass due to shoreline erosion of newly inundated but unstable (and unsuitable) sediments. These losses may be further exacerbated during storm events. The implications of this physical disturbance regime are addressed in section 8.2.3.

8.2.2.4 Adaptive capacity – sea level rise

All seagrasses are capable of responding to light reductions by altering their physiological capacity and morphological structure. However, at the depth limit, the meadows are already at the extreme edge of their light tolerance range and are unlikely to adapt to further light reductions. For shallower seagrasses some response to reduced light availability is certain. This is likely to include reduced growth and biomass but may also include some physiological responses, such as changing carbohydrate utilisation and pigment concentration, or even a change in morphology[87,148] (Figure 8.6).

Seagrasses are well adapted to growing both vertically and horizontally. Given this, seagrasses should be capable of growing up slope as sea level rises. The potential rate of vertical growth of most seagrasses will be greater than the predicted rate of sea level rise. Being flowering plants, seagrasses are also capable of seed production and dispersal. Tropical species typical of the GBR are particularly reliant on sexual reproduction strategies[67]. Intertidal regions are currently inhabited predominantly by *Halophila ovalis, Halodule uninervis* and *Zostera muelleri*. All of these species have been known to rapidly colonise newly available substrate, usually following disturbance[67,19,123,94].

The sediment type of newly inundated shoreward regions will influence the capacity of species to colonise. Amongst the sediment characteristics likely to influence suitability for seagrasses are nutrient status, particle size and redox potential. Physical obstructions to shoreward migration may force an overall contraction of the meadow. In built-up areas where structural features such as rock walls or groynes are in place, shoreward migration will be inhibited. The interaction of seagrasses with other habitats is less well known. For example, it is speculated that sediment accretion within mangroves will enable their current seaward margin to persist (Lovelock and Ellison chapter 9) and this may prevent

habitation of these areas by seagrasses. If inundation penetrates into cane fields this will encroach into substantial areas in the wet tropics region of the GBR. Another often-overlooked aspect of coastal inundation is the addition of nutrients to the marine environment as much of the low-lying land is coastal alluvial flats that have been utilised for agriculture for many years. It is unknown what the scale and impact of these additions may be to coastal marine ecosystems under these altered conditions.

8.2.2.5 Vulnerability and thresholds – sea level rise

Estimating thresholds for complex interactions between light and sea level rise is difficult given that we are only aware of the minimum light requirements for one tropical seagrass species (*Zostera muelleri*). Before estimates can be made, a better understanding of the variation in tropical species light requirements is needed. However, it is certain that some seagrass will be lost near their lower depth limits in turbid coastal waters. The shoreward migration of seagrasses in response to newly inundated areas will probably be at least partially blocked by physical obstructions. Whether this results in an overall gain or loss of seagrass will depend on a number of factors including the relative area of habitat lost at the depth limit versus that gained (potentially a wide margin in some areas) and the suitability of new areas for colonisation. We suggest some 3000 km^2 of potential habitat will become available for seagrasses in the GBR under a one metre sea level rise (NB this is currently an overestimate for 2100 by climate change models). However, we do not know the extent of deep-edge seagrass loss or shallow-edge competition with mangroves and other hard substrates. Modelling of the relative depth limit changes would be required once a greater understanding of species-specific light limitation are available.

8.2.3 Physical disturbance – tropical cyclones and major storms

Less frequent tropical cyclones and major storms are predicted in the next 100 years; however, the number of events in the central and southern GBR may increase. In contrast, the intensity of cyclones and major storms is likely to increase, resulting in events with stronger winds, greater turbulent water motion, lower atmospheric pressure, greater storm surge and greater rainfall. The frequency and intensity of cyclones and major storms is also linked to the El Niño Southern Oscillation (ENSO) cycle, so any changes with this cycle will affect the frequency and intensity of cyclones and major storms.

8.2.3.1 Exposure – physical disturbance

There are four main threats from storms and cyclones that result in physical disturbance: sediment movement (erosion and deposition), turbulent water motion and storm surge. Tropical cyclones and major storms are likely to cause sediment movement within seagrass habitats due to strong winds, creating turbulent water motion. Sediment movement will impact seagrasses through erosion or depositional processes. Compounding these impacts, low atmospheric pressure cyclones and storms may create storm surge and turbulent water motion that will also cause sediment movement[125] and dislodge seagrass.

All seagrass regions in the GBR are likely to be affected by physical disturbance from cyclones and major storms. However, deep water habitats are unlikely to suffer physical disturbance as they are more protected due to the dissipation of energy with water depth[118].

8.2.3.2 Sensitivity – physical disturbance

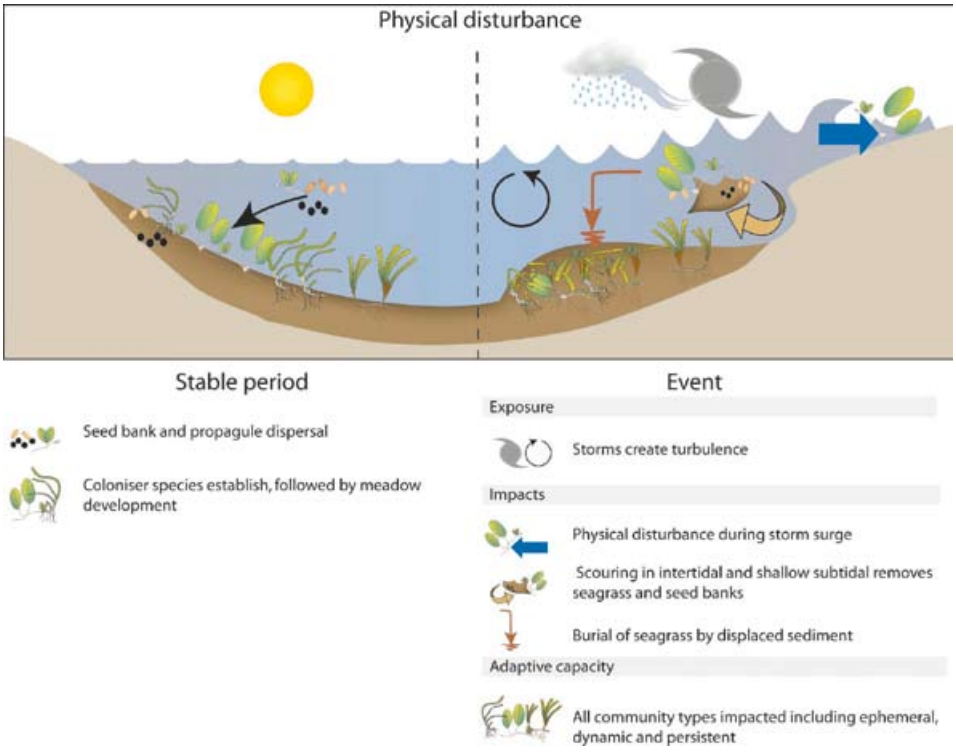
The sensitivity of seagrasses to physical disturbance from cyclone and flood events is dependent on the strength of the wind, energy of the turbulent water motion (sheer stress), atmospheric pressure, storm surge height, direction of cyclone and storm movement and tide position during the event. The location of seagrass, especially depth, will influence their sensitivity. Intertidal and shallow subtidal meadows will be more sensitive due to the greater energy at these shallower depths. Thus the tide height at the time a cyclone or storm passes may determine the area that is impacted. Although deeper habitats (greater than 10 metres) are less sensitive, in some cases seagrass habitats at depths of 23 metres have almost been completely removed by tropical storms in the Caribbean[150].

There is spatial variability in the impact of a cyclone or storm. In some events a meadow may be removed but adjacent meadows remain intact[113]. Similarly, some cyclones may have no impact on the seagrass meadows while others may completely remove meadows[112]. The cause of this variability in meadow response to such disturbances is unknown.

8.2.3.3 Impacts – physical disturbance

The high energy generated from cyclones or storms in Queensland have caused localised sediment movement, and removal of plants[112,113,19], whole meadows[8,113,118,19] and seed banks[114] (Figure 8.8).

Figure 8.8 *Expected disturbance cycle impacts based on climate change predictions for the GBR*



Areas up to 1000 km^2 have been impacted from a single cyclone event[118], though this event included the additive impact of turbidity from flood plumes. Of the four potential physical disturbance threats, the mechanism that will cause the greatest impact from a cyclone or storm event is not known.

