SEAGRASS PRODUCTIVITY, RESILIENCE TO CLIMATE CHANGE AND CAPACITY FOR RECOVERY IN THE TORRES STRAIT 2011-2012

Report No. 13/26

July 2013

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Australian Government
Torres Strait Regional Authority
TropWATER
James Cook University Australia

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2011-2012

A Report for Torres Strait Regional Authority
(TSRA)

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EXECUTIVE SUMMARY

- The Tropical Water & Aquatic Ecosystem Research (TropWATER) Seagrass Group in collaboration with the Torres Strait Regional Authority Land and Sea Management Unit (TSRA LSMU) established a program to develop critical information for the management of dugong and turtle in the Torres Strait by understanding how their key food resource, seagrass, is affected by seasonal change, climate and their ability to recover from impacts. The project also provides key information on how seagrasses in the Torres Strait may be affected by climate change and how this may impact on turtle and dugong management.

- Several experimental sites were set up on intertidal and subtidal seagrass meadows examining seagrass recovery, productivity and potential environmental and climate drivers of change including light, temperature, salinity and pH.
- The first twelve months of the study show that seagrasses at Mabuiag Island undergo distinct seasonal and inter-annual changes in biomass as a result of complex interactions with natural drivers of change. Water temperature, daytime tidal exposure, salinity and rainfall were identified as the environmental variables contributing most significantly to the observed seasonal and inter-annual variation in intertidal seagrass biomass at Mabuiag Island.
- The recovery experiments found that there were strong differences between meadow locations (subtidal and intertidal) and species in their capacity for recovery and the mechanisms employed to recolonise from disturbances. For intertidal mixed species meadows in this study, asexual colonisation was the most important mechanism for recolonisation of cleared plots (gaps), whilst in the subtidal, recovery via a combination of sexual and asexual means was evident.
- Most seagrass species at Mabuiag Island would likely be able to recover from small scale disturbances over a period of months where adult plants remain by capitalising on their highly clonal nature. However recovery from larger scale disturbances would have to rely more heavily on colonisation by sexual propagules and therefore may take years to recover, if at all.
- Productivity levels of Mabuiag Island seagrasses appear to compare highly with other globally important ecosystems. The net primary productivity of the intertidal study meadow at Mabuiag Island at its peak in October (0.71 g C m^{-2} day^{-1}) was higher than that of tropical coastal seagrasses at Abbot Point, Queensland (0.65 g C m^{-2} day^{-1}), and far above terrestrial grassland systems (0.50 g C m^{-2} day^{-1}). This provides evidence that intertidal seagrasses at Mabuiag Island make a major contribution to local productivity and in supporting dugong and turtle populations.
- Predicted changes to climate variables in Torres Strait and the Pacific region could have far reaching consequences for local seagrass community distribution and structure, which in turn may have profound implications for local dugong, turtle and commercial fisheries species. Management of seagrass resources in the Torres Strait should be focused on reducing any anthropogenic impacts to seagrass so as to ensure resilience levels of local seagrass populations remain high.

We recommend continuation of the monitoring and research program at Mabuiag Island to allow better correlations and further identify key climate impacts to Torres Strait seagrasses. These relationships require data to be collected over several seasons and years to be fully developed. Results will provide much-needed information on how natural climate variability, and future scenarios of climate change, may impact seagrass meadows and therefore dugong and turtle feeding opportunities. Information that is collected will be incorporated into modelling of the consequences of climate change on Torres Strait seagrass distribution to develop appropriate dugong and turtle management strategies that respond to potential shifts in seagrass distribution and communities.

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1 INTRODUCTION

1.1 Background

The Torres Strait region covers an area of more than 35,000 km^2 and is located on one of the world's most extensive continental shelves. It comprises 247 islands, eighteen of which are permanently inhabited. Local island communities in the Torres Strait are deeply connected to their sea country through their culture, economy, spirituality and social way of life. The health of their marine resources has been, and continues to be, vital to Torres Strait Islanders from a subsistence, commercial and cultural point of view. Seagrass ecosystems are of particular importance to Torres Strait Islanders as they support fisheries, dugong and turtle populations which are of key importance, as well as driving much of the marine primary productivity in the region.

The importance of seagrasses as structural components of coastal ecosystems is well recognised. Seagrass/algae beds have been rated the third most valuable ecosystem globally (on a per hectare basis) for ecosystem services, preceded only by estuaries and swamps/flood plains (Costanza et al. 1997). The Torres Strait is estimated to contain between 13,425 km^2 (Coles et al. 2003) and 17,500 km^2 (Poiner and Peterkin 1996) of seagrass habitat, providing critical habitat for commercial and traditional fishery species as well as important food resources for endangered dugong and green turtle populations (Coles et al. 2003; Marsh and Kwan 2008; Sheppard et al. 2008). The largest population of dugongs in the world is in Torres Strait (Marsh et al. 1997, 2002), where the long-standing importance of dugongs for subsistence by Torres Strait Islanders has been traced in archaeological deposits dating back at least 7000 years (Vanderwal 1973; Wright 2011). For the indigenous people of Torres Strait, the dugong is the most significant and highest ranked marine food source in the traditional subsistence economy (Nietschmann 1984; Raven 1990; Johannes and MacFarlane 1991; Kwan 2002).

The dynamics of seagrasses in Torres Strait may be strongly influenced by natural and anthropogenic pressures. At the Orman Reefs, Torres Strait, the biomass and growth of seagrasses can vary by up to a factor of 3.5 during one year (Rasheed et al. 2008) while in South East Asia, they can vary by a factor of four (Brouns 1985; Erftemeijer and Herman 1994; Lanyon and Marsh 1995). There are a variety of factors that influence seagrass meadow biomass, area, and species composition including: physical disturbance (Duarte et al. 1997), herbivory (Klumpp et al. 1993), intraspecific competition (Rose and Dawes 1999), nutrients (Short 1988), seasonality of environmental factors (Mellors et al. 1993; McKenzie 1994) and flooding (Campbell and McKenzie 2004). Studies have shown substantial seagrass dieback (up to 60%) on two occasions in central Torres Strait (Long and Skewes 1996; Marsh et al. 2004). The causes for these diebacks are unclear. Although suggested to be the result of flooding (Long and Skewes 1996), recent investigations have shown that neither the movements of large sandbanks nor turbidity from rivers on the south coast of Papua New Guinea are likely to affect seagrass communities of Torres Strait on a regional scale (Daniell et al. 2006). Nevertheless, these diebacks have been linked to declines in the dugong population (Marsh et al. 2004).

Whilst we are beginning to gain an idea of the distribution, abundance and productivity contribution of important seagrass habitat in the Torres Strait, a lack of detailed experimental studies in the Torres Strait which quantify potential impacts to seagrass from the effects of physical disturbances such as shipping accidents or changes to environmental factors associated with climate and predicted climate change, has limited our ability to predict the consequences of disturbances on seagrass habitats and their associated ecosystems and fisheries. This is despite the fact that the potential for impacts from shipping activities is acknowledged as being very high (Queensland Transport and Great Barrier Reef Marine Park Authority 2000) and Torres Strait ecosystems are likely to be particularly vulnerable to the effects of climate change (Suppiah et al. 2007). Seagrasses around the Orman Reefs in particular, were identified as one of the most important areas of seagrass habitat in the Torres Strait and Queensland for dugong (Rasheed et al. 2008; Chartrand et al. 2009; Taylor and Rasheed 2010). Rasheed et al. (2008) determined that the above-ground productivity of Orman Reefs' seagrass meadows were high compared with other tropical seagrass communities and likely to be a key contributor to fisheries production, supporting dugong and turtle populations, and carbon cycling in the central Torres Strait. Understanding the dynamics of these seagrass communities and how they may be impacted by changes to climate and their ability to recover from impact are a critical component for developing effective management strategies for dugong and turtle that depend on these areas for food.

1.2 Sampling approach

The Tropical Water & Aquatic Ecosystem Research (TropWATER) Seagrass Group in collaboration with the TSRA LSMU launched a program to develop critical information for the management of dugong and turtle in the Torres Strait by understanding how their key food resource, seagrass, is affected by seasonal change, climate and their ability to recover from impacts. The project also provides key information on how seagrasses in the Torres Strait may be affected by climate change and how this may impact on turtle and dugong management.

The specific objectives of the present study were to:

1. Determine the value of seagrass meadows in terms of primary productivity and how this changes over time;
2. Determine the capacity for, and rate of, recovery following disturbance; and
3. Assess the local water temperature, light, salinity and pH levels in connection to seagrass change.

This report details information collected from experiments still in progress. The information presented refers to the first thirteen months of the experiments, from April 2011 to June 2012.

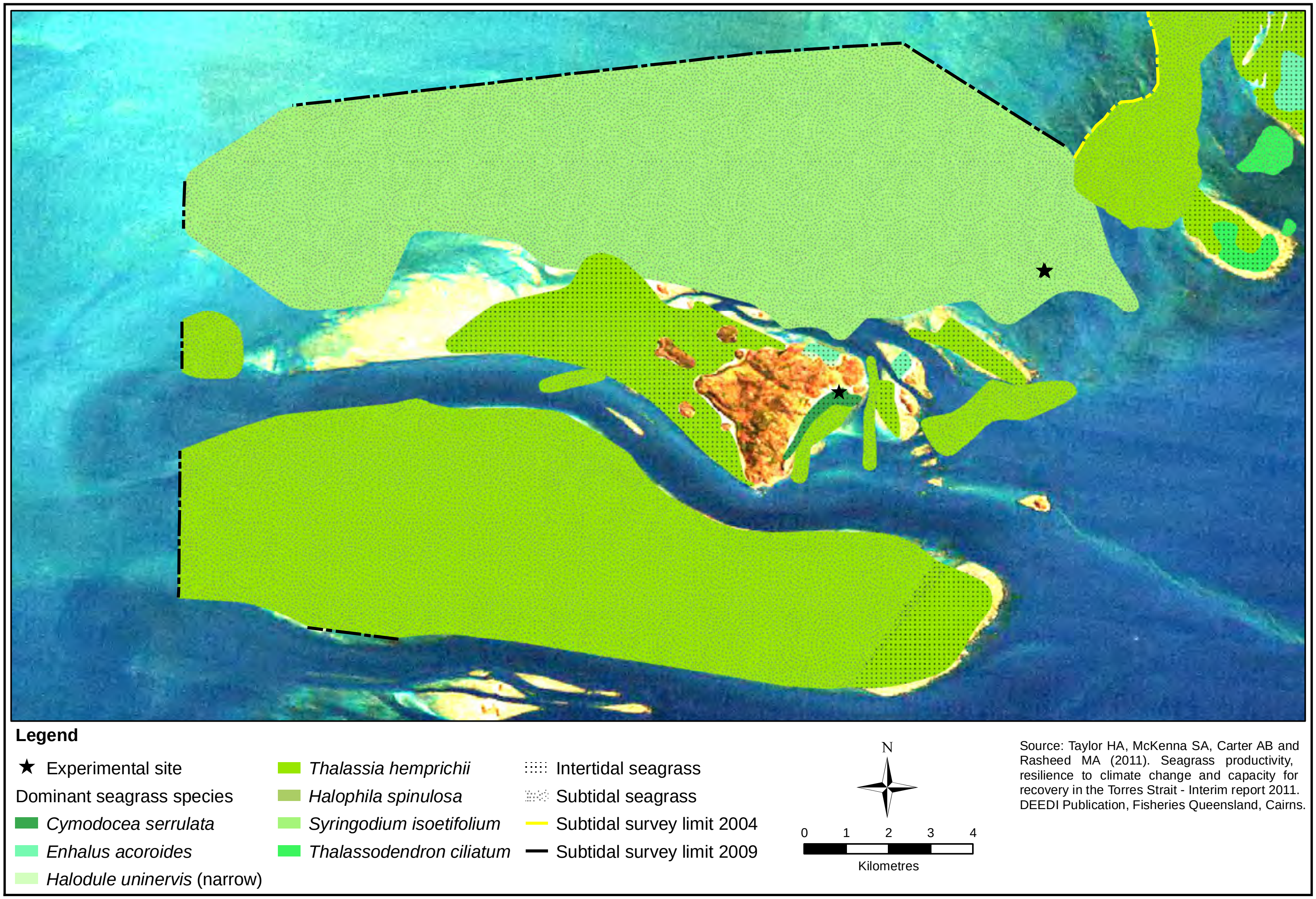
1.3 Study location

Mabuiag Island is located in the Western region of the Torres Strait, approximately 100 kilometres north of Thursday Island. It once formed part of the now submerged land bridge that joined Cape York with Papua New Guinea. A baseline assessment of intertidal and subtidal regions surrounding Mabuiag Island in 2009 and 2010 revealed an extensive coverage of highly diverse seagrasses (Map 1). These seagrasses, along with those at the nearby Orman Reefs, were identified as one of the most important areas of seagrass habitat in the Torres Strait and Queensland for dugong (Rasheed et al. 2008; Chartrand et al. 2009). Additionally, the above-ground productivity of Orman Reef seagrass meadows was high compared with other tropical seagrass communities, indicating that the habitat is likely to be important to fisheries, dugong and turtle, and carbon cycling in the central Torres Strait (Rasheed et al. 2008).

Manipulative seagrass experiments were set up in March/April 2011 in one subtidal and one intertidal location (Map 1) where the seagrass assemblage was reflective of ‘typical’ community types for the region and targeted a majority of species found in baseline surveys conducted in 2009 and 2010. A second round of recovery experiments only was established in late August 2011 (intertidal) and early November 2011 (subtidal) to determine if recovery of seagrasses were affected by seasonal change.

The experimental design for the recovery experiments involved three experimental blocks that were subject to a randomised block design of 12 (0.25 m^2) treatment plots of seagrass. Within each block, the 12 plots were subject to three replicates of four different treatments (see section 2 below). The seagrass data used to examine natural and climate related change in section 1 comes from the control, unbordered replicates within the experimental blocks. Finally, productivity measurements (seed cores, rhizome tagging and leaf marking; section 3) were conducted on seagrass near to the recovery experimental blocks.

