Chapter 7:
General discussion – Mitigating climate change with seagrass ecosystem services
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Seagrasses alter their surrounding environment both chemically and physically. Through this alteration, seagrass meadows provide ecosystem services that are important for surrounding organisms, including people. Although the ecosystem services provided by seagrass meadows are acknowledged within the scientific community, there has been little quantification of these services, the factors that affect them and how they contribute to shaping the physical landscape of the coastal zone. With this thesis, a mechanistic understanding of the ecosystem services provided by seagrass meadows within the Caribbean was established, in the effort to determine the full effect that these services have on shaping the Caribbean coastal environment. Utilising this mechanistic knowledge, the future of seagrass ecosystem services under the threats of climate change and other increasing anthropogenic pressures was predicted, thereby gaining an insight into how the Caribbean’s seagrass-dominated bays will look in the future. Only by understanding how ecosystems function and the ecological feedbacks between the biotic and abiotic components, can we realise the true value of specific ecosystems and their potential for mitigating issues we are facing now and in the future.

Dynamic pH within coastal vegetated ecosystems

The coastal zone is a dynamic system that exhibits a wide range of environmental conditions, this variability enables a great diversity of productive ecosystems (Mann 1973; Short et al. 2007; McLeod et al. 2011). Recognising the drivers of this environmental variability is required to understand the ecosystem functioning within the coastal zone, and thereby, improve our ability to forecast the response of coastal ecosystems to global change. Up until recently, forecasts of future ocean acidification conditions were based on the stable pH of the open ocean (Caldeira and Wickett 2005). More recently, the temporal pH fluctuations within vegetated ecosystems have been recognised and included in studies examining the response of coastal organisms and communities to ocean acidification (Price et al. 2012; Cornwall et al. 2013a; Rolenda et al. 2015; Boyd et al. 2016; Mangan et al. 2017). Indeed, the metabolism of tropical seagrass meadows causes substantial pH fluctuations within the meadows locality that are greater than the predicted pH of the ocean in a high-CO$_2$ world (Chapter 2). Diurnal pH fluctuations of more than 0.3 units were observed within an expansive dense seagrass meadow of *Thalassia testudinum* (Chapter 2). Similar pH fluctuations have been observed in dense seagrass meadows of *Posidonia oceanica* in the Western Mediterranean, which exhibited pH fluctuations of 0.24 units over a diurnal cycle during the summer months (Hendriks et al. 2014).
Such fluctuations create pH conditions that are distinct to the pH environment within the open ocean (Hofmann et al. 2011), and expose organisms living within these vegetated habitats to much more extreme pH conditions than originally considered. However, further complicating the pH environment within vegetated coastal ecosystems is the hydrodynamic setting, which controls the magnitude and the spatial extent that vegetation alters the pH of the surrounding seawater (Chapter 2).

Hurd (2015) hypothesised that slow flow habitats would experience greater pH fluctuations than those sites with stronger hydrodynamic forces. This hypothesis insinuates that the pH environment within the coastal zone varies both temporally and spatially depending upon the hydrodynamic setting. This spatial variability of the pH was displayed within the tropical seagrass meadows of the Caribbean (Chapter 2). The magnitude of pH fluctuations within similar seagrass meadows varied between sites with contrasting hydrodynamic regimes, displaying the counteracting effect that hydrodynamic forces have on the alteration of the pH by the photosynthesising seagrass meadow (Chapter 2). In addition, the pH variability increased in magnitude from the coral reef to within the seagrass meadow, displaying how biotically-altered seawater travels downstream and becomes further altered by the seagrass meadows that it passes (Chapter 2; Koweek et al. 2018; Wahl et al. 2018). The measured spatial variability of pH within the seagrass meadows leads to the conclusion that organisms living within coastal vegetated ecosystems not only experience fluctuating pH conditions but also unique pH conditions depending upon their location within a vegetated site. Such a finding complicates our forecasting of the response of coastal ecosystems to future low-pH conditions, but could also explain the variation in observed responses of marine organisms to supposedly low-pH conditions (Hall-Spencer et al. 2008; Ries et al. 2009; Kroeker et al. 2011; Price et al. 2011; Johnson et al. 2012; Noisette et al. 2013).