8.2.3.4 Adaptive capacity – physical disturbance

In all documented cases of seagrass loss from cyclones and storms in Queensland, there has been recovery[8,113,118,19]. Recolonisation of seagrass to completely denuded areas can take from months to years[113,118,19]. The time to return to the pre-disturbance cover, biomass, or species composition may take from one to ten years after the initial disturbance[8]. When all seagrass plant material (shoots and rhizomes) in the meadow is lost, recovery has been documented via seeds[19]. Dispersal of seeds between meadows has been inferred from population genetic studies and is likely to be an important mechanism for meadow recovery when large-scale disturbance removes entire meadows[94] (Figure 8.8).

Seagrass communities have been defined in this chapter based on their persistence. Species growing in ephemeral and dynamic communities (eg *Halophila* spp., *Halodule uninervis, Syringodium isoetifolium* and *Zostera muelleri*) are better adapted to live in disturbed environments. Therefore, these species are likely to recover faster than other later successional species such as *Cymodocea* spp., *Thalassodendron ciliatum, Thalassia hemprichii,* and *Enhalus acoroides*[8,144]. If the time between successive cyclone and storm disturbance events is not long enough for slower recruiting species to recover, then there may be a shift in species composition in areas that have repeated high intensity disturbance events.

8.2.3.5 Vulnerability and thresholds – physical disturbance

Due to the ability of tropical seagrasses to recover from physical disturbance associated with cyclones and storms we predict a low vulnerability to this exposure threat. However, this prediction does not include interaction with river flood plumes, which deliver another set of threats due to turbid, fresh water that may carry excessive nutrients and toxicants. It is not possible to present thresholds for seagrass persistence to cyclone and storm events.

There is no information for any seagrass species found in Queensland on the energy (sheer stress) or velocity they can withstand, or the energy required to move sediment that may erode or deposit sediments on seagrass resulting in a negative impact. Intertidal seagrasses have been shown to recover from loss in the GBR within two years, taking up to five years to re-establish fully[19,148]. Recovery from dugong grazing can be very rapid, in the period of months[94]. Coastal reef seagrass habitats near Townsville have been observed to recover over a period of five to ten years following loss due to cyclonic impacts[8]. No data is available to estimate recovery times for other habitats and it is unknown what the impact of meadow loss will be locally or regionally on co-habiting species or those that feed upon them.

8.2.4 Rainfall and river flood plumes

Climate change predictions indicate that total rainfall may increase in the southern and northern GBR but may decrease in the central GBR. As a result of changing rainfall patterns, large-scale river flood plumes may occur more often in the central and southern GBR, with no expected change in the northern region. Across all regions flood events are likely to be more extreme, generating plumes

extending further into the GBR lagoon and the impact will be longer lasting. The major impacts of flooding and river flood plumes are expected to be salinity fluctuations (Figure 8.9) and the introduction of sediments (Figure 8.8 for disturbance) and nutrients (Figure 8.10).

8.2.4.1 Exposure – rainfall and river flood plumes

The immediate effects of small-scale rainfall and river flood plumes are that they potentially reduce salinity in shallow water such as intertidal pools (Figure 8.9). Rainfall associated with cyclones and major storms will cause large-scale river flood plumes that influence large areas of habitat in the GBR (Figure 8.11). River plumes transport nutrients, sediment and land sourced toxicants from the catchment to the GBR with larger events generally delivering greater loads[53]. Coastal habitats, both intertidal and subtidal, are, and will continue to be, the most impacted by changes in rainfall and river flood plume activity. Deep water habitats close to river mouths may also be impacted.

Heavy rainfall can directly affect salinity in shallow water such as intertidal pools. A minimum of 11 parts per thousand was recorded in Bolger Bay, Magnetic Island for up to 48 hours during a cyclonic rainfall event (Collins[33] in Birch and Birch[8]). Such a change in salinity is highly likely to have a negative impact on seagrass growth through salinity stress. River flood plumes can be vast – extending for 1000 km along the coast – and can be persistent – lasting for weeks[53]. These low salinity events are likely to impact intertidal seagrass both in coastal and offshore reef habitats (rainfall), and all coastal seagrass habitats (river plumes).

Figure 8.9 *Proposed impact of salinity extremes on seagrasses emphasising changes expected under climate change models*

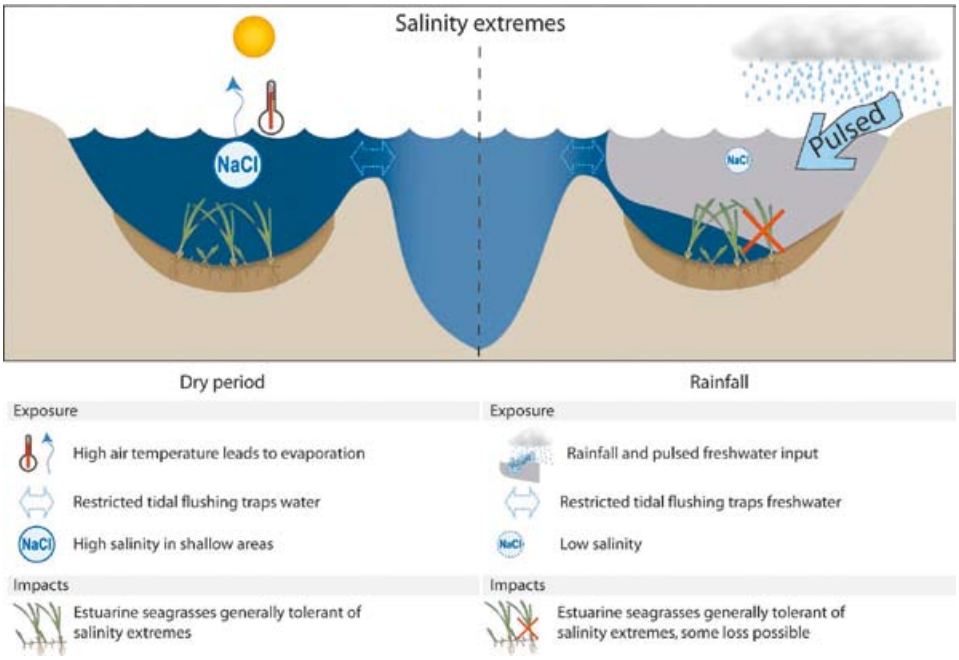
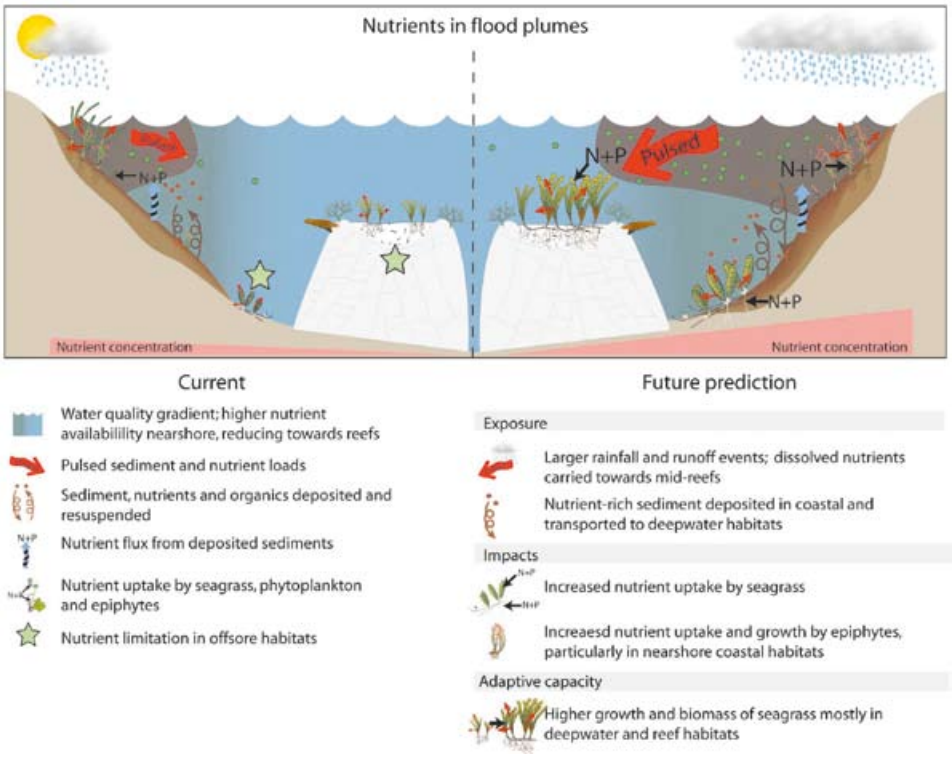