Map 1. Location of subtidal and intertidal seagrass around Mabuiag Island (2009-2010) and Orman Reefs (2004) and location of seagrass manipulative experiments (2011-2012).



Source: Taylor HA, McKenna SA, Carter AB and Rasheed MA (2011). Seagrass productivity, resilience to climate change and capacity for recovery in the Torres Strait - Interim report 2011. DEEDI Publication, Fisheries Queensland, Cairns.

2 LOCAL CLIMATE, BENTHIC PAR AND SEASONAL SEAGRASS TRENDS

2.1 Introduction

Historically, very little information was known on the distribution and abundance of important seagrass habitat around Mabuiag Island, despite the nearby Orman Reefs being identified as one of the most important areas of seagrass habitat in the Torres Strait and Queensland for dugong (Rasheed et al. 2008).

Light, temperature, exposure and nutrients affect biochemical processes of organisms, and are considered as major factors controlling seagrass growth (Mellors 2003; Duarte et al. 2006). Many of these factors vary seasonally, and also change between years. This leads to tropical seagrass meadows varying substantially in density and area between seasons (Rasheed 1999; 2004; McKenzie 1994) as well as between years (eg. Chartrand et al. 2010; Taylor and Rasheed 2011). Seagrasses of tropical Queensland are generally at their peak in distribution and abundance during late spring/early summer and decline during winter months (Mellors et al. 1993; McKenzie 1994; Rasheed 1999; 2004).

Extensive coverage of seagrass was identified in baseline surveys on and around Mabuiag Island in 2009 and 2010 (Chartrand et al. 2009; Taylor et al. 2010). Subsequent to that, a Community Ranger Seagrass Monitoring Program was established in 2010 to examine intertidal seagrasses each quarter. The information from this program has given us some level of understanding of intra-annual change to intertidal seagrasses at Mabuiag Island; however we have little to no information on the drivers of this change.

Information on the extent of natural seasonal change is essential in interpreting potential impacts from disturbances and climate change on seagrasses. Recent studies at Hay Point and elsewhere in Queensland have shown that there can be considerable variation in the timing and extent of seasonality in different seagrass meadow types (Chartrand et al. 2008).

The objectives of the seasonal seagrass monitoring study were to;

1. Conduct quarterly monitoring of seagrass abundance at subtidal and intertidal sites;
2. Relate changes measured in seagrass meadows to light, temperature and water quality data collected at those sites; and
3. Compare results of monitoring with data from other locations in Queensland and assess any changes in seagrass abundance, health and resilience in relation to natural events or human induced activities.

2.2 Methods

Sampling methods were similar to those used in the established seagrass monitoring programs for baseline assessment at Mabuiag Island (Chartrand et al. 2009 and Taylor et al. 2010) and long-term seagrass monitoring for other Queensland Ports such as Thursday Island, Cairns, Mackay, Weipa and Karumba (see Rasheed et al. 2001a; 2001b; Campbell et al. 2003; Rasheed et al. 2003; Roelofs et al. 2003).

2.2.1 Seasonal seagrass trends

Seagrass metric data was recorded in nine permanent habitat characterisation quadrats each month in the intertidal and opportunistically when the weather allowed in the subtidal. Seagrass species composition, above-ground biomass, per cent cover and species shoot counts were recorded. Seagrass above-ground biomass was determined using a “visual estimates of biomass” technique described by Mellors (1991). This technique involved an observer ranking seagrass biomass in the field in each of the nine 0.25m^2 quadrats while referring to a series of quadrat photographs of similar seagrass habitats for which the above-ground biomass had been measured. This method was used for both the intertidal and subtidal areas. Two separate biomass ranking ranges were used: low biomass and high biomass. The relative proportion of the above-ground biomass of each seagrass species within each quadrat was recorded. Field biomass ranks were then converted into above-ground biomass estimates in grams dry-weight per square metre (g DW m^{-2}). At the completion of sampling each observer ranked a series of calibration quadrats that represented the range of seagrass biomass in the survey. After ranking, seagrass in these quadrats was harvested and the actual biomass determined in the laboratory. A separate linear regression of ranks and biomass from these calibration quadrats was generated for each observer and applied to the field survey data to determine above-ground biomass estimates.

2.2.2 Environmental parameter monitoring

To develop a relationship between changes in light and temperature and other water quality parameters to seagrass condition and to help model the potential impacts of climate and natural inter-annual changes to seagrasses, water temperature, light (recorded as photosynthetically active radiation (PAR)), salinity and pH levels were assessed both intertidally and subtidally using in-situ loggers. Three different types of loggers were used: (i) Autonomous iBTag submersible temperature loggers recorded temperature (°C) within the seagrass canopy every 15 minutes intertidally and 30 minutes subtidally (Plate 1); (ii) Submersible Odyssey^{TM} photosynthetic irradiance autonomous loggers (light loggers) recorded PAR light measurements every 15 minutes (Plate 1); and (iii) Submersible MX5 Sonde’s measured pH and salinity every 45 minutes (Plate 1).

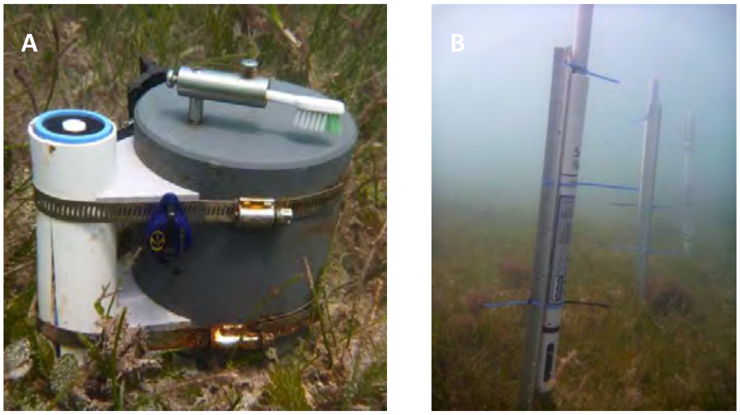


Plate 1. A) Autonomous iBTag attached to a “wiper unit” that cleans the surface of the Odyssey light logger to prevent fouling; and B) three submerged MX5 Sonde units.

Environmental data on total rainfall, mean daily rainfall daily tidal exposure and mean daily global solar exposure were collected. Rainfall (mm) and global solar exposure (megajoules per square metre; MJ m^{-2}) data are publicly available from the Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/data/) for the nearest weather station at Horn Island (station # 027058). Tidal data was provided by Maritime Safety Queensland. Tidal exposure of the intertidal meadow was calculated by summing the total daylight hours that the tidal height was ≤ 0.8m.

For each of the eleven intertidal and five subtidal sampling periods (not including time zero), a mean value was determined for all environmental data for the week, fortnight, 1, 2 and 3 months prior to the day of seagrass monitoring.

2.2.3 Statistical analysis

All data presented are shown as means (± standard error), except where otherwise stated. Percent cover and above-ground biomass data were analysed to determine intra-annual differences for each month between March 2011 and June 2012. Analysis of variance (ANOVA) was conducted in SigmaPlot v.11.0. Where data did not conform to the assumptions of ANOVA, data were transformed. Where data continued to differ from the assumptions of ANOVA the test was still conducted, but in order to minimise the possibility of recording a Type 1 error, an α level of 0.01 was used instead of α = 0.05 (Underwood 1997). Where a sigificant treatment difference (α = 0.01) was detected, a post-hoc Behrens Fisher Test (unequal variances) was permformed to determine differences amongst months. Detailed results are presented in Appendix 1.

To examine relationships between meadow biomass and environmental variables linear regression models were fitted for each intertidal and subtidal meadow. The strength of the predictive relationship was tested for each of the five time periods (1 and 2 weeks, 1, 2 and 3 months). When more than one time period was a significant predictor of biomass for an environmental variable an analysis of covariance (ANCOVA) was used to test for differences in the intercepts and slopes of the relationships. The time period with the highest predictive power for each environmental variable was determined by comparing R^2 values of significant relationships.

Total rainfall, mean rainfall and tidal exposure data were log(x+1) transformed to meet the assumptions for regression and ANCOVA statistical analyses.

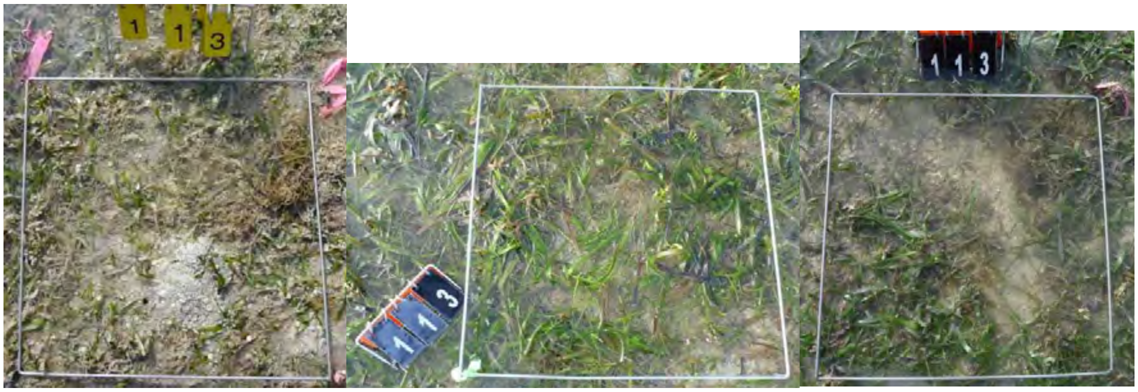
2.3 Results

2.3.1 Seasonal seagrass trends

Seven species of seagrass were recorded in the intertidal site. In decreasing order of abundance (biomass) they were: *Cymodocea serrulata; Cymodocea rotundata; Thalassia hemprichii; Syringodium isoetifolium; Halodule uninervis* (wide and narrow leaf morphologies); *Enhalus acoroides and Halophila ovalis*. Subtidal seagrasses consisted of six seagrass species: *Syringodium isoetifolium; Halophila spinulosa; Cymodocea serrulata; Halophila ovalis; Cymodocea rotundata* and *Halophila decipiens*.

Meadow biomass was significantly higher in the spring/summer season than in the winter season (Figures 1 and 2; Plate 2; Appendix 1). Total above-ground biomass of intertidal seagrasses at Mabuiag Island showed a gradual increase to a maximum during January-February (68.9 ± 9.3 g DW m^{-2}). Subsequently, their biomass decreased considerably from March before reaching minimum levels in May-June (27.9 ± 1.8 g DW m^{-2} May 2011 and 44.1 ± 3.5 g DW m^{-2} June 2012). Subtidal seagrasses similarly were at their lowest biomass in August (29.6 ± 3.1 g DW m^{-2}) before reaching almost 3.5 times higher in December (102.6 ± 5.2 g DW m^{-2}).

Interannual change to intertidal seagrass was also evident, with significantly higher biomass recorded in May 2012 (53.8 ± 5.0 g DW m^{-2}) than in May 2011 (27.9 ± 1.8 g DW m^{-2})(Figure 1; Plate 2; Appendix 1). The same was not true of the subtidal where seagrass was at the same level in April 2011 and April 2012 (Figure 2; Appendix 1). Further data over multiple seasons and years will continue to strengthen and resolve the pattern of seagrass change.



May 2011 **February 2012** **May 2012**

Plate 2. Seasonal and interannual change in above-ground biomass of seagrass in a permanent plot, Mabuiag Island.

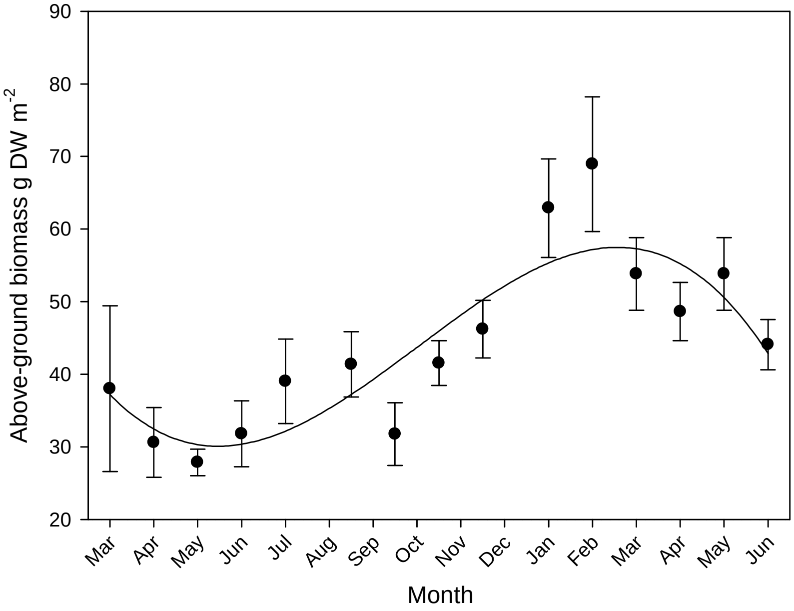


Figure 1. Seasonal variation in above-ground biomass (± standard error) of intertidal seagrass, Mabuiag Island, March 2011 – June 2012. Line represents cubic polynomial best fit curve (R^2=0.842).