Spatially and temporally variable seawater pH is an inherent component of vegetated coastal ecosystems. Calcifying organisms are considered sensitive to pH changes as they require high pH conditions for calcification (Doney et al. 2009; Nelson 2009), yet many calcifying organisms inhabit these vegetated coastal ecosystems where the pH conditions are constantly fluctuating. These calcifying taxa must, therefore, possess strategies to overcome the dynamic pH regime for them to continue to thrive. Calcifying green macroalgae from the Bryopsidales order (such as Halimeda spp. and Penicillus spp.) grow within and adjacent to tropical seagrass meadows, and therefore, would experience a wide range of pH conditions. The response of calcifying green (chlorophyta) macroalgae to low pH conditions is minimal (Johnson et al. 2014; Vogel et al. 2015), which contrasts that of temperate red (rhodophyta) coralline macroalgae (Hall-Spencer et al. 2008; Andersson et al. 2009; Cornwall et al. 2014). This lack of response could be due to the calcareous bryopsidales algae calcifying within intracellular spaces where pH can be controlled by photosynthetic activity and proton pumps (Borowitzka
and Larkum 1976; De Beer and Larkum 2001; Koch et al. 2013). This mechanism contrasts vulnerable coralline algae, which calcify at their cell walls where it is more exposed to the surrounding low-pH seawater (Borowitzka and Larkum 1987). Other calcifying organisms, such as Blue mussels (*Mytilus edulis*), have been shown to only require short periods of favourable pH conditions to calcify and construct their skeletons (Frieder et al. 2014; Wahl et al. 2018), allowing them to utilise short periods of high-pH conditions. Furthermore, many marine calcifying animals have an organic layer (termed periostracum) that protects their shells from corrosive low-pH seawater (Rodolfo-Metalpa et al. 2011; Peck et al. 2016). Mechanisms that increase marine organisms’ tolerance to low pH conditions appear to be widespread amongst coastal calcifiers, and could be adaptations to the variable pH within the coastal zone. Whether these strategies will help organisms to withstand the lowering seawater pH conditions predicted for the future ocean remains unclear.

**Variable pH habitats as pH refuges against ocean acidification**

Predictions of future ocean acidification estimate a lowering of the mean seawater pH by 0.13-0.42 units (Caldeira and Wickett 2005; Pörtner et al. 2014). This reduction is equivalent to the biotically-induced pH fluctuations within the coastal zone. Henceforth, habitats that exhibit large pH fluctuations, such as seagrass meadows, coral reefs and kelp forests, have been hypothesised to buffer organisms against the low pH bulk waters, thereby providing a high-pH refuge where conditions are favourable for calcification (Semesi et al. 2009; Kleypas et al. 2011; Unsworth et al. 2012; Hurd 2015; Wahl et al. 2018). Monitoring of the diurnal pH fluctuations within the Caribbean seagrass meadows display that the biotically-driven fluctuations do not alter the mean daily pH (*Chapter 2*). A drop in the mean pH of the bulk water will, therefore, also cause a relative shift in the diurnal pH fluctuations to approximately 7.77 - 8.11 or 7.48 - 7.82 under more extreme scenarios. It is hence questionable as to whether the fluctuating pH conditions within vegetated ecosystems will provide a pH refuge for those organisms already inhabiting pH variable areas, as the relative pH conditions they are exposed to will also decrease. Such a decrease in the overall seawater pH will make organisms more dependent on those strategies that allow them to withstand periods of low-pH, thereby increasing their energetic costs (Mangan et al. 2017). A high pH refuge may, therefore, only be relevant to those species that shift their distribution from a region without pH fluctuations to an area that does exhibit pH fluctuations.