Figure 8.10 *Proposed impact of nutrients deposited by flooding on seagrasses emphasising changes expected under climate change models*

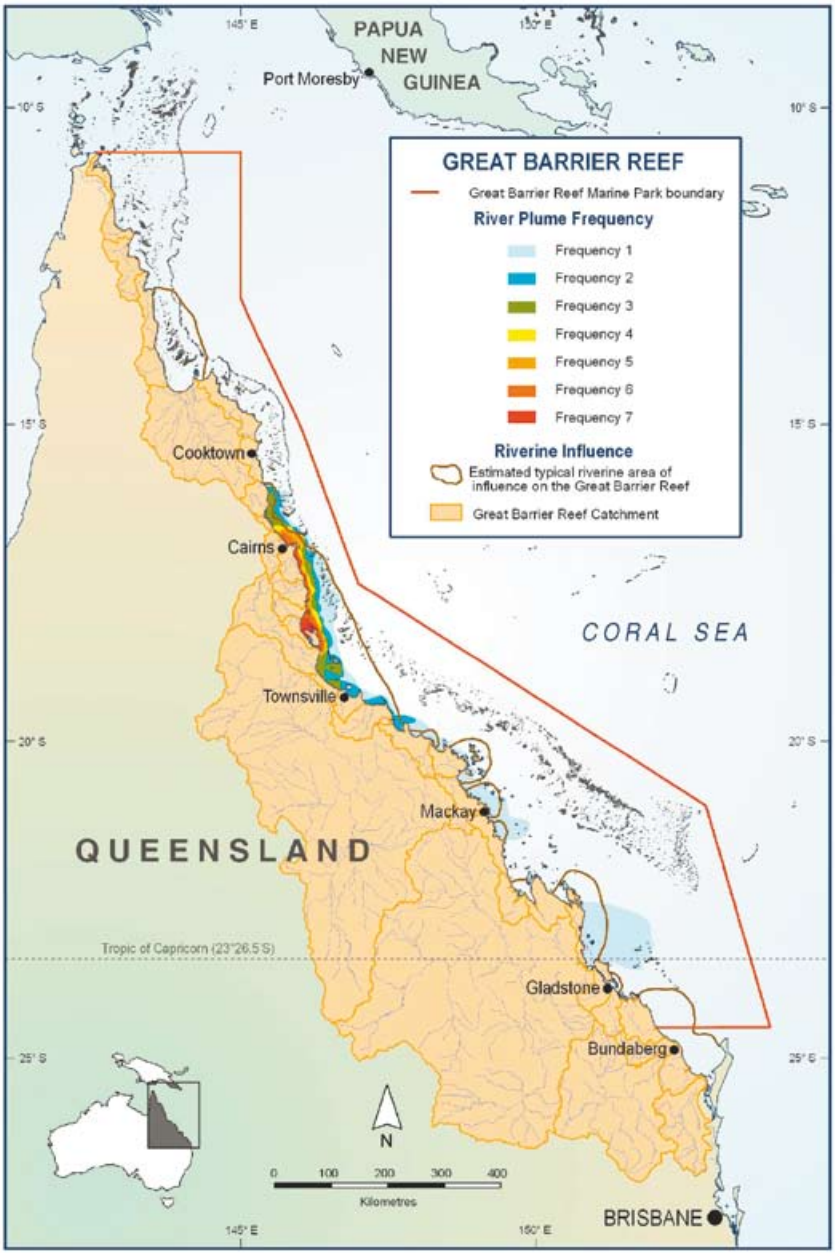


Sediments transported by river flood plumes have an immediate effect on coastal seagrasses through sediment deposition. Smothering of subtidal and intertidal plants occurs as most sediments are deposited within the first few kilometres of a river mouth[76]. In addition, while sediments remain suspended in the water column turbidity is high, and light reaching the seafloor is reduced, impacting coastal and deep water seagrasses that are beneath the plume. River flood plumes can extend 50 km from the coast[41] (Figure 8.11) and last for up to three weeks[118,88]. Sediments also carry nutrients[14] and toxicants[108], thus the concentrations of these associated elements delivered to seagrass meadows will decrease with distance from the river mouth.

8.2.4.2 Sensitivity – rainfall and river flood plumes

If seagrass meadows occur within the spatial extent of either sediment deposition or the flood plume itself, they are likely to be impacted. Seagrasses are sensitive to the deposition of sediments directly on top of them. Where sediment deposition is greater than the ability of the seagrass beneath it to grow through the sediments using energy reserves, plants will die. Anecdotally, seagrass meadows in the GBR are regularly lost due to the deposition of sediments. For example, after flooding of the Bohle River, north of Townsville, intertidal meadows of *Halodule* and *Halophila* were completely covered by sediment (J Mellors and M Waycott, personal observations) and in Sarina Inlet near Mackay seagrass

Figure 8.11 *Area of influence by flood plumes based on data for the past 80 years in the GBR. Includes river plume frequency during cyclonic events (colour fills indicate the frequency with which a cyclone has generated a flood plume in the region), estimates of riverine influence derived from flood plume and river discharge studies, and modelling results (brown outline)[56]. (Source: C Honchin, Great Barrier Reef Marine Park Authority)*



loss resulted from sediment related smothering (L McKenzie personal observation). No data on the specific sensitivity of seagrasses in the GBR to burial is available although it is intuitive that larger, more robust species such as *Thalassia hemprichii* and *Enhalus acoroides* are more likely to survive than smaller ephemeral species. River flood plumes are also associated with strong currents during their movement from the river out to sea. There is limited information on the strength of currents seagrasses can withstand. A northern hemisphere species, *Zostera marina* can live in habitats with a current speed of up to 1.8 cm per second[69]. This is equivalent to about 3.5 knots, similar to tidal currents in the GBR. At current strengths greater than 4 cm per second (8 knots) the leaves of seagrass are likely to be dislodged by shear forces[70]. It can be assumed therefore that currents greater than 4 cm per second will remove seagrass.

In coastal habitats of the GBR, current evidence suggests light is the main factor limiting seagrass growth[21,86,102,148]. However, in the mid and outer reefs of the GBR, where light is not likely to be limiting due to the absence of terrestrial sourced sediments, nutrients can the dominant limiting factor (Figure 8.11). As such, nutrient enrichment may lead to increases in plant growth and biomass[137,139,102,127] that could result from a greater influence of river flood plumes. Seagrasses are not sensitive to small changes in salinity, and can survive over a large salinity range[64]. As *Halophila ovalis* and *Zostera muelleri* are regularly found growing near river mouths in the GBR it is assumed they can withstand variations in salinity[81]. There are experimental or observational studies on salinity tolerance and exposure that support this for three species found in the GBR, *Halophila ovalis*[64,7], *Halodule uninerivs*[101,64] and *Zostera muelleri*[57,90]. *Halophila* and *Zostera* species can survive in salinities between 10 and 40 parts per thousand, and can survive short-term exposure (approximately two weeks) to salinities less than 10 parts per thousand[64,90,7]. The salinity range for *Halodule* is recorded as low as 3.5 and as high as 62 parts per thousand[101]. Flowering and seed germination of *Zostera* is enhanced in low salinity[34,13,121]. The effect of salinity on other species is unknown.

The extent of sensitivity of seagrasses to a variety of toxicants remains largely unresolved. Based on short-term exposure to herbicides, a few studies have identified water column herbicide concentrations of diuron, atrazine and simazine that impact seagrases (lethal exposure at 100,000 nanograms per litre; or sub-lethal exposure where photosynthesis is impacted at 10,000 nanograms per litre)[60,98]. However, smaller species of seagrass such as *Halophila ovalis* can be impacted by concentrations of diuron as low as 100 nanograms per litre[60]. It is not known what concentration in the sediment impacts seagrasses.