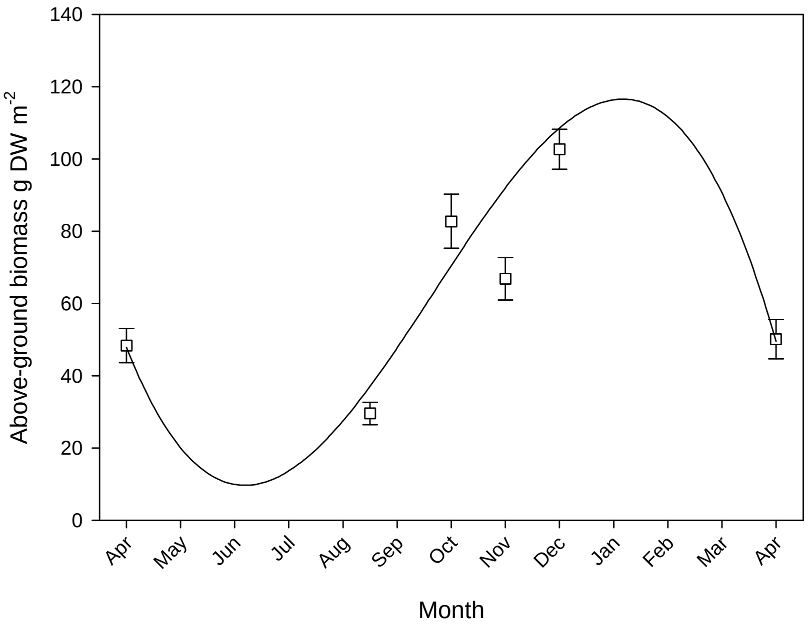


Figure 2. Seasonal variation in above-ground biomass (± standard error) of subtidal seagrass, Mabuiag Island, March 2011 – June 2012. Line represents cubic polynomial best fit curve (R^2=0.93).

2.3.2 Environmental parameter monitoring

Seagrasses in the intertidal zone were exposed during daylight hours on low tide (1-3 days duration) most months between March 2011 and mid June 2012. Typically exposure was for 1-3 hours each day (Figure 3). Seagrasses were most exposed between August and October 2011. Conversely, no daylight exposure was recorded between January and February 2012.

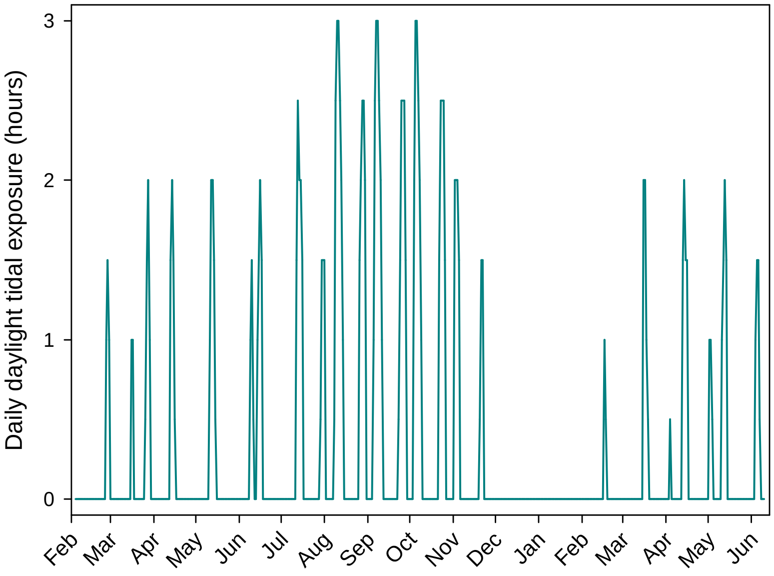


Figure 3. Total daily tidal exposure during daylight hours (0600-1800) at Mabuiag Island, Torres Strait, March 2011 – June 2012.

The maximum water temperature recorded in the intertidal was 35.6°C in late March 2011 followed by 34.8°C in March 2012, indicating that the shallow pools of water that are retained over the seagrass meadow became super heated during low tide exposure events (Figure 4). The average intertidal water temperature slowly declined from April 2011, as expected with the transition from the hot months of the monsoon season to the cooler dry season. Interestingly, the mean daily water temperature as recorded at the canopy height of seagrasses in the subtidal (6m below mean sea level) was very similar to that of the intertidal region, minus the sharp peaks observed in the intertidal zone during exposure times (Figure 4).

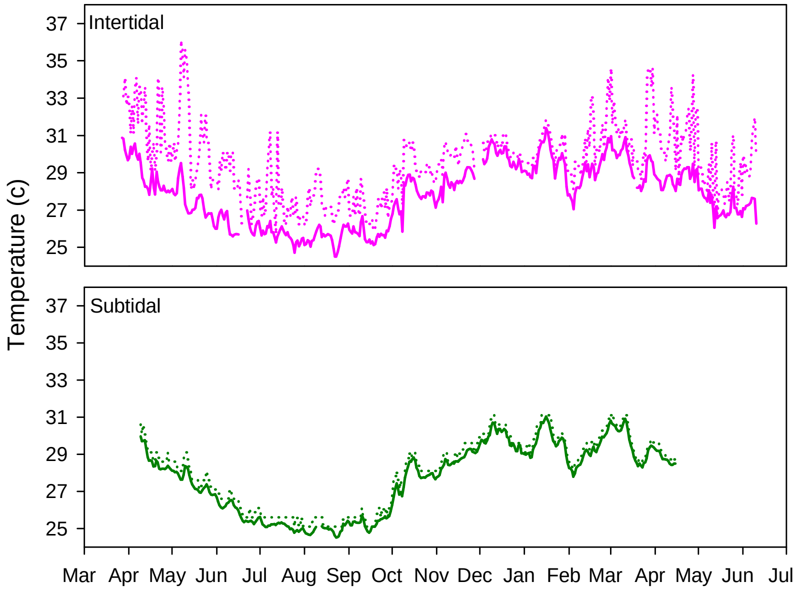


Figure 4. Mean (solid line) and maximum (dashed line) daily water temperature (°C) recorded by in situ temperature loggers in the seagrass canopy for intertidal and subtidal meadows at Mabuiag Island, Torres Strait, March 2011 – August 2012.

Light data collected in the intertidal and subtidal regions demonstrated the high variability exhibited in the amount of light that reaches seagrasses and is available for use in photosynthesis. Average monthly PAR levels ranged from 9.51 to 30.8 mol m^{-2} d^{-1} in the intertidal and 1.9 to 8.46 mol m^{-2} d^{-1} in the subtidal (Figure 5). PAR levels showed expected responses to weather and tidal patterns. During periods of heavy rainfall, PAR decreased in both the intertidal and subtidal, likely due to a high percentage of cloud cover lowering atmospheric PAR (Figure 5 and 6). Average benthic total PAR was greatest between August and December 2011, and lowest during April to July. Average PAR levels were approximately three times higher in the intertidal than in the subtidal (Figure 5). Variability was also much greater in the intertidal, likely due to influences from tidal regimes. A low tide at midday (for example) would have left the PAR loggers exposed during the time when sunlight was strongest, substantially increasing PAR. Conversely, on a midday high tide the PAR loggers would have been completely submerged and would have reported lower PAR levels.

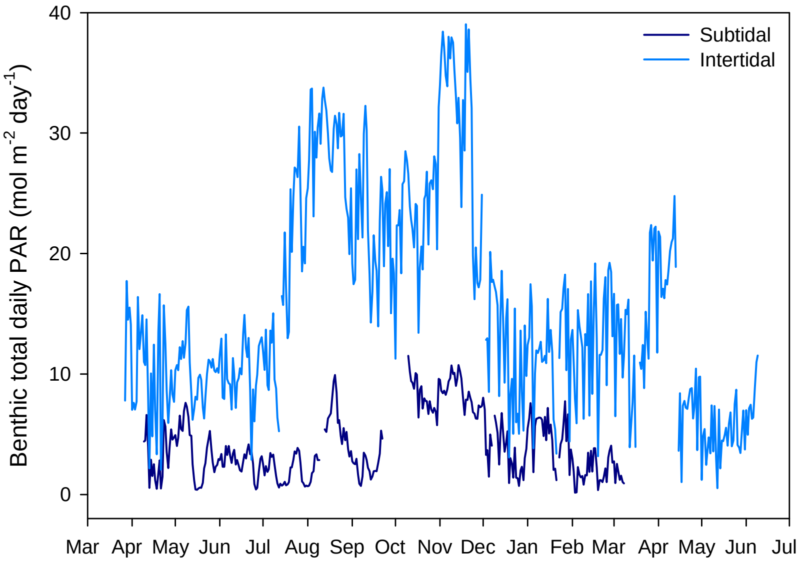


Figure 5. Benthic total daily PAR (mol m^{-2} day^{-1}) recorded by *in situ* PAR loggers in the seagrass canopy of intertidal and subtidal meadows at Mabuiag Island, Torres Strait, March 2011 – June 2012.

There was a distinct wet and dry season evident in the Torres Strait in 2011 and 2012 with little to no rainfall recorded between June to December and a peak of over 100mm per day in February 2012 (Figure 6). Solar exposure was greatest in the summer and lowest in winter (Figure 6). Variation in solar exposure was greatest during the wet season.

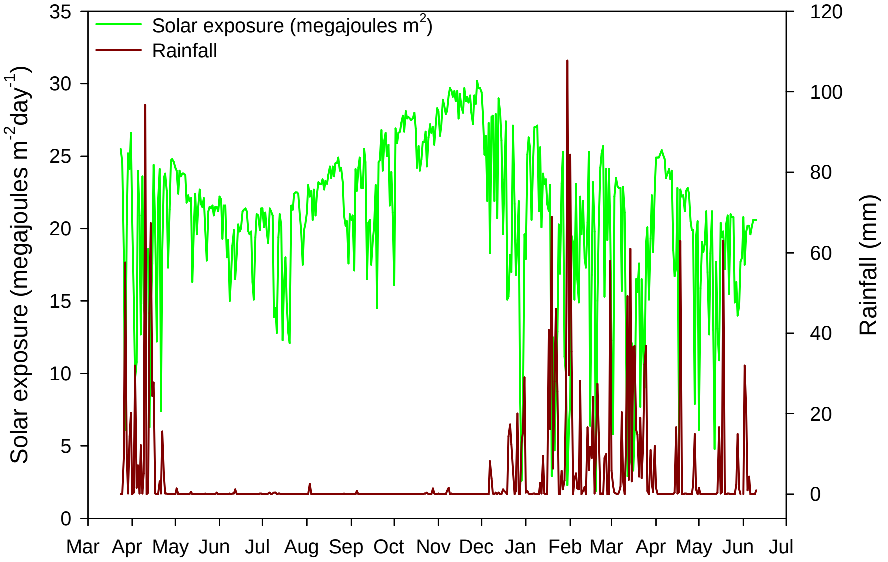


Figure 6. Daily global solar exposure (megajoules m^{-2} day^{-1}) and total daily rainfall (mm), March 2011 – June 2012.

In intertidal meadows the strongest negative relationships between seagrass biomass and environmental variables were with 1-month and 2-month total daytime tidal exposure (R^2=0.55 for both time periods) and 1-month salinity data (R^2=0.55) (Figures 7 and 8; Appendix 2). The strongest positive relationships between seagrass biomass and environmental variables were with 3-month water temperature data (R^2=0.59), 7-day total rainfall (R^2=0.53) and 7-day mean daily rainfall (R^2=0.58) (Figure 8; Appendix 2). When salinity-, mean water temperature-, mean daily rainfall- and total rainfall-biomass relationships were compared between time periods there were no significant differences in the slopes or intercepts (Appendix 2). However, the intercepts of the total daytime exposure-biomass relationships differed between 1-month and 3-month data (Figure 8; Appendix 2). There were no detectable relationships between intertidal meadow biomass with mean daily solar exposure, pH and PAR in intertidal meadows.

In subtidal meadows there were no detectable relationships between meadow biomass with any of the environmental variables we measured, likely as a result of limited number of occasions that seagrass metric data was able to be sampled.

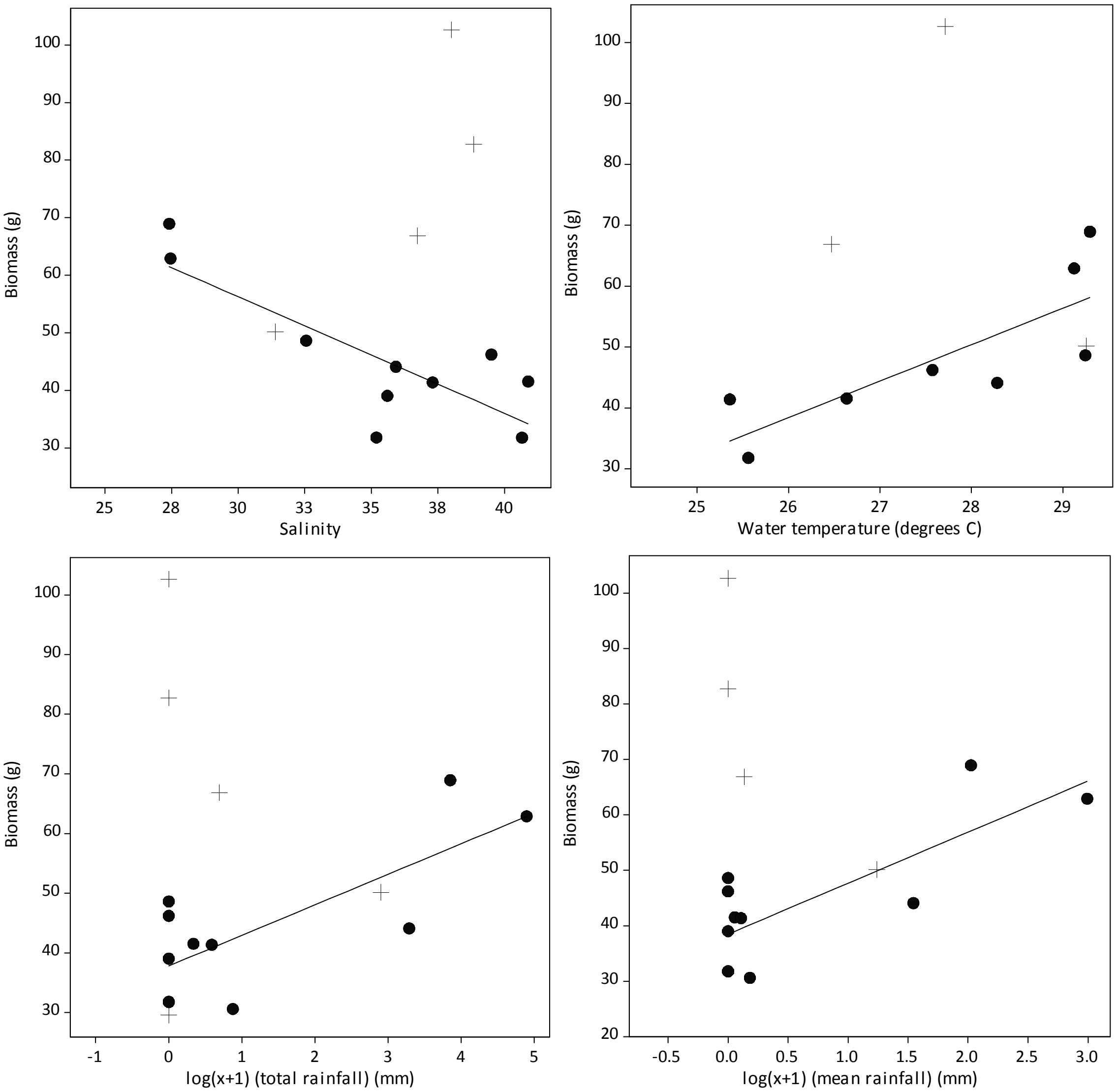


Figure 7. Significant relationships between seagrass meadow biomass with (a) salinity (ppt; 1-month data) (b) mean daily water temperature (°C; 3-month data), (c) log(x+1) total rainfall (mm; 7-day data) and (d) log(x+1) mean daily rainfall (mm; 7-day data) for intertidal meadows. Line of best fit: intertidal data. Symbols: circles, intertidal; crosses, subtidal.