Further limitations of the biologically-driven pH fluctuations as pH-refuges are evident when examining the night-time pH. Although the Caribbean seagrass meadows increase the local seawater pH by 0.18 units during the day, there is a 0.1 reduction in the mean bulk seawater pH (pH ~ 8.1) at night. We should therefore be cautious when describing habitats that exhibit large pH fluctuations as pH-refuges, and acknowledge that the favourable pH conditions only
occur during the day. Respiration at night actually exacerbates the unfavourable conditions of a future low-pH ocean. Any species that are able to shift their distribution to areas with pH fluctuations, will also require a mechanism to tolerate or avoid the very low pH conditions at night.

Although there is still little evidence to support the hypothesis that pH fluctuations within vegetated ecosystems may act as pH refuges, the spatial and temporal pH variability is likely to have a secondary indirect affect by improving organisms’ tolerance to ocean acidification. The variable pH environment within coastal vegetated ecosystems increases the habitat complexity, and could promote organisms to acclimate and adapt to variable pH conditions (Botero et al. 2015). Multi-generational studies have shown how adult populations of mussels and oysters from sites with naturally varying-pH are more resilient to low pH conditions than those from sites exhibiting a stable pH (Parker et al. 2012; Thomsen et al. 2017). Thereby, a complex ecosystem with dynamic conditions is more likely to produce organisms tolerant of changes in their environment, compared to habitats with stable and uniform conditions. This tolerance to variable conditions is likely to be beneficial in a world where climate is driving rapid changes in ecosystems.

Global change reducing pH variability in Caribbean coastal regions

The variable pH within vegetated coastal regions is under threat from habitat degradation (Chapter 6). As the biotically-induced fluctuations by vegetation are counteracted by water motion (Chapter 2), the increase in the hydrodynamic forces caused by sea level rise could reduce the spatial extent and magnitude of the seagrass-driven pH fluctuations at more exposed sites. Expansion of the seagrass meadows into new subtidal habitat created by the rising sea level (Short et al. 2016; Keyzer 2018) could potentially compensate for the loss of pH variability within the more wave-exposed regions. However, local and global stressors, such as eutrophication, coastal infrastructure, and rising temperature could limit the ability of seagrass to colonise these new areas (Orth et al. 2006; Short et al. 2016). If the seagrass and fringing coral reef remain, the reduction in pH variability within the Caribbean coastal ecosystem should be relatively minimal (Chapter 2 & 6). Unfortunately, both coral reefs and seagrass meadows are rapidly degrading across the planet (Hughes and Connell 1999; Orth et al. 2006; Waycott et al. 2009; Burke et al. 2011).

Local stressors such as increasing sediment and nutrient runoff (McGlathery et al. 2007), physical disturbance (Eckrich and Holmquist 2000), invasive species (Williams 2007; Christianen et al. 2018), disease, commercial fishing practices, overgrazing (Christianen et al. 2018) and algal blooms (van Tussenbroek et al. 2017) are resulting in a 7% reduction per year in global seagrass habitat (Waycott et al. 2009) and 60% of coral reefs to be classified as seriously damaged (Hughes and Connell 1999; Burke et al. 2011). These local pressures are
being exacerbated by rising seawater temperatures and ocean acidification (Hoegh-Guldberg et al. 2007; Hughes et al. 2017a). Without a fringing coral reef, the hydrodynamic forces entering the bays are greatly increased (Chapter 6), which could reduce the influence vegetation has on the pH variability within the coastal ecosystems (Chapter 2), depending upon the depth change (Chapter 6). Degradation of seagrass habitat will directly reduce pH variability (Chapter 6).