8.2.4.3 Impacts – rainfall and river flood plumes

The impact of rainfall and river flood plumes to seagrass will depend upon the amount of sediment deposited and the persistence of the plume. From a major event in Hervey Bay, just south of the GBR, it was inferred that seagrass loss occurred due to a number of factors such as physical removal, sediment deposition and light reduction[118,88,19]. The importance of smothering by sediments as a contributing factor to this seagrass loss was supported by the observation of up to 10 cm of sediment covering dead rhizomes of *Zostera* at an intertidal meadow in Hervey Bay, Urangan which were lost following the 1999 flood event (L McKenzie, personal observations). No direct evidence of seagrass loss due to lowered salinities or physical scouring due to currents has been reported. However, we can infer a contribution of reduced salinity to seagrass loss during large-scale flood plume events although the scale and nature of the impacts to the seagrass meadow remains obscure. Seagrass loss

due to toxicants has not been observed, although based on herbicide concentrations observed in seagrass meadows following periods of moderate flow[59,95,130], we may assume that loads are greater during high flow events. It is possible that concentrations will reach sub-lethal levels, especially close to river mouths[94]. From limited information on toxicant concentrations in marine waters in the GBR, it appears unlikely that lethal concentrations will be reached.

Where seagrass growth has been limited by availability of nutrients, expansion of seagrass meadows is possible. For example, seagrass meadows have responded to experimental nutrient additions on mid-reef islands of the GBR, such as Green Island[140]. Coupled with observations made through monitoring seagrass meadows at Green Island, the demonstrated increases in meadow extent and density (Queensland Department of Primary Industries and Fisheries, unpublished data) may be related to ongoing increases in nutrients in some mid-shelf reefs. Nutrient rich flood plumes reach Green Island almost every year[42] and it has been inferred that the increase in seagrass biomass is due to nutrient enrichment from these flood plumes.

8.2.4.4 Adaptive capacity – rainfall and river flood plumes

The adaptive capacity of seagrass species to rainfall or flood plumes will partially depend on their capacity to recover from disturbance via seed or vegetative fragments and partially on their initial resistance to the impact. More persistent species (eg see Figure 8.4) should have a higher tolerance for localised impacts, particularly where the impact is moderate and/or short term. There may also be community shifts from more stable communities to more ephemeral communities because of a major event.

8.2.4.5 Vulnerability and thresholds – rainfall and river flood plumes

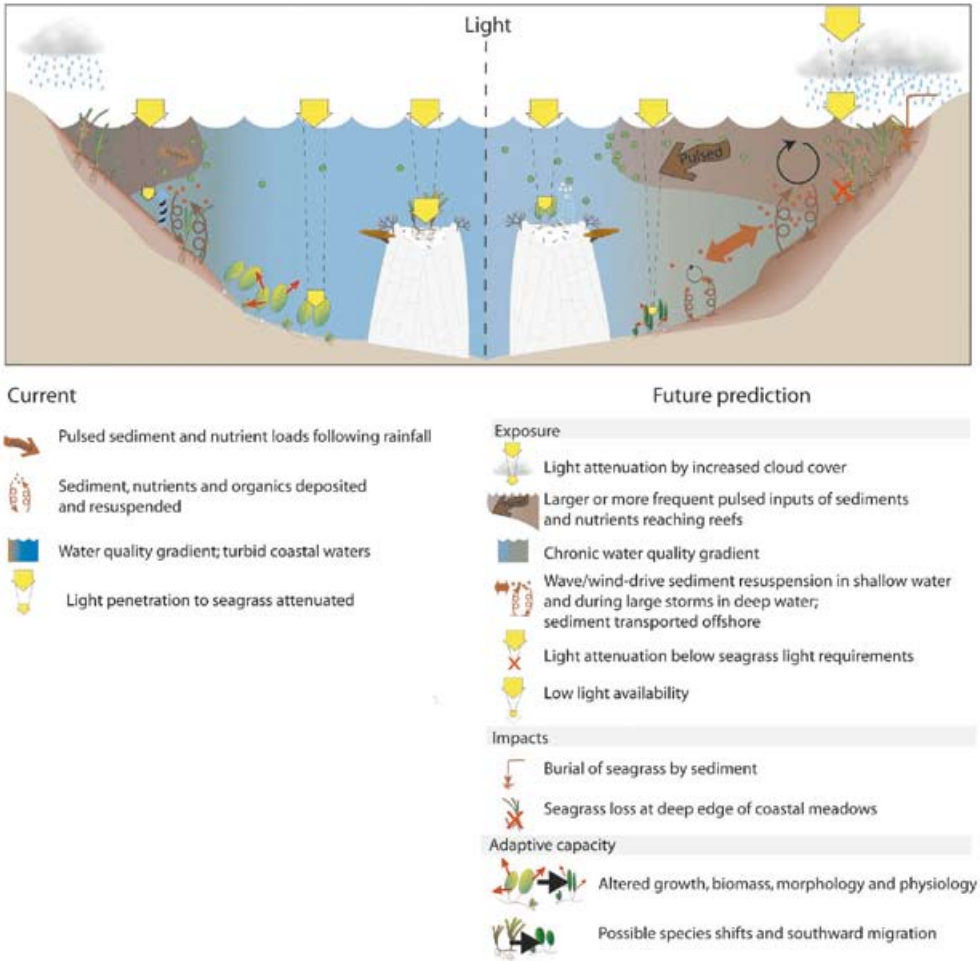
The vulnerability of seagrasses to rainfall and river flood plumes will also vary with community structure. Species growing near river mouths and frequently exposed to these conditions, such as *Halophila, Zostera* and *Halodule*[81], have a low overall vulnerability to this threat. Known thresholds to lowered salinity based on experimental evidence do exist for *Halophila ovalis* (less than 10 parts per thousand for two weeks) but not for other species. Species will be more vulnerable if the growing tissue (meristems) is exposed to low salinity water, particularly those species with areal meristems such as *Thalasodendron* spp. and *Halophila spinulosa*. However, most species have their meristems below ground where exposure to low salinity is not likely to occur. Due to the ability of seagrasses living near the mouth of rivers to recover from sediment burial, we predict a low vulnerability to this exposure threat. Structurally smaller species such as *Halophila* spp., *Halodule uninervis* or some forms of *Zostera muellerii* will be more vulnerable to the impacts of sediment deposition as a small change in sediment profile will cover or erode them. This does not take into account the consequences of reduced light from river flood plumes and resuspension of sediments through wind.

In summary, seagrass can be lost or be negatively impacted when exposed to river flood plumes due to a combination of processes including: sediment deposition, water currents, toxicants, suspended sediments in the turbid plume and the long-term resuspension of sediments causing reduced light. Increased nutrients and decreased salinity are unlikely to have any negative effects. Seagrass meadows can recover from existing cyclone, storm and flood events but if more extreme events occur in the future, it may take longer for the meadows to recover. Communities may shift towards more ephemeral or dynamic types.

8.2.5 Light and ultraviolet radiation

A number of factors can affect light availability to seagrasses. Flood plumes carry suspended sediments and dissolved nutrients that can stimulate phytoplankton blooms. Phytoplankton blooms are generally suppressed by high turbidity during flood plumes and tend to follow after most of the sediment has settled out[53]. Wind-driven resuspension of sediments will reduce light to benthic organisms in the GBR. These events will alter light quality and quantity reaching benthic habitats such as seagrass. Cloud coverage may increase in certain regions depending upon the time of year, although an overall increase in cloud cover is expected in the northern GBR. Finally, levels of ultraviolet (UV) are predicted to increase under climate change scenarios. The expected impacts of these changes on seagrasses are depicted in Figure 8.12.

Figure 8.12 *Predicted causes and impact of changing light regimes on seagrasses based on climate change predictions for the GBR*



8.2.5.1 Exposure – light and ultraviolet radiation

Most seagrasses in the GBR will be influenced by any change to light quality and quantity[21]. Frequent small rainfall events provide chronic impacts but are constrained to regions close to the point of river discharge including coastal intertidal and subtidal habitats. Heavy rainfall events, including storms and cyclones, have the potential to transport these plumes northward across the GBR lagoon towards the mid-reef[53] where reef and deep water seagrass meadows may be affected. If these events become more intense and intermittent, as predicted under climate change scenarios, substances accumulated within the catchment during the long dry periods will be released in one large event resulting in more turbid and extensive flood plumes.

Turbid water conditions in nearshore coastal waters are sustained by the resuspension of sediments deposited during rainfall events, with near-bottom turbidity levels caused by resuspension often exceeding those within flood plumes[77,53]. Turbidity generally increases with wind speed[3] with stronger winds required to generate waves that are sufficient to reach the bottom in deeper water[53]. Coastal seagrasses in habitats of less than five metres deep are the most heavily impacted by wind-driven sediment resuspension. Intense storm and cyclone events expected to occur in climate change predictions also expose deeper meadows to resuspension events as storms can generate waves capable of moving and resuspending sediments in waters up to 20 metres[53]. Turbidity can affect light quality; blue light (400 to 500 nanometres) and red light (600 to 700 nanometres) are preferentially removed, changing its quality to a more yellow light, which is less useful for photosynthesis[86].