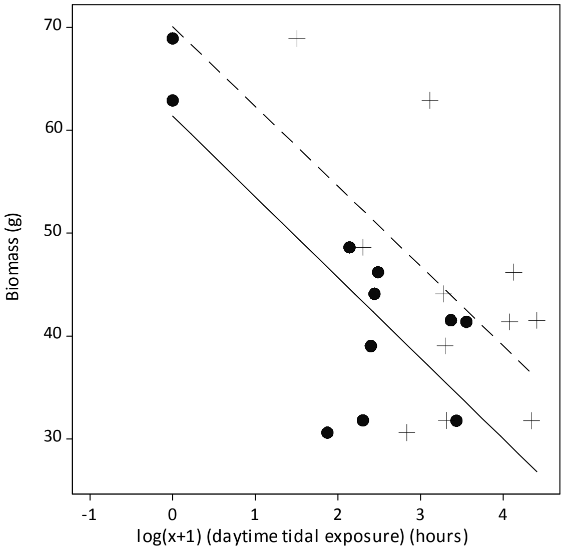


Figure 8. Negative relationships between intertidal seagrass meadow biomass and log(x+1)(daytime tidal exposure) (hours) using 1-month and 3-month data. Lines of best fit: solid line, 1-month data; dashed line, 3-month data. Symbols: circles, 1-month data; crosses, 3-month data.

2.4 Discussion

The key finding of this study was that seagrasses at Mabuiag Island undergo distinct seasonal and inter-annual changes in biomass that are associated with a range of complex interactions of natural and climate related drivers, particularly water temperature, daytime tidal exposure, salinity and rainfall. These findings present concern given the expected future climate scenarios of increased sea surface temperatures and more variable rainfall (Australian Bureau of Meterology and CSIRO 2011). Such changes could have a major impact on the productivity of this critical shallow water ecosystem in the Torres Strait.

Seasonal change in seagrass biomass was greater than two-fold in the intertidal and three-fold in the subtidal site. Mabuiag Island subtidal and intertidal seagrass meadows exhibited a unimodal seasonal pattern in which above-ground biomass reached maximum abundance in summer and minimum in winter. Historically it was reported that tropical seagrass meadows underwent little to no seasonal change (e.g. Brouns 1985; 1987; Hillman et al 1989) however evidence in more recent years suggests that this is not the case. At the Orman Reefs, Torres Strait, the biomass and growth of similar multi-species seagrass meadows can vary by up to a factor of 3.5 during one year (Rasheed et al. 2008) while in South East Asia they can vary by a factor of four (Erftemeijer and Herman 1994; Lanyon and Marsh 1995). Water temperature, daytime tidal exposure, salinity and rainfall were identified as the environmental variables contributing most significantly to the observed seasonal and inter-annual variation in intertidal seagrass biomass at Mabuiag Island. These factors all operated over differing time scales. Whilst no correlative patterns between subtidal seagrass abundance and environmental factors were identified, this was likely due to low number of seagrass sampling times rather than a lack of interaction. Further data collection in the future should reveal associations of subtidal seagrass dynamics with the climatic drivers of change.

As average daily water temperature increased at Mabuiag Island, seagrass biomass similarly increased. As temperature significantly affects the biochemical processes involved in photosynthesis and respiration, it has long been considered a major factor controlling seasonal seagrass growth (Tutin 1942; Phillips et al. 1983; Lee and Dunton 1996; Lee et al. 2005). Leaf productivities (growth) of many tropical seagrass species increase with increasing water temperatures (from 23°C to 29°C) (Lee and Dunton 1996; Lee et al. 2007) however inhibition of growth occurs once temperature reaches a threshold >35°C due to thermally induced physiological stress (Bulthuis 1983; Ralph 1998; Campbell et al. 2006). Average daily water temperatures at Mabuiag Island were within the optimal range for tropical seagrass species growth for most of the year, with the exceptions of a few spikes greater than 35°C in the summer months. These spikes in water temperature corresponded with periods of low tide exposure. When exposed, intertidal seagrass meadows retain a thin layer of water that can become 'super-heated'. Temperatures in excess of 40°C have been commonly observed in *Halodule uninervis* seagrass meadows throughout Queensland (McKenzie and Unsworth 2009).

A high incidence of low waters at spring tide that occurred during the daytime was associated with a decline of above-ground material at Mabuiag Island. This was most likely due to the deleterious effect of intense midday insolation, and, when the seagrass plants became fully emerged, of severe desiccation and 'burning'. 'Burning,' or browning of the leaf material, was regularly reported in the intertidal region, particularly for *Enhalus acoroides* during the spring months when hours of exposure and light levels (PAR) were greatest. Other studies of Indo-Pacific and north Queensland seagrass meadows have found that long and frequent periods of tidal exposure during the day can result in desiccation, temperature and high light stress, leading to permanent morphological and physiological damage to intertidal seagrasses (Erftemeijer and Herman 1994; Stapel 1997; Unsworth et al 2012). The mechanisms by which exposure leads to seagrass decline are likely related to physiological stress to the leaf structure and photosystems, probably through excess light causing photodamage (Bjork et al. 1999; Kahn and Durako 2009). This occurs when excess irradiance causes the production of oxygen-free radicals, which in turn ''damage'' the photosynthetic apparatus (Demmig-Adams et al. 2004).

When rainfall was high and average daily salinity levels were low, there was a positive relationship with seagrass abundance, and seagrass declined when the opposite was true. Typically the influence of rainfall on seagrass change would be attributed to increased run-off and river flow resulting in increased nutrients to the seagrass plants (e.g. Rasheed and Unsworth 2011). However, in the absence of large river systems in the Torres Strait we believe that rainfall is likely to be affecting salinity levels which are the most likely driver of change. Salinity is known to influence the structure and function of seagrass communities (Montague and Ley 1993). Salinity fluctuations can alter important plant biochemical and physiological processes, influencing plant metabolism, growth, development and reproduction (Koch et al. 2007; Touchette 2007).

Studies conducted on a limited number of seagrass species suggest that most have optimal growth in salinities between 30 and 40 ppt. Salinity levels were between 28 to 40 ppt at Mabuiag Island which is within this range, however our results suggest that the optimal range in the Torres Strait may not be as high as 40ppt, as lower salinities were associated with increased seagrass abundance. This is in opposition to Fernandez-Tourquemada and Sanchez-Lizaso (2005) and Marin-Guirao et al. (2011) who both found that stress (decreased leaf growth and shoot survival) in the temperate seagrass species *Posidonia oceanica* was not observed until seagrass was exposed to 40 and 41ppt respectively. From our study the pathway of how high salinity may influence seagrass growth has not been established. It is possible that salinity levels near 40ppt impact upon seeds at Mabuiag Island and their ability to germinate. *Thalassia testudinum* and *Ruppia maritime* seeds were found to have a narrower salinity tolerance range than seedlings and mature plants (Kahn and Durako 2006). High salinity can also affect a number of physiological processes in the plant that could result in negative impacts on growth.

The growth, survival and depth penetration of seagrass is directly related to the quality and quantity of light (Dennison and Alberte 1985; Dennison 1987), which is the primary driver of photosynthesis. Seagrasses live in distinct bands from the intertidal to depths at which plants receive minimum light requirements (MLRs) for survival (Longstaff and Dennison 1999). There is a paucity of data on MLRs for the majority of species found in the Torres Strait (Lee et al. 2007; Collier and Waycott 2009). However, we can assume based on their distribution patterns world-wide that reef and coastal species, including *Enhalus, Thalassia* and *Syringodium* existing in high light environments probably have much higher MLRs than low light adapted species, such as *Halophila*, which can grow to depths of 60m (Coles et al. 2009).

The lack of a significant relationship between seagrass biomass and light levels (PAR) indicate that seagrasses at Mabuiag Island are likely receiving greater than their minimum requirements. Intertidal light levels were highly variable, however approximately 10-12 mol m^{-2} d^{-1} was reaching the seagrass canopy in the wet season and approximately 20-25 mol m^{-2} d^{-1} in the dry season. These are likely to be in excess of the minimum light requirements for most tropical seagrass species. Recent studies in Gladstone have demonstrated that intertidal *Zostera capricorni* relies on greater than 6 mol m^{-2} d^{-1} over a two week rolling average of light during the “growing” season (between July – January for Gladstone seagrasses) to remain stable or increase in abundance (Chartrand et al. 2012). Similarly, Collier et al. (2012) reported that *Halodule uninervis* at three island locations in the northern Great Barrier Reef required between 5 and 8.4 mol m^{-2} d^{-1} for growth.

At Mabuiag Island these seasonal and inter-annual observations have thus far only been conducted over a relatively short time frame encompassing one seasonal cycle. Continued seasonal monitoring in the future will substantially improve our understanding of the range of natural change and links to seasonal climate and light cues.

3 CAPACITY FOR SEAGRASS RECOVERY

3.1 Introduction

Physical loss of seagrass has been documented to occur due to many types of physical disturbances such as storms (Poiner et al. 1989), grazing - particularly by dugong (Preen 1995), anchor and boat damage (Zieman 1976; Williams 1988) and shipping accidents (Kenworthy et al. 1993). In the Torres Strait, the threat of seagrass loss due to shipping accidents may be considerable given that one of the most heavily used shipping lanes in Australia transits the region. The Great North East (GNE) Shipping Channel connects the eastern seaboard of Australia with many Asian countries to the north, including China. Approximately 3000 voyages are undertaken by shipping vessels (bulk tankers) through the GNE channel each year (Neil Trainor, AMSA, pers. comm. 2008) and with the heavy reliance by Australian trade industries on export and import, the level of use is expected to rise by 20% in the next five years (AMSA 2011). The Torres Strait region has a high rate of shipping incidents compared to other shipping passages. There are at least 20 separate accidents recorded back to 1970, 18 of which were ship groundings on reefs, with the remaining two being discharge accidents while docked at the Port of Thursday Island (Queensland Transport and the Great Barrier Reef Marine Park Authority, 2000).

A key aspect in understanding the resilience of seagrass meadows to stressors is their capacity to recover from impact (Kenworthy 2000). The responses of seagrasses to removal related disturbances have been assessed through both experimental and descriptive studies highlighting the different responses of seagrass communities following loss and the importance of reproductive strategy to recovery of gaps. Gaps in *Halodule uninervis* meadows recovered within four months at Abbot Point, Queensland (Unsworth et al. 2010) while at Green Island, Queensland, required seven months to recover (Rasheed 2004). Seagrass communities dominated by larger, slower growing species (i.e. *Enhalus acoroides, Cymodocea* spp.) have been reported to take over five years to recover from disturbances (Rollon et al. 1998).

Seagrasses may colonise cleared patches both by dispersal of sexual propagules (seeds, fruits, flowers) and/or asexual vegetative extension of plants at the periphery and replacement of above-ground structures (Rollon et al 1998; Rasheed 1999; 2004). Differences in the means of recovery (asexual vs sexual) between species may also be an important factor in determining the sequence in which individual species return to disturbed patches. Means of recovery are also likely to play a role in recovery rates in small versus large scale disturbances. In larger scale disturbances where few remnant plants remain, initial colonisation can occur by seeds or other sexual propagules (Duarte and Sand-Jensen 1990; Phillips et al 1983). Subsequent development of seagrass patches may then depend on asexual reproduction (Duarte and Sand-Jensen 1990).

With increasing levels of shipping activity in the Torres Strait and the associated threat of negative effects on seagrass communities, an understanding of the recovery process is essential in developing strategies to deal with potential disturbance. Information on how seagrass systems naturally recover is likely to be useful in attempts to artificially rehabilitate seagrasses, which have met with mixed success in the past (Thorhaug and Austin 1976; Phillips 1982; Thorhaug and Cruz 1988), and in developing management plans where seagrasses are highly impacted.

The goals of this study were to:

1. Determine the capacity for, and the rate of recovery of Torres Strait seagrasses;
2. Identify the roles of sexual versus asexual reproduction;
3. Establish whether seasonality of seagrass abundance affects recovery rates; and
4. Ascertain patterns of succession of seagrass species following artificial disturbance in a mixed species meadow

3.2 Methods

3.2.1 Seagrass recovery following disturbance

The rate of seagrass recovery, the role of sexual and asexual reproduction, and the species involved in re-colonisation following loss/removal, was investigated at the two experimental locations. These investigations followed the methodology developed by Rasheed (1999; 2004) and more recently applied at Abbot Point (Unsworth et al. 2010) for investigating seagrass recovery after loss/removal. At each location, three experimental blocks were subject to a randomised block design of 12 (0.25 m^2) treatment plots of seagrass. Within each block, the 12 plots were subject to three replicates of four different treatments (Table 1).