The reduction of variable pH regions within Caribbean bays will cause the bay ecosystem to have a more homogenous seawater chemistry reflecting the bulk water from the open ocean. Such a change, leaves organisms vulnerable to the full effects of ocean acidification. Constant unfavourable calcification conditions of a low pH and low $[\text{CO}_3^{2-}]$ will dominate the bay area. A loss of habitat complexity is often associated with a reduction in species diversity (Heck and Wetstone 1977; Davis et al. 2017). Shifts in species dominance is likely to occur as the variety of mechanisms to withstand low pH conditions cause an unequal response among species. Those species that are dependent upon the transient high pH conditions during the day are likely to be negatively impacted by losing this important period in which calcification is favoured (Frieder et al. 2014; Kapsenberg et al. 2018). Mechanisms that protect calcifying organisms from unfavourable carbonate chemistry conditions will be more crucial but may become more energetically expensive (Mangan et al. 2017). $\text{H}^+$ pumps that maintain favourable pH conditions within the cell (Hofmann et al. 2016) will require more energy to continuously create a pH gradient between the cell and the low-pH bulk water, while maintenance of organic periostacum layers will become more crucial (Rodolfo-Metalpa et al. 2011). Further work, however, is required to understand how reliant species are on the fluctuating pH conditions produced by photosynthesising organisms, and, therefore, what will happen if the variable pH conditions are lost.

Seagrass meadows shape the Caribbean beach landscape

Seagrass meadows in the Caribbean stabilise the seabed and attenuate waves to an extent that they alter the beach landscape. By attenuating waves (Chapter 5) and deflecting flow, seagrass meadows shelter the sediment surface creating a stable seabed in which erosion is reduced (Chapter 3). This reduction in erosion allows sediment to accumulate within the seagrass meadow (Potouroglou et al. 2017). Over time, as the seagrasses continue to grow on top of the stable sediment surface, the sediment gets trapped within the root network. For long-living seagrasses with extensive root networks, such as the late-successional seagrass species $T. testudinum$, this sediment capture can result in raised seagrass beds. The combination of raised seagrass beds with unvegetated deeper regions results in the formation of a complex biogeomorphic landscape (Chapter 5). These complex landscapes along with the seagrass canopy are positioned within the beach shoreface region where they combine to greatly attenuate waves propagating through the beach system (Chapter 5). The robustness of the
seagrass meadows ensure that the seagrass-biogeomorphic landscapes are maintained over long periods (Chapter 4), resisting erosion and attenuating waves even during strong storm events (Chapter 5), and thereby providing effective coastal protection.

Direct measurements of the sediment stabilisation ability of contrasting seagrass patches showed how long-leaved dense seagrass canopies provide the most protection to the sediment surface. Extensive and robust below-ground biomass (roots and rhizomes), however, are required to maintain the seafloor integrity for extended periods and throughout storm events (van Tussenbroek et al. 2008; Christianen et al. 2013). Given that *Thalassia testudinum* possesses all of these characteristics, this dominant Caribbean seagrass species was found to be incredibly effective at stabilising the sediment surface and reducing erosion in the beach foreshore region (Chapter 4 & 5). Other late-successional seagrasses have similar traits to *T. testudinum*, such as *Posidonia* spp. found within the Mediterranean and Australia, *T. hemprichii* found in the indo-pacific and *Thalassodendron* spp. also in the indo-pacific. These seagrasses are therefore also likely to be effective at stabilising sediment and reducing erosion in the coastal zone. Indeed, the well-studied *P. oceanica* in the Mediterranean has been identified to effectively reduce sediment resuspension (Gacia and Duarte 2001) and to alter the bathymetry within the littoral zone through wave attenuation and sediment stabilisation (Tigny et al. 2007).

*Coastal protection by seagrass to combat sea level rise and increasing storm intensity*

The coastal protection services provided by late-successional seagrass meadows could mitigate much of the negative impacts of sea level rise and increasing storm intensity. A concerning consequence of these climate-driven pressures is that they increase coastal erosion, which would intensify the deepening of bays and coastal regions (Zhang et al. 2004). This could lead to a positive feedback with larger hydrodynamic forces entering the beach region, exacerbating coastal erosion and continually deepening the beach shoreface, thereby creating a more unstable seabed prone to erosion (Chapter 4). The stabilisation of sediment and creation of an erosion-resistant seabed by seagrass meadows helps to combat coastal erosion, thereby limiting the depth increase caused by sea level rise. By maintaining a shallow shoreface and through the wave attenuation by the seagrass meadows, the risk of coastal flooding is reduced (Barbier et al. 2008; Jones et al. 2012; Arkema et al. 2013). The ability of the robust late-successional seagrass meadows to withstand extreme hydrodynamic forces, ensures that they continue to provide these vital coastal protection services during and after extreme storm events (Chapter 5).