Furthermore, increased storm activity associated with climate change may also increase cloud cover during these events. Cloud cover has been shown to create a feedback loop where elevated temperature increases evaporation producing more clouds that reduce light and reduce temperature.

8.2.5.2 Sensitivity – light and ultraviolet radiation

The sensitivity of seagrasses to chronic long-term light reduction is dependent on the duration and intensity of light reduction as well as their minimum light requirements and ability to adapt to changing light. Seagrasses are capable of gross phenotypic plasticity and have numerous biochemical, physical and ecological mechanisms to cope with alterations in light. However, intense light reduction events can lead to complete loss of *Halophila ovalis* after just 30 days[88] while *Halodule* may last up to 100 days[87]. The ability of species to endure pulsed turbidity events is probably related to their ability to store carbohydrates, which can be utilised during periods of low light. The sensitivity of other species in the GBR to light reduction is not as well known. As a number of reef-colonising species are not found in more turbid coastal waters they may be more sensitive to chronic light reduction, but as they tend to form larger rhizomes capable of carbohydrate storage, it is possible they may be able to endure short term pulsed events. Subtidal coastal seagrasses that are permanently submerged are likely to be more sensitive to both pulsed and chronic light reductions than intertidal or deep water seagrasses. The sensitivity of seagrasses to light reduction can be further exacerbated by cloud cover.

Most seagrasses are sensitive to elevated levels of UV. Fluctuations in total light available can be tolerated (within a certain range), however if tolerance for UV is exceeded, a range of tissue damages will result. Thinner leaved seagrasses such as *Halophila ovalis* and *Halodule uninervis*, which are often found in intertidal areas, are known to be more susceptible to elevated UV than those with thicker leaves are[37]. There are some exceptions, for example, the thin leaved *Halophila johnsonii* from Florida

(closely related to *Halophila ovalis* from the GBR[146]) is not sensitive to high levels of UV[71]. Epiphyte accumulations on the surface of leaves, although detrimental to overall light availability, can reduce the sensitivity of seagrasses to UV damage[136,12]. Recent analysis of the impact of tiny grazers of epiphytes on the leaves of seagrass supports the important role of these epiphytes in shielding seagrass leaf tissue from the full impact of UV damage (B Bendel unpublished data).

8.2.5.3 Impacts – light and ultraviolet radiation

Intense run-off events have led to the loss of seagrass, due primarily to reduced light penetration caused by high turbidity such as that observed in Hervey Bay in 1999[86,19]. Whether future flood plumes will result in seagrass loss depends on the intensity and duration of the plume, while the spatial scale of the impact will also depend on the spatial extent of the plume. Complete loss of seagrass will result if turbidity and light reduction persists at below the minimum light requirements for an extended duration. The tolerable level for complete light reduction is highly variable for the two studied species (*Halophila ovalis* at about 30 days and *Halodule pinifolia* at about 100 days) and is unknown for most other GBR species.

Ongoing resuspension of sediments resulting in light reduction have been linked to fluctuations in seagrass coverage[104] and to complete seagrass loss[39]. The impacts of sustained reductions in light availability due to resuspension of sediments is likely to be a reduction in seagrass depth limits and long-term impacts on meadow biomass and growth.

In nearshore coastal habitats, cloud cover accounts for about 14 to 17 percent of the variability in light availability[3] and, on average, is not likely to strongly impact seagrass survival. However, dense cloud cover is known to exacerbate the impacts of turbidity or shading. Responses to shading could be used to extrapolate to the impact of reduced light linked to cloud cover, however, the intensity and duration of light reduction associated with cloud cover is likely to be substantially less than those used in previous experiments. In regions where cloud cover is expected to increase (ie northern GBR), intense, prolonged cloud cover will exacerbate the effects of other light reducing processes, if they co-occur. Increased UV will have negative impacts on shallow intertidal seagrasses as high UV levels damage photosystems and reduce photosynthetic efficiency[37,44].

8.2.5.4 Adaptive capacity – light and ultraviolet radiation

Seagrasses respond to reductions in light availability through a range of morphological and physiological adjustments[148]. Some of these, such as increases in chlorophyll concentration, are responses that improve light capture and carbon fixation[79]. Other responses reduce the plant's carbon requirements, for example growth and biomass are often reduced. However, all seagrasses have threshold minimum light requirements below which such adjustments are insufficient to meet their carbon balance demands. These thresholds are not known for most seagrasses of the GBR.

Following complete loss of meadows, recovery can be rapid if conditions at the site are suitable for recolonisation. For example, *Zostera muelleri* showed complete recovery three years after a flood event in Hervey Bay[19]. Recruitment into new areas occurs primarily through seed dispersal or import of vegetative fragments, and proximity to a donor meadow may be important for recovery rates. Dynamic communities are more adapted to periods of disturbance than late successional species and therefore ongoing disturbances are likely to affect species composition.

Most species demonstrate photosynthetic damage from short-term periods of elevated UV but the long-term adaptive capacity is unknown. *Halophila johnsonii* from Florida contains UV absorbing compounds that can increase in response to elevated UV[71] and *Halodule wrightii* from Florida, is thought to have photorepair mechanisms to minimise the impact of UV on photosynthesis[136]. Whether these UV adaptation mechanisms occur in other species is unknown.

8.2.5.5 Vulnerability and thresholds – light and ultraviolet radiation

Species inhabiting coastal intertidal and subtidal regions (eg *Halophila, Halodule* and *Zostera*) will be most at risk from pulsed turbidity events and are probably the least tolerant to intense light reduction (see Figure 8.7). Later successional species, such as *Thalassia*, may be more tolerant to pulsed light reduction as they have greater carbohydrate storage capacity[36]. These species tend to occupy reef habitats that will infrequently be exposed to large flood events. Therefore, recovery will be species-specific and could result in changes in the community composition.

The minimum light required to sustain meadows over longer durations is largely unknown for GBR seagrasses with the exception of *Zostera muelleri*, which has been determined to require 16 to 36 percent of sub-surface irradiance for survival[86]. Seagrasses globally have light requirements in the range of 4 to 36 percent of sub-surface irradiance[40,86]. If light availability is sustained below this level, complete loss of seagrass is expected. Within the GBR, current distributional patterns suggest that species occurring in reef habitats probably have a lower threshold for long-term light reductions as they inhabit high-light environments. We should point out however that species-specific light requirements for GBR seagrasses have not been determined and may vary beyond this range of light requirements.

8.2.6 Elevated carbon dioxide concentrations and ocean acidification

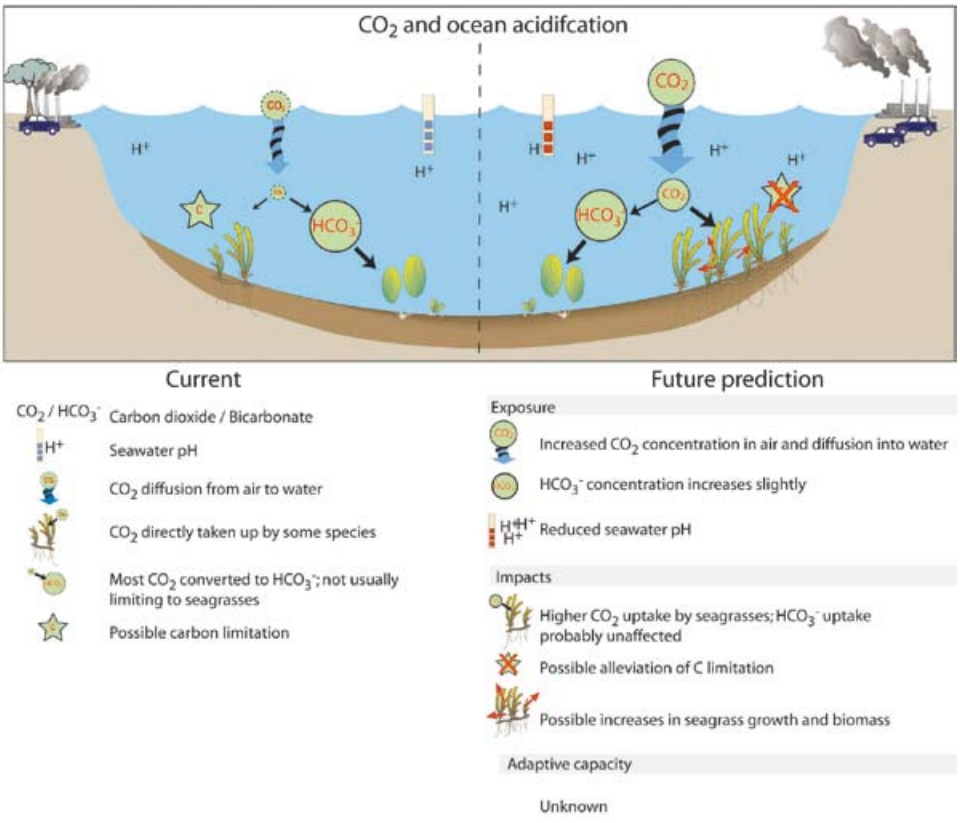
Over the 20th century, atmospheric CO_2 has increased by 25 percent from 290 to 350 parts per million and over the course of the coming century the concentration will have doubled. The most significant changes for seagrass physiology will be due to changes in dissolved CO_2 and any increase in bicarbonate (HCO_3^-) concentration as seagrasses can utilise both these carbon sources (Figure 8.13). The possible influence of changes to both will be considered here and collectively referred to as inorganic carbon, unless otherwise specified.