Table 1 Description of treatments for re-colonisation experiments.

Treatment	Cleared	Not Cleared	Bordered	Not Bordered	Replicates
C1		✓	✓		3
C2		✓		✓	3
E1	✓		✓		3
E2	✓			✓	3

Within each block, six of the 0.25 m^2 plots of seagrass had seagrass material, including roots and rhizomes, removed. To determine how recolonisation was influenced by asexual reproduction (seagrass runners), half (three) of the cleared plots in each block had an aluminium border sunk 500mm into the sediment. The border isolated treatments from asexual colonisation by stopping rhizome extension from seagrass surrounding the plots. To investigate how recolonisation was influenced by the availability of sexual propagules (seeds), recovery of seagrass was compared among plots that had all material removed but the seed bank left intact. Recolonisation of all the cleared plots were compared monthly to control plots in each block that were left undisturbed. Seagrass recovery and re-growth from each individual 0.25 m^2 plot was measured using non-destructive techniques including leaf shoot density and visual estimates of above-ground biomass (Mellors 1991; Rasheed 1999; 2004). The number of flowering and fruiting bodies of each seagrass species present in the plots was also counted by observers.

Manipulative seagrass experiments were set up in the seagrass senescent season March/April 2011 in one subtidal and one intertidal location. A second round of recovery experiments was established in the seagrass growing season in late August 2011 (intertidal) and early November 2011 (subtidal) to determine if recovery of seagrasses were affected by seasonal change. The intertidal blocks for both rounds one and two were sampled monthly on a spring low tide. Unfortunately, consistently poor weather meant that the subtidal blocks had only been re-sampled intermittently when the weather allowed. Results for both intertidal and subtidal sampling up to thirteen months post clearing for round one and approximately eight months post clearing for round two are presented here.

3.2.2 Seagrass reproductive assessment

Seagrass reproductive health was assessed quaterly by taking 12 randomly placed cores (100mm diameter and depth) from an area adjacent to experimental locations and frozen for transport to the laboratory. The density of seeds in the meadow (seeds m^{-2}) was determined from the average number of seeds per core. Cores were sieved through a series of sieves between 4mm - 250µm to separate out the seagrass and reproductive material from the sediment. In the > 710 µm size fraction of the sediment, reproductive structures (male and female flowers, spathes, fruits and seeds) were identified and counted. Furthermore, the 250-710 µm fraction was inspected using a dissecting microscope to find the much smaller *Halophila* seeds. In addition, seagrass reproductive structures (flowers and fruits) for each species were counted within seed cores and recorded in the experimental plots (see part A above) during sampling events for the seagrass recovery experiments.

3.3 Results

3.3.1 Seagrass recovery following disturbance

The role of sexual and asexual reproduction (seeds versus runners) was a major factor in the initial recovery of cleared experimental plots. In general, preventing asexual colonisation (bordering) had a significant impact on the rate at which cleared plots recovered in relation to control plots. Fifteen months after clearing, no bordered plots had recovered to control levels of above-ground biomass in either the intertidal or subtidal zones. In contrast, where asexual colonisation was permitted seagrass above-ground biomass had recovered within 6-8 months for intertidal and 12 months for subtidal seagrass (Figures 9 and 11; Appendix 3 and 4). However, species composition of seagrasses in the intertidal had yet to return to an undisturbed state by 15 months post clearing, while species composition in the subtidal was similar at 12 months.

The presence of a border did not have an impact on biomass of established seagrass in control treatments intertidally or subtidally (Figures 9 and 11; Appendix 3 and 4).

Timing of disturbance to seagrasses appeared to have little effect on recovery rates. Seagrasses in the cleared treatments from the second round of experiments which were set up near the beginning of the seagrass growing season actually recovered slower than those cleared in the senescent season in round one.

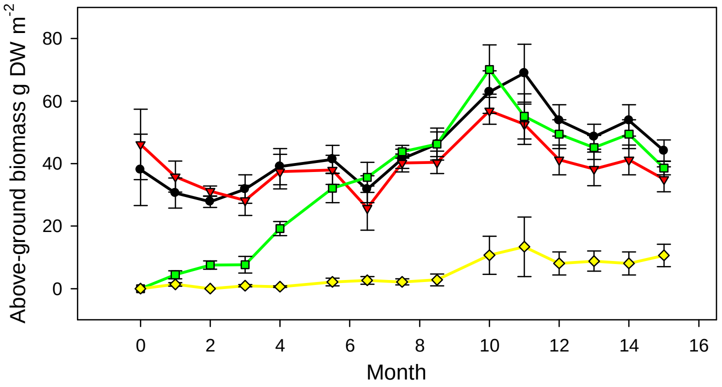
Intertidal recovery

In the intertidal sites, initial recolonisation was observed in the cleared plots from as early as one month after clearing occurred (Figures 9 and 10). Where recovery was able to occur through asexual means (no border), seagrass shoot density and above-ground biomass was significantly higher than in plots which relied on sexual means (bordered) from as early as 2-3 months post clearing. At the last sampling event (June 2012 - 15 months after clearing Round 1 and 9 months after clearing Round 2), treatments that had been cleared and which were surrounded by a border (preventing asexual recolonisation) had significantly lower above-ground biomass than treatments that were cleared and not enclosed by a border.

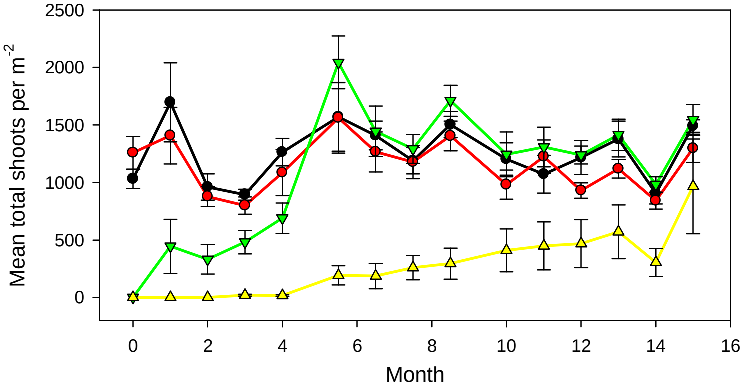
Above-ground biomass in treatments that could be colonised asexually (cleared, no border) recovered to the same density as undisturbed controls 5.5 months after clearing for Round 1 plots (September 2011) and 8 months for Round 2 plots (April 2012) and remained at the same levels as controls until June 2012 (Figure 9; Appendix 3 and 4). In these same treatments (cleared, no border) shoot density recovered to undisturbed levels 5.5 and 7 months (Rounds 1 and 2 respectively) after clearing (Figure 9; Appendix 3 and 4). Where recovery was dependent on sexual means (i.e. recovery from seed bank or seed recruitment; bordered), seagrass had shown little recovery up to 15 months post clearing. Above-ground biomass of these treatment plots was only 30% of controls at 15 months after clearing for Round 1 of experiments and 17% at 10 months for Round 2. The density of shoots in the cleared, bordered treatments recovered much quicker however, reaching 75% of controls at 15 months and 30% at 10 months (Rounds 1 and 2 respectively) reflecting a different species composition (smaller species) recruiting into these treatments.

Shoot density and above-ground biomass varied seasonally (see section 1 above) in the control treatments for both rounds of experiments with spring/summer highs and winter lows (Figure 9). Periods of decline in shoot density and biomass for cleared, no border treatments coincided with the lows in the uncleared control treatments (Figure 9).

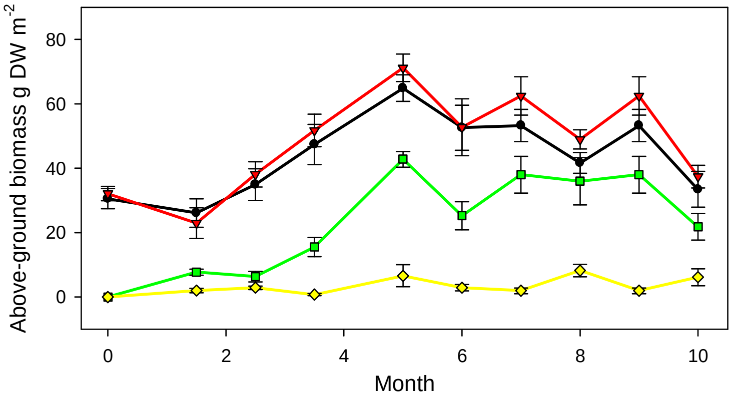
A) Round 1



B) Round 1



C) Round 2



D) Round 2

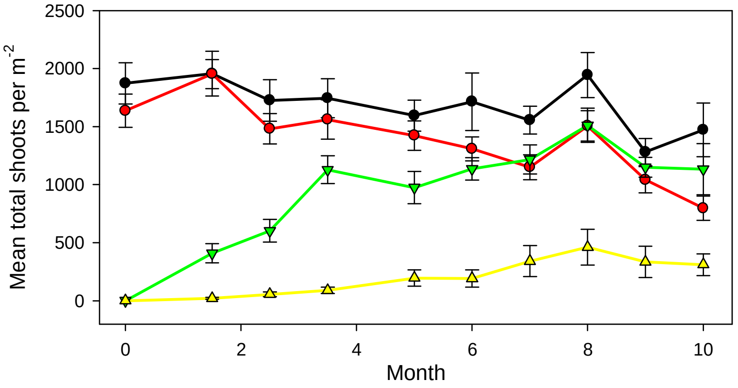


Figure 9. Mean above-ground biomass + standard error (g DW m^{-2}) and mean total shoot density + standard error (shoots m^{-2}) for each treatment in Round 1 (A, B) and Round 2 (B, C) in the intertidal region. Control, no border (black); control, border (red); cleared, no border (green); border (yellow).

The most dominant species in the uncleared controls for the intertidal sites by shoot count were *Halodule uninervis* and *Syringodium isoetifolium*, accouting for between 25-35% of the species composition each. The species composition in treatments where asexual colonisation could occur (non-bordered) remained different to uncleared controls throughout the study despite total shoot density recovering to the level of uncleared controls. Overall, *Halodule uninervis* was over-represented in these treatments while *Thalassia hemprichii* was highly reduced.

Halodule uninervis was the most rapid asexual coloniser, dominating recovery of seagrass into non-bordered treatments. *Cymodocea serrulata, Halophila ovalis* and *Syringodium isoetifolium* also played a role in early recolonisation into non-bordered treatments (Figure 10). Densities of *Halodule uninervis* remained lower than uncleared controls until 6-9 months (Rounds 1 and 2) after clearing when densities became considerably higher than in corresponding controls. At 15 months post clearing (Round 1) *Halodule uninervis* accounted for 45% of the species composition in cleared, non-bordered treatments as opposed to 30% in its corresponding uncleared controls.

Recovery of seagrass into plots where asexual colonisation was prevented by a border was almost solely by *Halodule uninervis*. *Halodule uninervis* first appeared in these plots three months post clearing and remained the dominant species (by shoot count) up to 15 months post clearing (Figure 10). Shoots of *Cymodocea serrulata, Thalassia hemprichii, Cymodocea rotundata, Enhalus acoroides* and *Halophila ovalis* had been recorded intermittently in cleared, bordered plots from five months post clearing, however these did not persist. Recovery may have been by seed germination or from settling of vegetative fragments.

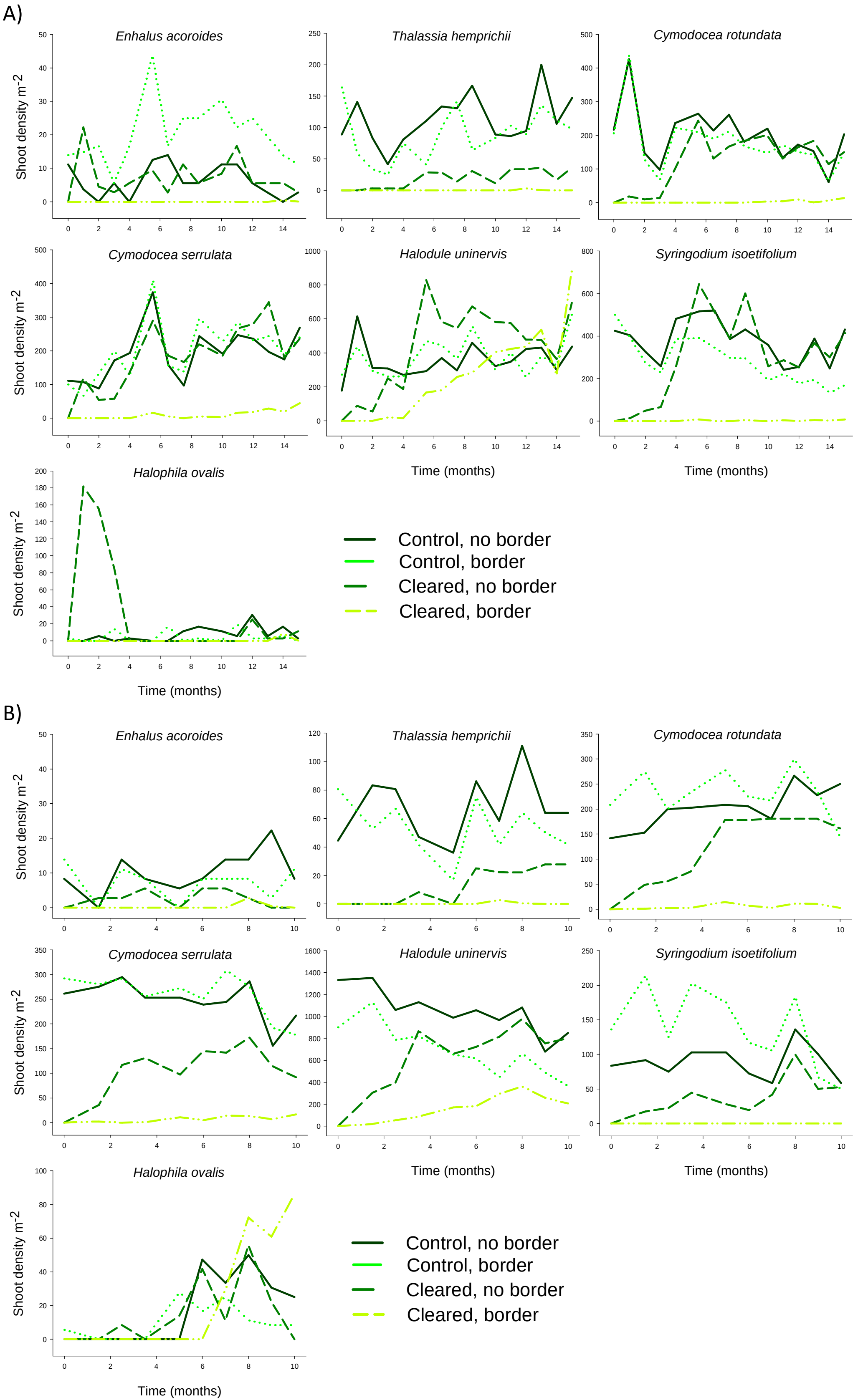


Figure 10. Mean species shoot density (shoots m^{-2}) for each treatment in the Intertidal region in A) "Round 1" and B) "Round 2".