In some cases, where a continuous supply of sediment is present, the sediment stabilisation of the seagrass meadows could allow for the vegetated ecosystems within Caribbean bays to accrete and keep up with sea level rise. Indeed there was approximately a 200 mm increase in
the bed level within the sheltered, landward portions of the seagrass meadows at both Baie de L’Embouchure and Orient Bay (St Martin) over an 18 month period, which equates to an accretion rate of 133 mm y\(^{-1}\) (Chapter 5). Extrapolating this rate of accretion suggests that some sheltered seagrass meadows with an ample sediment supply will be able to keep up with sea level rise, given the projected rate of sea level rise in the Caribbean of 9.3 mm y\(^{-1}\) with a 5°C temperature increase (Jevrejeva et al. 2016). Sediment accretion, however, is dependent upon the sediment stabilisation ability of the seagrass meadow, the hydrodynamic regime and the sediment source. Seagrass meadows experiencing stronger hydrodynamic regimes exhibit minimal or no sediment accretion (Chapter 5), indicating that higher energy sites will struggle to keep up with sea level rise. Nevertheless, the minimal erosion observed within higher-energy sites (Chapter 5) and the long-term beach profiles from the naturally vegetated beach of Puerto Morelos (Chapter 4), display how even when accretion does not occur, the seagrass meadows of \(T.\ testudinum\) help to maintain a stable bed-level. Absence of seagrass meadows, however, can lead to severe coastal erosion (Chapter 4 & 6).

Seagrass meadows can provide effective self-sustaining coastal protection which benefits both human communities and the natural environment (Chapter 4). It has been established, however, that not all seagrasses provide the same level of coastal protection. In regions with robust late-successional seagrasses, such as \(P.\ oceanica\) in the Mediterranean and other Posidonia and Thalassia species around Australia and the Indo-pacific, there is great potential for utilising seagrasses for coastal protection. In cooler temperate climates, pronounced seasonal variation in environmental conditions leads to fluctuations in the seagrass density throughout the year (Meling-lópez and Ibarra-Obando 1999; Dahl et al. 2020). Temperate seagrass meadows do attenuate flow within their canopy (Gambi et al. 1990; Heiss et al. 2000; Paul and Amos 2011) and can capture and prevent resuspension of sediment (Heiss et al. 2000). However, the coastal protection services vary seasonally, declining in winter when the shoot density of the seagrass meadows decreases (Paul and Amos 2011; Lawson et al. 2012; Adhitya et al. 2014; Marin-Diaz et al. 2020). This decline in winter occurs when storms are more frequent, and thereby, coastal erosion is more likely to occur. It, therefore, has to be acknowledged that the ability of seagrass species with a strong seasonality will have a more limited ability to mitigate sea level rise and coastal flooding.

**Global change threatening seagrass coastal protection services**

Established seagrass meadows can provide important coastal protection services, however, the effectiveness of these coastal protection services is dependent upon the density of the meadow, the seagrasses morphology, the meadow location and the hydrodynamic regime. Through the decline of important late-successional species and the increase in hydrodynamic forces within the beach zone due to sea level rise (Chapter 6; Zhang et al. 2004), the vital coastal protection
services provided by seagrass are under threat. Late-successional seagrass species possess traits that allow them to withstand strong hydrodynamic forces. This robustness is expected to be beneficial when exposed to an increasing hydrodynamic regime caused by sea level rise (Chapter 6) and more frequent extreme storm events (Chapter 5). The low rates of shoot turnover and reproduction of late-successional seagrasses, however, makes them susceptible to other disturbances (Kilminster et al. 2015; O’Brien et al. 2018). Trampling (Eckrich and Holmquist 2000), marine heat waves (Short and Neckles 1999), eutrophication (Burkholder et al. 2007; McGlathery et al. 2007) and intensive grazing (Chapter 3, Christianen et al. 2014, 2018) have all been attributed to the global decline of mature seagrass meadows (Orth et al. 2006; Waycott et al. 2009). Previously, natural community succession would allow the seagrass meadows to recover (Williams 1990). Sustained pressure from local stressors and the spread of invasive opportunistic species, however, threatens this natural recovery.