8.2.6.1 Exposure – changing CO_2 concentration

All regions of the GBR will be influenced by the predicted elevated atmospheric CO_2 concentrations and ocean acidification. All seagrass habitats are within a zone of well-mixed water to 20 metres depth[53,140]. Thus all tropical seagrasses will be exposed to the increased inorganic carbon. Temperature changes will also influence the solubility of dissolved gases. Thus, water column inorganic carbon concentrations may vary across the GBR depending upon local ambient water temperature. Different seagrass species may respond to these changes in inorganic carbon and the concomitant changes in pH and bicarbonate.

Competition for inorganic carbon uptake with other marine autotrophs may also impact the ability of seagrass to access CO_2. Elevated photosynthetic rates of other marine autotrophs, such as epiphytes, may stimulate their growth, out-competing seagrass. Björk et al.[9] suggested that marine macroalgae

Figure 8.13 *Influences of changes in CO_2 concentration on seagrasses*



were more efficient at concentrating inorganic carbon than seagrasses, though Beer and Koch[5] suggest that this difference will probably be negligible in reduced pH (higher CO_2) waters. Further research is needed to assess these interactions in a greater range of macroalgal species as well as microalgal epiphytes on seagrass leaves.

8.2.6.2 Sensitivity – changing CO_2 concentration

Most seagrasses are inorganic carbon-limited under maximum irradiance conditions. In addition, they have adapted to bicarbonate uptake or the conversion of dissolved CO_2 at the leaf surface[78, 79]. Two basic inorganic carbon uptake pathways exist in seagrasses (direct CO_2 and HCO_3^-), and the presence of these pathways appears to be species-specific[135,79,154]. Use of bicarbonate as an inorganic carbon source is common in tropical seagrass (eg *Halophila ovalis, Cymodocea rotundata, Syringodium isoetifolium* and *Thalassia testudinum*)[135], whereas others use enzymes to make CO_2 available as the inorganic carbon source (eg *Enhalus acoroides, Halodule wrightii, Cymodocea serrulata*). Seagrass species that directly use CO_2 will benefit from elevated atmospheric concentrations[43]. It is also expected that HCO_3^- concentrations will increase slightly under elevated CO_2 conditions; therefore, species using bicarbonate will have some benefit from increased CO_2 or acidification. Zimmerman[154]

suggests that most seagrass species will be able to utilise increased inorganic carbon under the various climate change scenarios to increase their production and areal extent. However, some species of seagrass such as *Cymodocea serrulata*[128] have been shown to be carbon saturated, so irrespective of atmospheric CO_2 levels, those species will not have enhanced productivity as a result of elevated inorganic carbon. Unfortunately, few species have been assessed for their inorganic carbon requirements and saturation status.

8.2.6.3. Impacts – changing CO_2 concentration

No detectable change in seagrass health or distribution has been observed as a direct result of elevated CO_2 concentration and at present few manipulative experiments have been performed to assess the potential impact[5,6,128]. It is generally accepted that under climate change scenarios of elevated atmospheric CO_2, seagrasses will not suffer[5,79,154,124], in fact, small increases in photosynthesis are expected (Figure 8.13).

8.2.6.4 Adaptive capacity – changing CO_2 concentration

There is contrasting evidence as to whether seagrasses can adapt to an increase in CO_2 concentration[131] based on disparate data sets. Most seagrasses evolved during a period of higher CO_2 concentration than is currently available[109] (Figure 8.1). This implies seagrasses may be well suited to making adjustments to long-term increases in CO_2. It is expected that species in the Zosteraceae are not as well adapted to elevated CO_2 concentrations as members of the Hydrocharitaceae, Cymodoceaceae and Posidoniaceae, as this group evolved more recently after the Palaeocene when ambient CO_2 was lower. Our ability to assess species adaptability is poor due to a lack of basic data.

8.2.6.5 Vulnerability and thresholds – changing CO_2 concentration

Seagrass responses to elevated CO_2 concentration or decreased pH are expected to be small and positive for most seagrass species (Figure 8.13). Not all species will benefit from higher CO_2 concentrations, specifically those that utilise HCO_3^-, and so a species shift favouring the former is possible. However, this is highly dependent on a range of other environmental variables, such as light availability, and the opposing responses to both variables may offset each other. Overall, the small pH change expected is unlikely to have a significant impact on seagrasses.

8.2.7 Changes in ocean circulation

Under climate change it is predicted that the major currents in the GBR will change, the East Australian Current (EAC) will move south, notably during ENSO events. There may also be a northward change in current direction and magnitude along the GBR coast and lagoon. Variations in ocean circulation may also influence heat transport processes and climatic conditions in the GBR although the extent of this influence remains obscure.

8.2.7.1 Exposure – ocean circulation

Movement of the EAC south, along with the resultant change in current direction and magnitude along the GBR coast and lagoon, will alter sea surface temperature in the entire GBR, impacting coastal, deep and offshore reef seagrass communities. How sea surface temperature will change at

fine scales is uncertain. Furthermore, it is uncertain how climatic conditions will vary as a result of change to heat transport in the GBR. The EAC upwells cold, saline, nutrient rich water in the southern GBR across the shelf break, and is an important source of nutrients for the region[107]. Movement of the EAC south along with the upwelling of nutrients, may impact upon offshore reef communities in the southern seagrass region. A northward change in current direction and magnitude along the GBR coast and lagoon may expose seagrass communities along the coast, in deep water and in offshore reefs to higher-energy events. Both the movement of the EAC south and change in direction and magnitude of coastal currents will be enhanced during an ENSO event.

8.2.7.2 Sensitivity – ocean circulation

A southward movement in the EAC and its effect on southern offshore reef seagrass communities is dependent on their reliance for nutrients from offshore upwelling. This relationship has not been quantified and so the sensitivity of seagrass communities to this event is uncertain. General sensitivity to temperature has been discussed above. An increase in magnitude of inshore northward currents in conjunction with strong south-easterly winds, tropical cyclones and severe storms will expose coastal and offshore reef (intertidal and subtidal) habitats to more energy than would otherwise exist. The direction and magnitude of inshore currents influence seed dispersal for species that distribute their seeds or vegetative fragments on the ocean surface and/or through the water column[147]. The sensitivity of seagrass communities to change in coastal and lagoon currents is dependent on species type, and their reliance upon currents for seed dispersal.

8.2.7.3 Impacts – ocean circulation

At present, maximum recorded current speeds in the GBR vary between one and two metres per second[152,151,107]. In association with strong south-easterly winds, tropical cyclones and severe storms, the predicted increase in magnitude of inshore northward moving currents will be further exacerbated, but it is uncertain what the current speed will be. *Zostera marina*, a northern hemisphere temperate seagrass species, can persist to varying degrees at current speeds between one and four metres per second[69,70]. The degree tropical seagrass species tolerate being exposed to high-energy currents is unknown. Negative impacts to seagrasses due to high-energy currents are a loss of seed banks, scouring, turbulent water motion and sediment movement. Changes in ocean circulation may also influence the distribution of tropical species, resulting in a more southerly distribution of species largely absent from the GBR at present (see Figure 8.4), or allow species currently limited to the subtropics (Moreton Bay) to extend farther south.