Subtidal recovery

In the subtidal region seagrass recovery into cleared treatments was slower than that observed in the intertidal. Initial recolonisation was observed in the cleared plots from as early as one month after clearing occurred (Figure 11 and 12). Where recovery was able to occur through asexual means (no border), seagrass shoot density was significantly higher than in plots which relied on sexual means (bordered) from 2.5-4.5 months post clearing, although above-ground biomass remained the same until 6 months (Figure 11 and 12; Appendix 3 and 4). At the last sampling event (April 2012 - 12 months after clearing Round 1 and 5.5 months Round 2), treatments that had been cleared and which were surrounded by a border (preventing asexual recolonisation) had significantly lower above-ground biomass than treatments that were cleared and not enclosed by a border.

Above-ground biomass in treatments that could be colonised asexually (cleared, no border) recovered to the same density as undisturbed controls 12 months after clearing for Round 1 plots (April 2012) and had yet to recover after 5.5 months for Round 2 plots (April 2012) (Figure 11; Appendix 3 and 4). In these same treatments (cleared, no border) shoot density recovered to undisturbed levels at a faster rate, by 5.5-6 months (for both rounds) after clearing (Figure 11; Appendix 3 and 4). Where recovery was dependent on sexual means (i.e. recovery from seed bank or seed recruitment; bordered), seagrass had shown little recovery up to 12 months post clearing. Above-ground biomass of these treatment plots was 42% of controls at 12 months after clearing for Round 1 of experiments and 3% at 5.5 months for Round 2. The density of shoots in the cleared, bordered treatments recovered at a similar rate, reaching 30% of controls at 12 months and 7% at 5.5 months (Rounds 1 and 2 respectively).

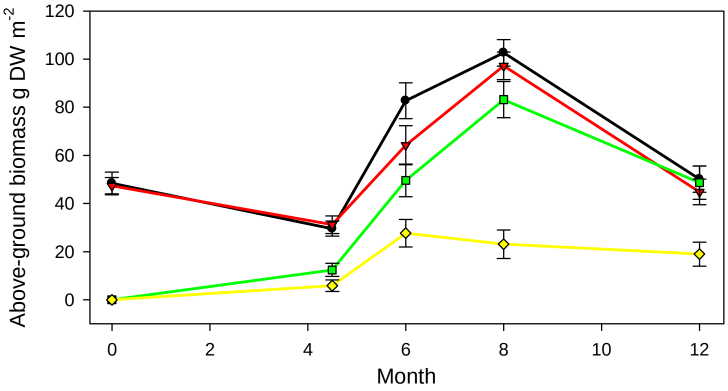
Shoot density and above-ground biomass varied seasonally (see section 1 above) in the control treatments for both rounds of experiments with spring/summer highs and winter lows (Figure 11). Periods of decline in shoot density and biomass for cleared, no border treatments coincided with the lows in the uncleared control treatments (Figure 11).

The most dominant species in uncleared controls for the subtidal sites by shoot count was *Syringodium isoetifolium*, accouting for between 60-70% of the species composition throughout the study. Seagrass colonisation of disturbed plots in the subtidal was heavily dependent upon *Halophila* species (*H. spinulosa* and *H. ovalis*). *Halophila* are well documented as pioneering species in tropical seagrass communities. Recovery was likely to have occurred by both asexual (rhizome extension) and sexual (seeds and vegetative fragments) means.

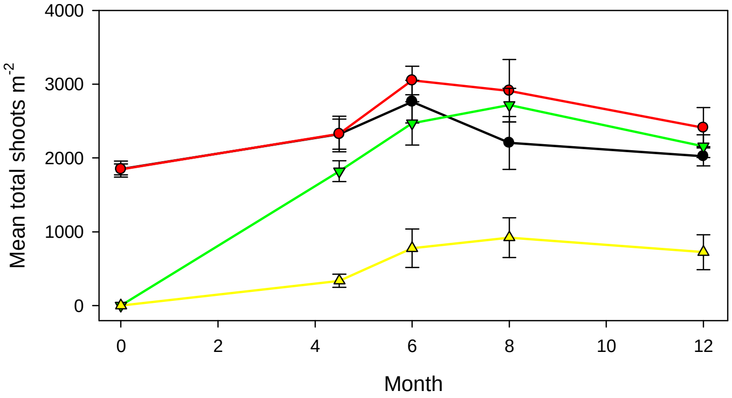
In cleared treatments open to asexual recovery (non-bordered) *Syringodium isoetifolium* also began to recolonise plots from an early stage and displaced both *Halophila* spp. as densities increased (Figure 12). Densities of *Syringodium isoetifolium* remained lower than uncleared controls until 12 months after clearing (Round 1) when the overall species composition was similar to undisturbed controls (Figure 12).

Where asexual colonisation was prevented with a border, recolonisation by *Halophila spinulosa* and *Halophila ovalis* occurred from as early as one month after clearing (Figure 12). *Halophila ovalis* remained the dominant species (by shoot count) up to 12 months post clearing, accounting for 79% of the species composition as opposed to 10% in its corresponding uncleared controls.

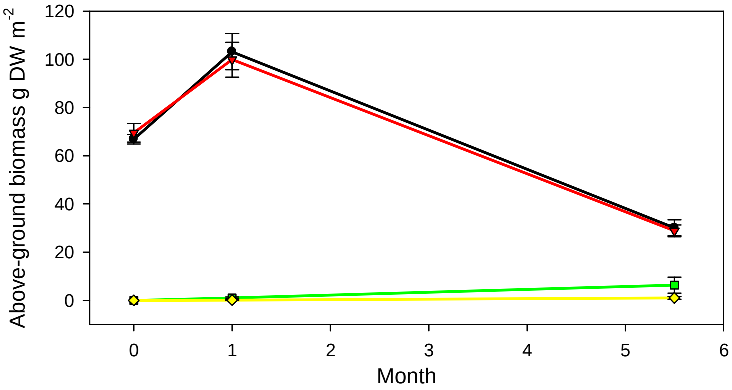
A) Round 1



B) Round 1



C) Round 2



D) Round 2

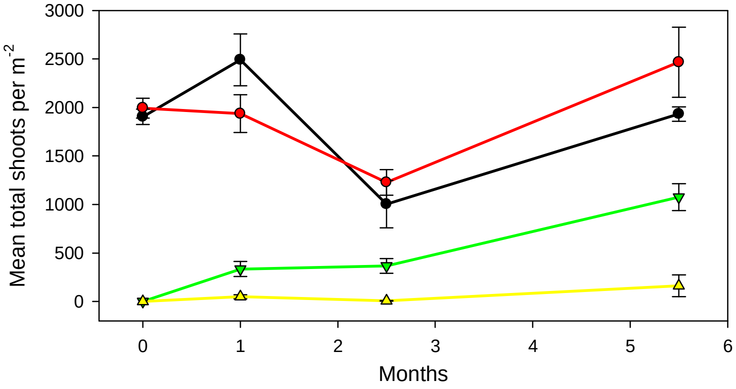


Figure 11. Mean above-ground biomass ± standard error (g DW m^{-2}) and mean total shoot density ± standard error (shoots m^{-2}) for each treatment in Round 1 (A, B) and Round 2 (B, C) in the subtidal region. Control, no border (black); control, border (red); cleared, no border (green); border (yellow).

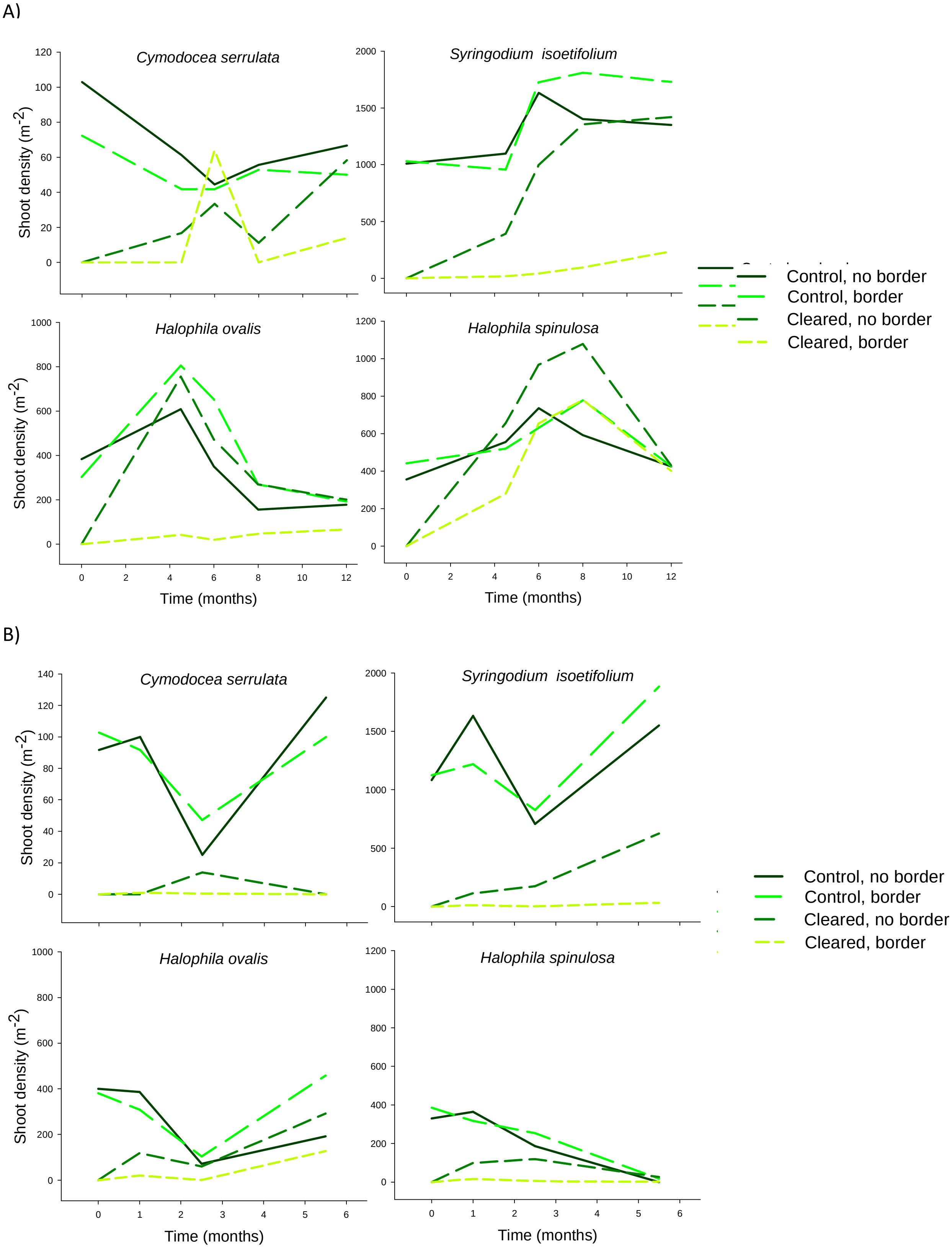


Figure 12. Mean species shoot density (shoots m^{-2}) for each treatment in the subtidal region in A) "Round 1" and B) "Round 2".

3.3.2 Seagrass reproductive assessment

The total density of seeds found at Mabuiag Island was high compared with other locations that have been assessed in north Queensland. Seeds were found for all five sampling times intertidally and in both sampling times subtidally. Seed densities (all species pooled) were at their highest in autumn and winter in the intertidal and lowest in spring and summer (Figure 13). Seeds peaked in April each year, reaching densities of 250.3 ± 145.9 m^{-2} in 2012. Seed densities in the subtidal were only sampled in April 2011 and April 2012 and reached a high 1478.8 ± 341.0 m^{-2} (Figure 14).

Although some seagrass species in both the intertidal and subtidal had significant seed banks, others did not despite their capacity to produce long-lived seeds. Seeds from five of the seven intertidal species were identified *Halodule uninervis, Cymodocea serrulata, Cymodocea rotundata, Syringodium isoetifolium* and *Halophila* spp. (Figure 13; Differentiation microscopically between seeds of *Halophila ovalis, Halophila decipiens* and *Halophila spinulosa* was not possible, therefore seeds were recorded as *Halophila* spp.). *Halodule uninervis* seeds were the most common each month, except in April 2011 when more than 50% of seeds were *Cymodocea serrulata.* Subtidally, seeds were dominated by *Halophila* spp. with low numbers of *Cymodocea serrulata* seeds identified (Figure 14). Seeds were absent for the most dominant subtidal seagrass species (by shoot count and above-ground biomass), *Syringodium isoetifolium*.