As global seagrass meadows shift from stable, dense late-successional meadows to fragmented meadows consisting of fast growing opportunistic species, coastal regions become more vulnerable to erosion and flooding. More frequent extreme storm events (Smith et al. 2010; Knutson et al. 2013) in combination with a shift to more opportunistic species in the marine environment (Williams 2007; van Tussenbroek et al. 2014; Willette et al. 2014; Christianen et al. 2018), increases the likelihood of sediment being exposed and unprotected during and after storm events (Preen et al. 1995). In addition, the continuously greater hydrodynamic forces reaching the beach region, driven by sea level rise, further increases the instability of bare sediment (Chapter 6). Through increasing hydrodynamic forces and degradation of seagrass communities, it is expected that coastal erosion will be exacerbated and could lead to a positive feedback that further discourages the growth of late-successional seagrass species (Chapter 4, van der Heide et al. 2007; Saunders et al. 2014). An increase in the vulnerability of coastal ecosystems to erosion will have wide-ranging implications by increasing the risk of flooding to coastal areas, as well as altering the ecosystem dynamics where seagrass presently dominate.

*Lowering light due to sea level rise*

An additional consequence of a rising sea level and thereby deepening of the bays is a decrease in the light reaching the seabed where seagrass exist. As light travels through seawater it is scattered and absorbed by dissolved and suspended particles, which leads to the light exponentially decaying with depth (Kirk 1994). Caribbean seagrasses have high light requirements, only growing successfully when they receive more than 10-15% of the surface irradiance (Kenworthy and Fonseca 1996; Kelble et al. 2005). Typically the water clarity within the Caribbean coastal zone is high, with few suspended particles to increase the decay of light. Comparisons of light measurements on the shore and within the three studied seagrass meadows in this thesis, show that the light within the seagrass meadows at 1 meter depth was
on average \(26.2 \pm 2.3\%\) of the surface irradiance, with higher light levels in the shallower seagrass meadow at the sheltered site (Fig. 1). The light reaching the seagrass in these shallow sites is currently well above the light required for the growth of the dominant Caribbean seagrass species: *Thalassia testudinum* and *Syringodium filiforme* (Kenworthy and Fonseca 1996; Kelble et al. 2005). An additional 0.87 m water depth, however, will greatly reduce the light reaching the existing seagrass meadows. Although seagrass may migrate into the shallower new subtidal regions around the edge of the bays, seagrass meadows in deeper regions where light is limiting are likely to be negatively impacted (Saunders et al. 2013). A loss of seagrass in the deeper regions will increase the spatial extent of the unvegetated region within the middle of the bay (Chapter 6), and could offset the gains from new habitable zones (Saunders et al. 2013).

![Percent Surface Irradiance](image)

**Fig. 1.** The percent surface irradiance that reaches the seabed in the seagrass meadows at the sheltered (Baie de L’Embouchure), exposed (Orient Bay) and unidirectional flow site (Islets de L’Embouchure) during daylight hours. Grey points represent mean ± 95% confidence intervals. Measurements were conducted with Onset HOBO® Pendant Temperature/Light loggers hourly for one month between October and November 2015.