8.2.7.4 Adaptive capacity – ocean circulation

It is likely that adaptations in seagrasses will be changing species distributions and community compositions for many of the regions of the GBR. Little can be predicted beyond these generalisations, as the impacts themselves remain tenuous.

8.2.7.5 Vulnerability and thresholds – ocean circulation

The quantitative relationship between ocean circulation and seagrasses is unknown. The vulnerability of seagrass communities to change in the EAC and coastal and lagoon currents cannot be determined confidently, this remains an area of research to be explored.

8.3 Interactions and linkages with other ecosystem components

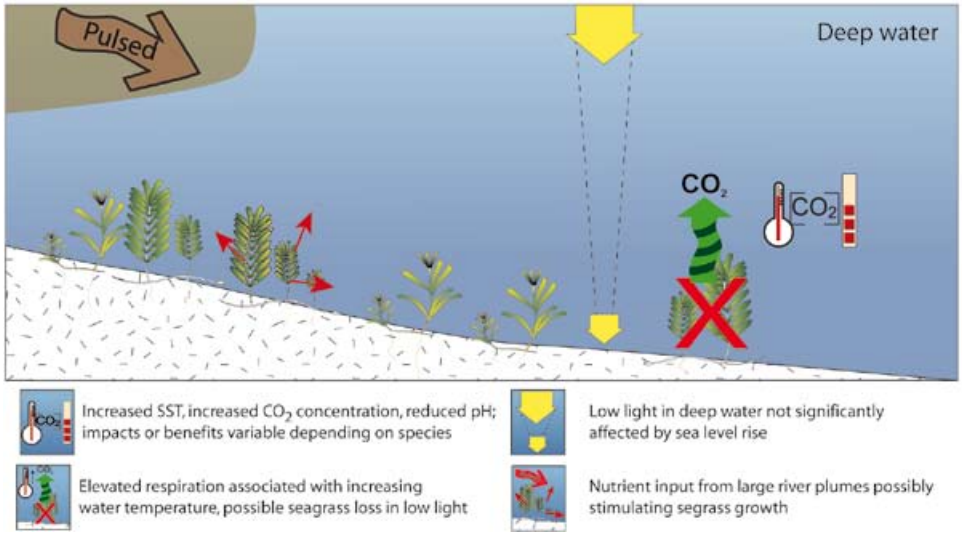
Habitat responses to multiple stressors

The impact of multiple stressors on seagrass habitats of the GBR is somewhat speculative due to the lack of specific threshold evidence for individual stressors. However, a conceptual understanding of these stressors can be developed based on the current knowledge. Coastal seagrasses experience greater exposure to the influence of terrestrial runoff; the most direct impacts being seagrass loss due to sediment deposition reduced light availability due to turbidity, and changing salinities. In addition, higher temperatures in shallow and intertidal habitats may become inhospitable for seagrasses. Finally, sea level rise will cause a loss of seagrass at the current depth limit, particularly in turbid coastal water, and new habitat may not be suitable for seagrasses to colonise due to physical barriers or unsuitable substrate for colonisation. It is predicted that coastal seagrasses will suffer a loss of overall habitat although the scale of that loss cannot be predicted at this stage.

In contrast to coastal seagrass habitats, reef habitats do not experience the full impact of land-based inputs. The combined impact of temperature, salinity fluctuations due to heavy rainfall and an elevated sea level will potentially reduce seagrasses in these habitats. However, as the majority of seagrasses in reef habitats are nutrient limited, the influx of additional nutrients via flood plumes may increase seagrass growth.

Deep water seagrasses will be relatively protected from disturbance impacts but the combination of multiple causes for reduced light and increased respiration demands may limit seagrass survival in this habitat type (Figure 8.14). The response of seagrasses growing in deep water is difficult to assess as so little data is available regarding this important seagrass resource in the GBR.

Figure 8.14 *Influence of multiple stressors on deep water seagrass habitats based on predicted climate change impacts*

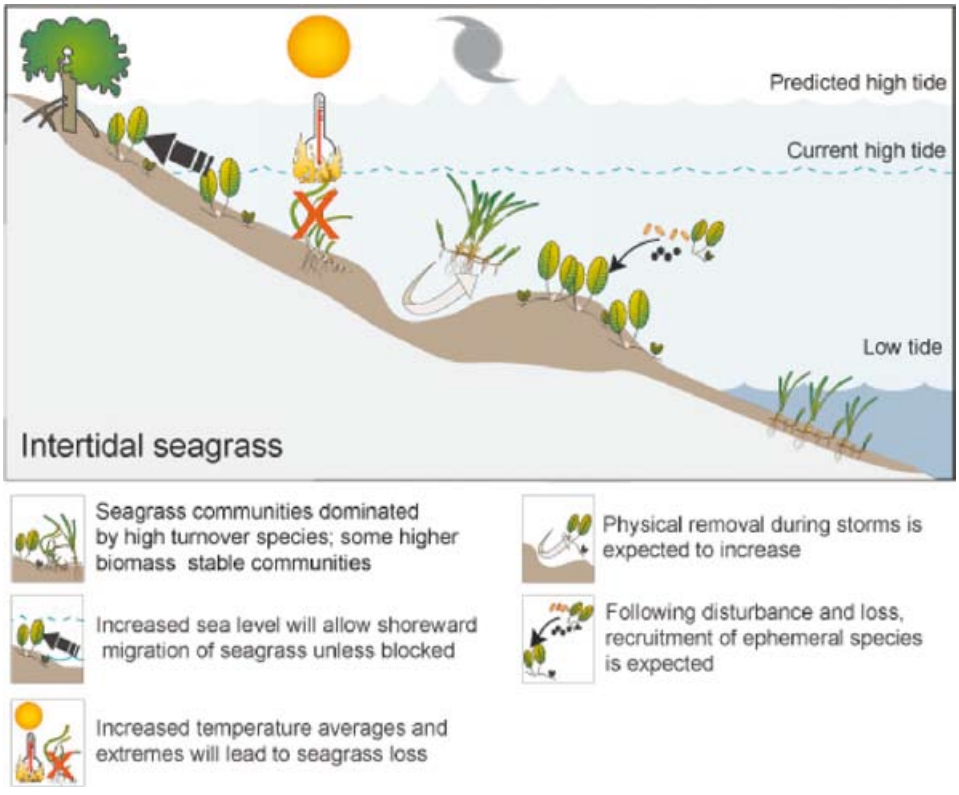


Seagrass habitats may experience change in community structure

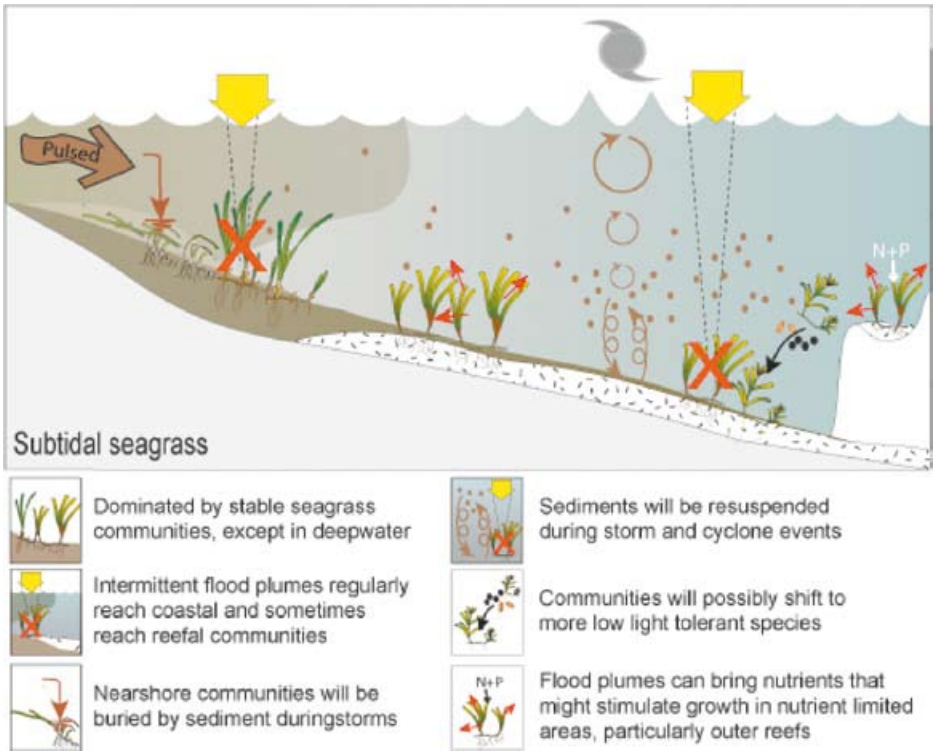
The interaction of changing environmental conditions are of particular concern in intertidal or shallow water habitats, where the combined impacts of temperature, storm and cyclone related disturbance and sea level change will result in a narrower habitat for seagrasses (Figure 8.15). Seagrass community structure in these habitats is predominantly high turnover, disturbance response species already. These seagrass communities have relatively low resilience to impacts and respond by reducing biomass, to the point of seagrass loss. They do, however, recover relatively quickly (months to years) once habitat quality improves. The intertidal and shallow-subtidal seagrass meadows that are higher biomass are more stable meadows, for example the *Zostera muelleri* meadows at Ellie Point, Cairns or Pigeon Island, Airlie Beach. Resilience of seagrasses in these higher biomass communities will be reduced locally by the impact of coastal developments such as marinas, roads and changed drainage systems which change land-based inputs or limit the ability of seagrasses to colonise potentially favourable habitat. These communities will most likely experience a shift in composition to disturbance resilient species such as *Halodule uninervis* and *Halophila ovalis*. This change in seagrass species composition will alter the associated ecological services these communities perform, although specifics of these services are poorly studied in the GBR.