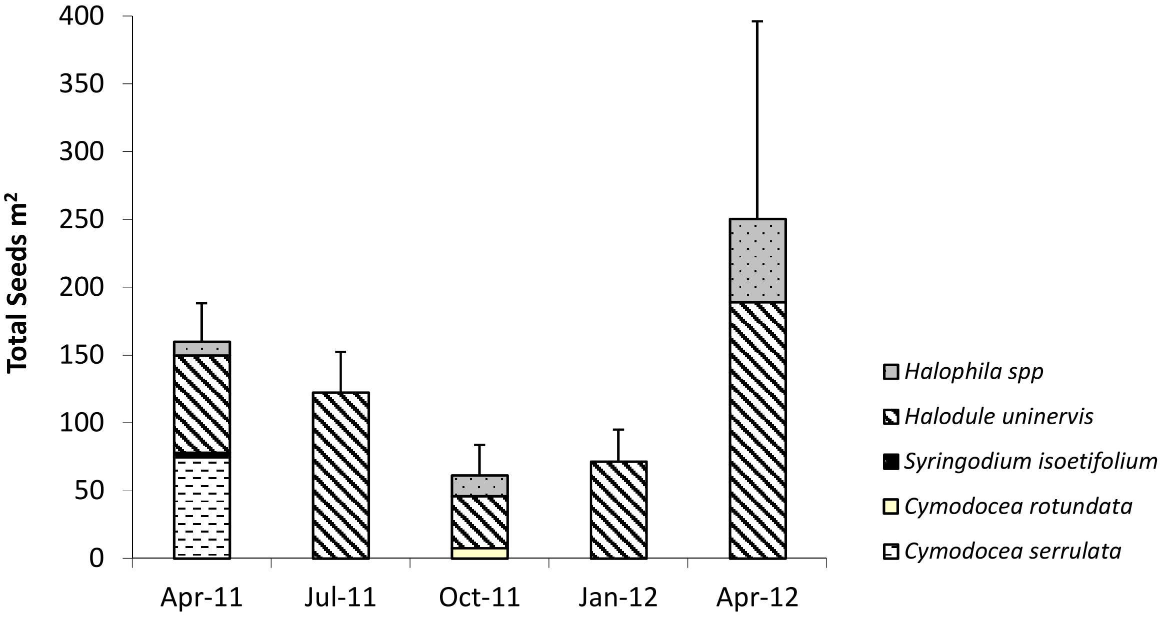


Figure 13. Mean number of seeds m^{-2} ($\pm$ standard error) for each seagrass species in the intertidal region, 2011-2012.

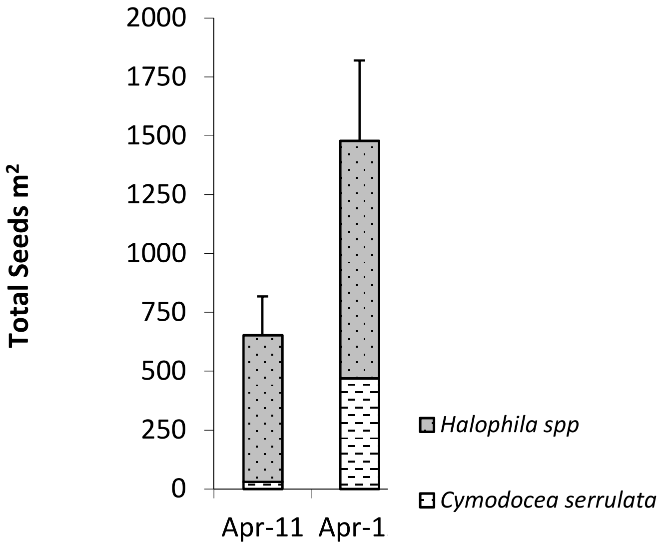


Figure 14. Mean number of seeds m^{-2} (+ standard error) for each seagrass species for the subtidal region, April 2011 and April 2012.

Flowering and/or fruiting was observed in both the intertidal and subtidal regions most months between April 2011 and June 2012 (Tables 2 and 3). Flowering of only two species, *Syringodium isoetifolium* (intertidal and subtidal) and *Enhalus acoroides* (intertidal only) was recorded. The density of flowering shoots in the intertidal was relatively low (maximum 16.7 ± 9.3 shoots m^{-2}) and reached much higher densities in the subtidal (maximum 119.1 ± 19.1 shoots m^{-2}). No flowering shoots were observed for any other species at sampling times examined. Flowering was generally greatest in spring and summer and lowest in autumn and winter (Tables 2 and 3). No flowering was observed subtidally in autumn and winter (April 2011, April 2012 and August 2011).

Syringodium isoetifolium had the most extended flowering period with flowering shoots recorded in 5 of the 15 months observed intertidally and 4 of 7 subtidally. Flowering of *Syringodium isoetifolium* only occurred in the two uncleared control treatments (bordered and unbordered) intertidally until December 2011 when low numbers (<3 shoots m^{-2}) were observed in cleared plots in which asexual regrowth was permitted (8.5 months post clearing). Subtidally, the same pattern was observed however flowering was first recorded in cleared plots in which asexual growth was permitted six months post clearing. No flowering was observed by *Syringodium isoetifolium* in any cleared plots in which asexual regrowth was prevented by a border. Densities of *Syringodium isoetifolium* flowering shoots were at their greatest in early summer, peaking intertidally and subtidally in December 2011 (16.7 ± 9.3 shoots m^{-2} and 119.1 ± 19.1 shoots m^{-2}, respectively).

Flowering shoots of *Enhalus acoroides* in the intertidal region was only quantitatively recorded in May 2011, February 2012 and June 2012, although flowers were also observed in April and May 2012 (Table 2). Flowering density peaked in February 2012 (0.8 ± 0.5 shoots m^{-2}) and only occurred in uncleared control treatment plots.

Fruits attached to shoots were observed in three species intertidally, *Enhalus acoroides, Thalassia hemprichii* and *Halophila ovalis* and three subtidally *Syringodium isoetifolium, Halophila ovalis* and *Halophila decipiens*. The density of fruiting shoots was very low both intertidally and subtidally (maximum 7.8 ± 7.8 shoots m^{-2} and 8.7 ± 6.1 shoots m^{-2} respectively). Fruiting occurred infrequently throughout the year, although densities were at their greatest in spring/summer (Tables 2 and 3).

Table 2. Mean monthly number of fruits and flowers m^{-2} in the intertidal region from seed cores and recovery experimental plots, April 2011 – June 2012.

Date	*Enhalus acoroides*		*Syringodium isoetifolium*		*Thalassia hemprichii*		*Halophila ovalis*		Total	
	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}
April 2011	0.00	0.00	0.00	0.69 ± 0.69	0.00	0.00	0.00	0.00	**0.00**	**0.69 ± 0.69**
May 2011	0.00	0.69 ± 0.69	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.69 ± 0.69**
June 2011	0.00	0.00	0.00	0.69 ± 0.69	0.00	0.00	1.33 ± 1.33	0.00	**1.33 ± 1.33**	**0.69 ± 0.69**
July 2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
August 2011	0.00	0.00	0.00	16.67 ± 11.79	0.00	0.00	0.00	0.00	**0.00**	**16.67 ± 11.79**
September 2011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
October 2011	0.00	0.00	0.00	0.00	7.65 ± 7.65	0.00	0.00	0.00	**7.65 ± 7.65**	**0.00**
November 2011	0.00	0.00	0.00	5.56 ± 5.56	0.00	0.00	0.00	0.00	**0.00**	**5.56 ± 5.56**
December 2011	0.00	0.00	0.00	16.67 ± 9.32	0.00	0.00	0.00	0.00	**0.00**	**16.67 ± 9.32**
January 2012	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
February 2012	0.69 ± 0.49	0.81 ± 0.5	0.00	0.00	0.00	0.00	0.00	0.00	**0.69 ± 0.49**	**0.81 ± 0.5**
March 2012	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
April 2012	0.00*	0.00*	0.00	0.00	0.00	0.00	0.00	0.00	**0.00***	**0.00***
May 2012	0.00*	0.00*	0.00	0.00	0.00	0.00	0.00	0.00	**0.00***	**0.00***
June 2012	0.00	0.35 ± 0.35	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.35 ± 0.35**

* *Enhalus acoroides* flowers and fruits observed around experimental site, although none were recorded within experimental plots

Table 3. Mean monthly number of fruits and flowers m^{-2} (± standard error) in the subtidal region from seed cores and recovery experimental plots, April 2011 – April 2012.

Date	*Syringodium isoetifolium*		*Halophila ovalis*		*Halophila decipiens*		Total	
	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}	Fruits m^{-2}	Flowers m^{-2}
April 2011	0.00	0.00	0.00	0.00	3.5 ± 3.5	0.00	**3.5 ± 3.5**	**0.00**
August 2011	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**
October 2011	0.00	11.81 ± 2.99	0.17 ± 0.17	0.00	0.00	0.00	**0.17 ± 0.17**	**11.81 ± 2.99**
November 2011	0.00	104.72 ± 25.95	0.00	0.00	0.00	0.00	**0.00**	**104.72 ± 25.95**
December 2011	8.68 ± 6.14	119.1 ± 19.8	0.00	0.00	0.00	0.00	**8.68 ± 6.14**	**119.1 ± 19.8**
January 2012	0.00	3.13 ± 1.97	0.00	0.00	0.00	0.00	**0.00**	**3.13 ± 1.97**
April 2012	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	**0.00**

3.4 Discussion

Physical disturbance is a key factor in the ecology and dynamics of seagrass meadows (den Hartog 1971; Fonseca and Bell 1998; Bell et al. 1999; Hemminga and Duarte 2000). Physical disturbance has been suggested to be critical to allow the co-existence of mixed seagrass meadows (Kirkman and Kuo 1990; Williams 1990; Duarte et al. 1997), which are generally restricted to the tropical and subtropical regions (Duarte 2001). However, understanding the capacity of a seagrass meadow to be resilient to physical disturbances and the impacts of disturbance on community structure requires knowledge of the ability of the plants to recover from a loss via sexual or asexual means.

The present study finds that there were strong differences between meadow locations (subtidal and intertidal) and species in their capacity for recovery and the mechanisms employed to recolonise from disturbances. For intertidal mixed species meadows in this study, asexual colonisation was the most important mechanism for recolonisation of cleared plots (gaps), whilst in the subtidal, recovery via a combination of sexual and asexual means was important.

Total above-ground biomass and shoot density of gaps in the intertidal site recovered asexually through rhizome extension to the undisturbed state between 5-8 months. The composition of species in asexually recovering gaps, however, remained different to undisturbed areas through to the end of the study reflecting the different reproductive strategies of the species. For the subtidal sites asexual recovery of seagrasses was slower and more variable with above-ground biomass taking up to 12 months to return to undisturbed levels. Unlike the interidal meadow species composition for the subtidal sites returned to be similar to the undisturbed state during the course of the study. This difference is likely a reflection of the dominance of species considered to be fast growing early colonisers in the subtidal site compared with the intertidal sites where a mix of species including larger slower growing species such as *Enhalus accoroides*, *Cymodocea* and *Thalssia* were more common.

Where recovery from surrounding seagrasses was prevented by a border (simulating larger scale seagrass loss), intertidal and subtidal seagrasses were unable to recover to pre-disturbance states during these experiments. Long-term recovery in the absence of rhizome or asexual propagules (seagrass fragments) would therefore be dependent on the external supply of seeds and *in situ* seed reserves.

The rate of recovery of seagrass (in terms of above-ground biomass) into experimentally created small gaps in the intertidal at Mabuiag Island was relatively fast compared to similar studies in tropical seagrass communities (Table 4). Recovery times of greater than 1.4 years have been reported from the Philippines (Rollen et al 1998). Conversely, recovery rates of seagrass in the subtidal region at Mabuiag Island were comparatively slow with one study by Unsworth et al (2010) reporting recovery of *Halophila spinulosa* from as early as 2 months post clearing. Of these studies, only three examined recovery rates when asexual reproduction was prevented (Rasheed 1999; 2004; Unsworth et al. 2010) and reported that recovery was not completed during the life of the studies, which was as long as 26 months in Rasheed (2004).

Table 4. Seagrass recovery rates into experimentally cleared gaps.

Study	Location	Species	Recovery time*
Rollon et al. 1998	Philippines (intertidal)	*E. acoroides, T. hemprichii, C. rotundata, S. isoetifolium, H. uninervis, H. ovalis*	1.4 – 5.7 years
Rasheed 1999	Cairns, Queensland (intertidal)	*Z. capricorni*	12 months
This study	Mabuiag Island (subtidal)	*S. isoetifolium, H. spinulosa, C. serrulata, H. ovalis, H. decipiens, C. rotundata*	12 months
Creed et al. 1999	Brazil (subtidal)	*H. wrightii*	9 months
Rasheed 2004	Green Island, Queensland (subtidal)	*H. uninervis, C. rotundata, C. serrulata, S. isoetifolium, H. ovalis, Z. capricorni*	7 months
This study	Mabuiag Island (intertidal)	*C. serrulata, C. rotundata, T. hemprichii, S. isoetifolium, H. uninervis, E. acoroides, H. ovalis*	5.5-8 months
Unsworth et al. 2010	Abbot Point, Queensland (subtidal)	*H. uninervis*	4 months
Unsworth et al. 2010	Abbot Point, Queensland (subtidal)	*H. spinulosa*	2 months

* In terms of above-ground biomass. Asexual recovery not prevented

Flowering and fruiting for a number of species was rarely seen at Mabuiag Island and seeds in the sediment were also limited to a few species. Available studies quantifying seagrass flowering intensity and seed bank production also demonstrate that reproductive effort varies greatly across species and sites (e.g. Gallegos et al. 1992; Cambridge and Hocking 1997; Inglis and Lincoln-Smith 1998; Inglis 2000). Flowering was only recorded for two species at Mabuiag Island, *Enhalus acoroides* and *Syringodium isoetifolium* despite flowering for all Mabuiag Island seagrass species being reported in other geographic locations (McMillan 1980). *Syringodium isoetifolium* flower density was four times greater at Mabuiag Island than has been reported at Green Island, north Queensland (>100 flowers m^{-2} compared to <30 m^{-2})(Rasheed 2004), however densities of *Enhalus acoroides* flowers were small in comparision to *Enhalus* dominated meadows in the Philippines (<1 flower m^{-2} compared to 26 m^{-2})(Rollon et al 2003). Lack of flowering for all other seagrass species may be due to an absence of favourable environmental conditions for flower development. Flowering in some seagrass species is only possible during a narrow range of environmental factors such as light (McMillan 1980; Rollon et al. 2003), temperature (DeCock 1981; Rollon et al 2003) and salinity (McMillan 1976). Presumably some of the other species did flower during the course of the study outside of specific sampling times as fruits attached to the shoots were recorded for both *Halopila ovalis* and *Halopila decipiens* and seeds were found for a number of the other species in sediment cores.