Mitigating climate change with seagrass meadows

Seagrass meadow are widespread within the Caribbean region and are an important habitat that shapes the Caribbean coastal landscape. The stable beach system maintained by the late-successional seagrass meadows provides vital ecosystem services that are beneficial for both human communities and associated organisms. Wave attenuation and sediment stabilisation in the beach shoreface region minimises coastal erosion (Chapter 3 & 4), and as a consequence, the likelihood of coastal flooding (Barbier et al. 2008; Jones et al. 2012; Arkema et al. 2013). Maintaining these stable beaches is also important for tourism within the Caribbean (Chapter 4). In addition, the sheltered habitat with a variable physio-chemical environment created by seagrass meadows, supports local fisheries (Unsworth et al. 2019b). Unfortunately, these vital
ecosystem services are under threat from global change. The continued degradation of fringing coral reefs (Hughes and Connell 1999; Burke et al. 2011), in particular, threatens the resilience of tropical seagrass ecosystems and the provision of their ecosystem services (Chapter 6). If these seagrass ecosystem services are lost, then the negative impacts of climate change will be exacerbated (Chapter 5 & 6). Coastlines will become more vulnerable to coastal erosion, which is escalating due to sea level rise and increasing storm intensity (Zhang et al. 2004). In addition, organisms adapted to the fluctuating pH conditions within vegetated habitats will be more exposed to uniform low-pH conditions from ocean acidification (Chapter 2 & 6).

In this thesis the importance of maintaining healthy vegetated beach ecosystems to ensure the continued provision of vital ecosystem services is highlighted. A natural healthy ecosystem can be resilient to many of the stressors imposed by climate change, such as alterations in the carbonate chemistry, greater hydrodynamic forces and increasing storm intensity. Unfortunately, years of continued intensification of activities that are harmful to the natural environment have left the world’s coastal ecosystems degraded (Orth et al. 2006; Hughes et al. 2017a) and at a tipping point where they are vulnerable to further stressors (Hughes and Connell 1999; Waycott et al. 2009; McCormick et al. 2013). Action is required now if we wish to maintain some sort of semblance of the natural environment within the Caribbean and other coastal regions around the world.

Restoring Caribbean seagrass ecosystems for coastal protection

Reversing the degradation of coastal ecosystems is not a simple matter. Only 37% of seagrass restorations have survived (van Katwijk et al. 2016). Restoration projects require time, money and support from local communities and stakeholders. Conducting restoration projects in the coastal zone is challenging, with waves and storms often undoing hours of intensive restoration labour (Bayraktarov et al. 2016). The first aspect of restoration should be identifying and improving the environmental conditions of a site to ensure successful re-plantings. Maintaining a high water quality in the coastal environment through adequate wastewater treatment and disposal is often a main concern in populated areas (McGlathery et al. 2007; Saunders et al. 2013). In addition, ensuring coastal infrastructure allows the natural sediment and wave dynamics to persist is of high importance (Phillips and Jones 2006; Silva et al. 2014). A site that has high wave reflection or where sediment is chronically eroding will require a greater effort to stabilise the sediment surface before a restoration project has a chance of success.

Seagrass require a stable sediment surface for colonisation, which is difficult to provide in the beach backshore region where wave forces are constantly moving exposed sediment. Naturally a stable sediment surface is created through the succession of the meadow species over time (Williams 1990). First those species tolerant of an unstable sediment surface colonise the bare sand, such as calcifying macroalgae and colonising seagrass like *Syringodium filiforme* and
Halodule wrightii. As the sediment surface becomes more stabilised then late-successional species will appear, such as Thalassia species (Birch and Birch 1984; Williams 1990). This succession can take many years and, therefore, is generally not suitable for restoration projects; which have a limited time frame. Methods of using weight to stabilise the plant, consistently perform better than other planting techniques (van Katwijk et al. 2016). Using hessian bags filled with sand and seagrass seeds and anchored to the seafloor have shown promising results (Zhang et al. 2015; Unsworth et al. 2019a). This method provides a stable sediment surface for the seagrass to grow upon, and over time the hessian bags naturally degrade.