Figure 8.15 *Influence of multiple stressors on (a) intertidal and (b) subtidal seagrass habitats based on predicted climate change impacts*

a.



b.



Inter-community linkages

Seagrass habitats exist in a continuum between terrestrial, freshwater, saltmarsh, mangrove, seagrass, inter-reef and coral reef habitats. In this series, seagrasses represent a buffer between the terrestrial and mangrove habitat and reef habitats. In many areas of the GBR, mangroves are the interface between the land and the sea. As a result, declines in mangrove habitats could expose seagrass communities to the enhanced effects of terrestrial inputs such as freshwater runoff, nutrients and sedimentation. In addition, in many areas, mangroves provide shelter from the influence of currents and oceanic swell providing additional habitat for seagrasses. In contrast, mangroves act as a barrier to seagrasses occupying upper intertidal and shallow-subtidal habitat and may in fact represent a limiting factor in seagrass adaptability to changing sea levels.

Where seagrass meadows occur adjacent to coral reefs, seagrasses provide food and shelter for mobile reef organisms such as fish and crustaceans[46]. In addition, seagrasses may act as nursery grounds for numerous species[23]. Seagrasses also grow within many coral reef communities throughout the GBR[21,147]. In these locations, seagrasses act to stabilise sediments, as food and shelter for many organisms and are an often-overlooked integral component of coral reef biodiversity[109]. It is possible that seagrasses will aid in buffering the impacts of climate change on coral reefs where they co-exist, although no research has been conducted on this. Given the lack of data about such interactions, the role seagrasses may play in future reef ecosystems is worthy of further exploration.

8.4 Major vulnerabilities to climate change

The major vulnerability of seagrass to climate change is loss of seagrass in the coastal zone, particularly near river mouths and in shallow areas (Table 8.1). The greatest impact is expected to result from elevated temperatures, initially during extreme events, eventually in a chronic manner. In addition, reduced light penetration from sediment deposition and resuspension after severe storm and rainfall events will cause seagrass loss. However, additional research on thresholds and the combined impacts of different stressors is critical to understanding the specific vulnerability of seagrasses to climate change impacts.

In addition to losses, changes in species composition are expected to occur particularly in relation to disturbance and recolonisation. Following such events, a shift to more ephemeral species and those with lower minimum light requirements is expected. If the period between events increases, it is expected that high-risk habitats will go through 'boom-bust' cycles. Such cycles pose significant risks to associated fauna such as dugong, turtle, and important fisheries species as habitat availability changes rapidly during events.

Finally, there is potential for seagrasses to increase in their extent, especially in currently low nutrient reef habitats where cumulative changes result in elevated nutrient concentrations and lower competition due to the loss of herbivores. However, it is more likely that macroalgae are better placed to take advantage of such changes, although little direct data exists to make a strong case either way.

8.5 Potential management responses

Mitigation of climate change is a key strategy, however as some climate change is inevitable, it is essential to protect and enhance seagrass resilience to climate change impacts. Therefore, impacts that reduce resilience need to be managed, for example, water quality and light availability. Effectively, this means limiting any factor that increases turbidity, and sediment resuspension such as flood plumes or strong winds. In short, this means avoiding many of the consequences of climate change *per se*.

Some specific high-risk factors may be mitigated directly. For example, it may be possible to reduce sediment, nutrient and toxicant inputs by improving quality of water entering the GBR or by trapping inputs in coastal buffer zones. Ongoing efforts to treat wastewater are essential to this process. Limiting soil erosion in catchments will not only improve catchment health but will have the downstream benefit of reducing sediment loads, turbidity, toxicants and nutrient inputs into the coastal ecosystem and subsequently seagrasses. In addition, it will be essential to minimise practices that physically disturb seagrasses or have downstream impacts of physical disturbance. Thus coastal development and the construction of marinas, channel dredging or boat harbours should consider the impact on seagrass habitat. Potential point source discharges of nutrients, freshwater or toxicants may also be the source of disturbances.

Management needs at the ecosystem diversity level are more complex. For example, dugong grazing has a strong influence on seagrass community structure and a decline in grazing will have an impact on seagrass habitats. Generally seagrasses are protected due to their role as a food source for dugong or as fisheries habitat, and as such these interactions are well recognised. However herbivores also play a role in maintaining seagrasses as some (eg fish and invertebrates) graze epiphytes off the leaves

of seagrass. The loss of such grazers may enhance seagrass susceptibility to light reduction.

Table 8.1 *Summary of major impacts on seagrass based on predicted climate change scenarios for the GBR where:* **predicted direction of change** *represents loss, gain or fluctuation compared to current state, including if a change in community might be expected;* **Vulnerability** *represents most likely habitats to be affected;* **Adaptability** *represents how resilient a seagrass community is to impacts;* **Significance** *represents an indication of the scale and likelihood of impact to seagrass meadows within the GBR*

Impact	Direction of change	Vulnerability	Adaptability	Significance
Temperature	Loss and community shifts	Shallow intertidal and shallow subtidal	Ephemeral species – high Persistent species – moderate to poor	Large areas across the range Highly likely
Sea level rise	Loss	All coastal habitats	Ephemeral species – high Others – unknown	Large areas across the range Moderately likely
Disturbance (cyclones and major storms)	Loss and intermittent gains and community shifts	All shallow habitats (less than 5 metres)	High where potential recruitment	Localised Highly likely
Flood plumes and rainfall	Loss and community shifts	All coastal habitats	High where flood plume does not persist	Localised Highly likely
Light and UV	Small potential loss but largely unknown	All habitats (light) Shallow and intertidal (UV)	High where change is ephemeral, low otherwise	Regionally and locally Limited likelihood
CO_2 and pH	Unknown impact, some small theoretical potential for loss and gain	All shallow habitats	High within ranges predicted	Regionally and locally Limited likelihood.
Ocean circulation	Loss and gain theoretical including community shifts	All habitats	Unknown	Regionally

* Highly resilient communities should recover quickly (months to years), moderately resilient should recover (although timescale may vary), and poorly resilient communities may not recover

The eventual survival of seagrass will be linked to factors related to the rate and magnitude of climate change and other environmental stressors that occur in coastal habitats. For example, coastal development probably reflects the major threat to seagrass habitats at present through its ongoing impact on water quality. Thus focusing management responses on reducing these impacts will assist in making seagrass meadows resilient enough to survive the impacts of climate change.

8.6 Further research

Species-specific tolerances across broad geographic and environmental gradients should be established including, the minimum and maximum light requirements to enable prediction of thresholds and more specific management strategies. In addition, factors to assess include:

- optimal temperature range,
- salinity range,
- pH range,
- maximum current velocity,
- sheer stress,
- toxicant exposure,
- nutrient exposure,
- and the interaction of these factors.

To develop predictive models of climate change impacts it will be important to establish species-specific thresholds for growth (vegetative growth rates and production), survival and resilience for the whole life history of seagrasses. At present, research has concentrated on responses to light limitation and nutrient enhancement in the GBR, yet many crucial information gaps remain. Even fewer data exist on the influence of toxicants, salinity, temperature and pH. The influence of these parameters should not only include standing biomass but flowering, seed production, seed germination, seedling growth and seedling survival as these are the factors that limit recovery potential.

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