It is clear that tropical seagrass meadows are not an independent ecosystem, instead fringing reefs are vital for providing wave-sheltered conditions (Chapter 6; Saunders et al. 2014), while vegetation on coastlines, such as mangroves, help to filter nutrient and sediment runoff from the land (Berkström et al. 2012; Gillis et al. 2014). Ideally, when restoring seagrass meadows, the neighbouring ecosystems in which the seagrass meadows are connected with, should also be restored. The continued degradation of coral reefs will lead to a significant increase in the wave forces entering tropical bays (Chapter 6). Stronger hydrodynamic forces will have implications for the structure and functioning of bay ecosystems, particularly seagrass meadows and their influence on the surrounding environment (Chapter 6). Improving water quality and enforcing more sustainable fishing practices is vital to increase the resilience of coral reefs to global warming and ocean acidification (Jordan et al. 2010; Hughes et al. 2017b; Roberts et al. 2017). Where reefs are already critically degraded, combining artificial reefs with coral-restocking will ensure that the sheltered environment that the fringing coral reefs provide can be maintained, even as the sea level rises at a rapid rate (Hughes et al. 2017a).

To ensure that coastal sandy bays of the Caribbean keep up with sea level rise, sediment input needs to be sustained. Although the degradation of coral reefs will result in an influx in sediment input from the erosion of the broken reefs, this will not provide a long term solution. The decline in coral growth, will eventually lead to a decline in the sediment input from coral reefs. Tropical calcified green macroalgae (i.e. Halimeda spp., Penicillus spp.) also currently provide a substantial amount of calcareous sediment to Caribbean bays and lagoons (Harney and Fletcher 2003; van Tussenbroek and van Dijk 2007a). Climate change response studies do show that these species are relatively resilient to ocean acidification (Campbell et al. 2016; Peach et al. 2016), and thereby, may continue to provide a sediment source. A potential decline in sediment input from the loss of coral reefs, would prevent the Caribbean bays from accreting and could shift the bays to an erosion regime. Effort is required to maintain conditions suitable for coral reefs and calcifying macroalgae so that the natural sediment dynamics can be sustained, otherwise, a new sediment source should be established. Sequential sand nourishments where small amounts of sand are distributed throughout the bays, or placed in an
area where flow and waves naturally distribute the sand (Stive et al. 2013) throughout the bay could be employed.

Outlook

The world’s ecosystems have evolved through time, adapting to their conditions so that they survive and continue to thrive. By researching ecosystems and understanding how they function, we can discover unique and effective strategies that can potentially be employed to mitigate problems facing our society. With this thesis it is shown that the bio-physical and biochemical feedbacks between seagrasses and hydrodynamic forces create a unique environment with diverse conditions. Through the presence of seagrass, the coastal landscape is greatly altered, which helps to protect the coastal region from erosion and flooding. The ecosystem services provided by seagrass, however, are under threat. Sea level rise and coral reef degradation increases the hydrodynamic forces entering the beach region where seagrasses exist, thereby counteracting the effect that seagrasses have on the surrounding environment. In addition, local pressures from large visitor numbers, and infrastructure that is built at the expense of the natural environment is degrading coastal ecosystems.

The research on the ecosystem services provided by seagrass meadows is clear. Seagrass ecosystems provide abundant coastal protection and habitat creation services that benefit both the surrounding environment and human communities. Protecting and harnessing these ecosystem services will improve the Caribbean’s resilience to increasing storm intensity and sea level rise. Contrastingly, the loss of seagrass ecosystems will only help to increase the vulnerability of the Caribbean region to climate change effects. Thereby, urgent effort is required to protect and restore seagrass ecosystems in the Caribbean.

Only healthy ecosystems will have a chance of withstanding the more extreme weather events and rising CO₂ and temperature brought about with climate change. The rapid rate in which climate change is occurring gives us, and present-day ecosystems, little time to adapt to the new climatic conditions on earth. Urgent effort is required to improve the health of seagrass ecosystems. Although this requires substantial investment in resources and money, the benefits will go far beyond coastal protection. “A society grows great when old men plant trees whose shade they know they shall never sit in.”