Substantial sediment seed banks have been documented in fast-growing seagrass species of *Halophila*, *Halodule* and *Cymodocea* (McMillan 1981; McMillan et al. 1982; Inglis 2000; Orth et al. 2000) with densities of *Halodule uninervis* reaching up to 10,000 seeds m^{-2} in some locations (Inglis 2000). Sizable seed banks for *Halophila* spp*.* (approx $1000m^{-2}$ in the subtidal), *Cymodocea serrulata* (approx $500m^{-2}$ in the subtidal) and *Halodule uninervis* (approx $200m^{-2}$ in the intertidal) were identified at Mabuiag Island. Very low densities of *Cymodocea rotundata* and *Syringodium isoetifolium* seeds were recorded in October 2011 only, while no seeds of *Enhalus acoroides* or *Thalassia hemprichii* were found in sediment cores which is to be expected as fruits and seeds of these species tend to float or remain on the surface of the sediments. Recovery of these species would be heavily dependent on asexual means or an external supply of seeds. Long-distance export outside *Enhalus acoroides* and *Thalassia hemprichii* meadows may be considerable, since seeds have the capacity to float for days and hours, respectively (Lacap et al. 2002). *Cymodocea rotundata* has smaller seeds that are set at or within the sediments, similar to *Halodule uninervis,* which in other studies has been shown to limit dispersal capacity (Inglis 2000).

Seagrasses commonly have a range of species-specific life histories and physiological adaptations enabling adaptation to different niches. Given that there is a trade-off between competitive ability and colonisation potential, recently disturbed areas tend to be dominated by pioneer species, such as *Halophila* spp*.* and *Halodule uninervis* (Rasheed 2004; Birch and Birch 1984), characterised by abundant seed production, high dispersal power and rapid growth, which will eventually be displaced by larger, slower-growing species that are superior competitors (Tillman 1994; Olesen et al. 2004). This pattern was evident in the subtidal region with *Halophila ovalis and Halophila spinulosa* dominating early recolonisation before being competitively displaced by *Syringodium isoetifolium*. In the intertidal, *Halophila ovalis* had already been displaced and we would expect *Halodule uninervis* to be displaced in the future as the larger species recover.

The results of this study so far indicate that most seagrass species at Mabuiag Island would likely be able to recover from smaller scale disturbances where some adult plants remain by capitalising on their highly clonal nature. However recovery from larger scale disturbances would have to rely more heavily on colonisation by sexual propagules and therefore may take years to recover, if at all for some species, with negative implications for a range of ecologically and economically important fauna in the region.

4 SEAGRASS PRODUCTIVITY

4.1 Introduction

Seagrasses form some of the most productive ecosystems on earth, rivalling many terrestrial based systems. They have high primary productivity and are the basis of many marine food webs (Hemminga and Duarte 2000), provide nutrients and organic carbon to the oceans and contribute significantly to carbon sequestration (Duarte et al. 2011), however, this can vary markedly between location and species (Rasheed et al. 2008). Seagrass meadow primary productivity is a function of seagrass species composition, daily growth rates, shoot and rhizome density and meadow size (Rasheed et al. 2006; 2008; Unsworth et al. 2010). Seasonal changes can have a strong influence on all factors and consequently on total productivity (Rasheed et al. 2008).

A study by Rasheed et al (2008) of productivity of seagrasses at the Orman Reefs (9 km north east of Mabuiag Island) found that net primary production of the reef platform seagrasses identified was higher than that determined for a mangrove forest in north Queensland and higher than many freshwater and brackish autotrophic communities. Sources of marine autotrophic production are likely to be critically important for local dugong and turtle populations, particularly as there is a general lack of terrestrial sources of carbon. Measuring productivity (growth) rates of seagrass meadows at Mabuiag Island provides a means to assess their potential contribution to marine primary productivity and how this may be influenced by future environmental and habitat change and including disturbances from anthropogenic impacts such as shipping accidents and climate change. Measuring meadow productivity also provides a means in which the amount of carbon being incorporated into the Mabuiag Island seagrass ecosystems can be measured.

The large intra-annual changes in seagrass abundance at Mabuiag Island are likely to have consequences for primary productivity. This is the first time that the seasonality of productivity of Torres Strait seagrasses will be measured. This data also provides an insight into seagrass productivity at the shoot (above-ground) and rhizome/root (below-ground) level.

The objectives of the seagrass productivity program were to:

1. Measure above-ground and below-ground seagrass productivity of Mabuiag Island seagrasses;
2. Determine any seasonal change in productivity.

4.2 Methods

The primary productivity of intertidal seagrass was measured quarterly from April 2011. Unfortunately, consistently poor weather prohibited the collection of productivity data for subtidal seagrasses and logistical issues prevented the collection of in situ productivity measurements for *Halophila* species found at Mabuiag Island. For this species values collected from the nearby Orman Reefs were used (Rasheed et al. 2008). We used techniques applied to determine productivity of seagrass meadows at the Orman Reefs, Torres Strait (see Rasheed et al. 2008) and at Abbot Point (see Unsworth et al. 2010). This followed methods outlined in Short and Duarte (2001), and was used to determine the productivity of each seagrass species found within the meadows, carbon produced and meadow turnover time for Mabuiag Island seagrass meadows (Figure 15).

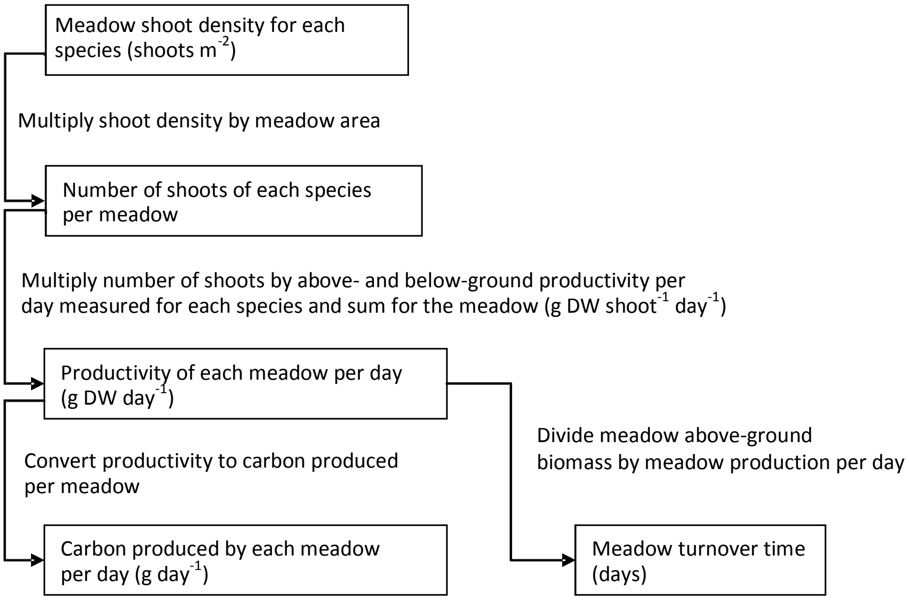


Figure 15. Flow chart detailing methodology for calculating primary productivity, carbon produced and turnover time for seagrass meadows at Mabuiag Island (adapted from Rasheed et al. 2008).

4.2.1 Meadow shoot density

Seagrass species shoot densities were collected monthly as part of the recovery experiment procedures. The mean shoot densities for each species in each meadow (shoots m^{-2}) was converted to number of shoots of each species per meadow by multiplying the shoot density by the meadow area which was determined from the baseline surveys in 2009 (subtidal meadow) and 2010 (intertidal meadow).

4.2.2 Above- and below-ground production of species

Productivity information for species found in the intertidal was collected. A combination of two methods were used according to the growth habits of the species found in the meadows:

1. *Leaf marking* - For leaf replacing seagrass species, the leaf growth rate was determined using an in situ leaf marking method. A hole was punched through all the leaves of an individual shoot using a syringe, just below the top of the basal meristem (sheath). As the leaves grow the pinhole scar from needle punching moves upwards from the basal meristem. The new leaf growth was any growth that occured between the hole in the sheath and the scar on the leaf. Plants were harvested a minimum of 12 days after marking and brought back to the laboratory for separation into old and new growth (Plate 3).
2. *Rhizome tagging* – Rhizome tagging was used to determine the leaf growth rate and the below-ground production of all species. Rhizomes were tagged at the basal meristem behind the growing tip with a coloured piece of wool (Plate 4). Subsequent growth of the tagged seagrass produced a new shoot and roots that trap the wool loop in the newly formed node. Tagged seagrasses were harvested a minimum of 12 days after tagging and biomass of new leaf material measured in the laboratory.

Plate 3: "New" and "old" leaf sections ready to be measured

Plate 4: *Syringodium isoetifolium* rhizome tagged with red wool to determine rhizome growth rate

In order to reduce the error associated with weighing very small and light sections of individual leaves, the samples for each species within each growth method (leaf marking or rhizome tagging) were pooled and the old and new leaf components were weighed. Dry weight per unit of leaf area was calculated by dividing the pooled weight by the surface area of leaves obtained from a CID Bio-Science Laser Leaf Area Meter or from the scanning software 'ImageJ'. The dry weight biomass of each leaf section was then calculated by multiplying the measured surface area of each leaf section by the weight per unit area.

4.2.3 Above-ground productivity of the intertidal meadow

To calculate the total above-ground productivity of the intertidal meadow the number of shoots (leaf replacing species) or basal meristems (non-leaf replacing) of each species in the meadow (section A) was multiplied by the biomass added for each shoot or basal meristem per day. It was assumed that new growth produced at the rhizome growing end would be equal to the death rate at the rhizome origin, therefore meadow productivity was based on only leaf marking techniques calculated in section B above. Meadow above-ground productivity was expressed as dry weight added for each meadow per day (g DW day^{-1}) and was calculated for each quarter. A literature derived value was used for *Halophila ovalis* from the nearby Orman Reefs (Rasheed et al. 2008) as we were unable to obtain in situ data for this species. Where we were unable to obtain species data for every quarter we used values derived two ways:

1. Where only one quarter of data was missing and variability between results from available data was minimal, an average of the quarterly values were used (*Enhalus acoroides* – January 2012 and *Thalassia hemprichii* – October 2011); or
2. Where two quarters were missing, it was deduced that growth rates would be similar during the growing season (as determined by seasonal biomass patterns and productivity experiment results) sampling events – July 2011 and October 2011; and during the senescing season sampling events – April 2011 and January 2012 and that these values could be applied to the missing months (*Cymodocea serrulata* and *Syringodium isoetifolium*).

4.2.4 Meadow turnover

The turnover time of the intertidal meadow was measured by dividing the meadow biomass (g DW m^{-2}) by the meadow productivity (section C) (g DW m^{-2} day^{-1}). The resulting figure represents the number of days required for a meadow to completely turnover its current standing above-ground biomass.

4.2.5 Above-ground carbon production

For this study a value of 34.34% of the total above-ground dry weight produced by seagrasses as being comprised of carbon was used. This value was used by (Rasheed et al. 2008) and was based on a range of literature values (Atkinson 1983; Koike et al. 1987; Erftemeijer 1994) that were geographically and environmentally applicable.

4.2.6 Statistical analysis

All data presented in the results are shown as means (± standard error), except where otherwise stated. The species leaf production values were analysed to determine differences between each quarter. Only data collected *in situ* was analysed; data derived from other means were excluded. Analysis of variance (ANOVA) was conducted in SigmaPlot v.11.0. Where data did not conform to the assumptions of ANOVA, data were transformed. Where data continued to differ from the assumptions of ANOVA the test was still conducted, but in order to minimise the possibility of recording a Type 1 error, an α level of 0.01 was used instead of α = 0.05 (Underwood 1997). Where a sigificant treatment difference was detected, a post-hoc LSD (equal variances) or Behrens Fisher Test (unequal variances) was permformed to determine differences amongst quarters. Detailed results are presented in Appendix 5.

4.3 Results

4.3.1 Productivity of Mabuiag Island seagrasses species

Net above-ground productivity varied markedly between species both within and between quarterly sampling events according to shoot size (Table 5, 6 and 7; Figure 16). The structurally largest species, *Enhalus acoroides*, consistently added the greatest dry weight per shoot per day (>6.0 mg DW shoot^{-1} day^{-1}) and was an order of magnitude higher than *Cymodocea serrulata, Thalassia hemprichii* and *Cymodocea rotundata* (Table 5). The smallest species, *Syringodium isoetifolium, Halodule uninervis* and *Halophila ovalis* added the least amount of biomass, contributing <0.7 mg DW shoot^{-1} day^{-1} (Table 5).

A seasonal change in above-ground productivity was evident for some species at Mabuiag Island, with production at a low in autumn, increasing during winter to a peak in spring before rapidly decreasing to low levels towards the end of summer (Figure 16; Table 5). New leaf growth production was significantly higher in October 2011 than in April 2011 for *Cymodocea rotundata, Cymodocea serrulata, Syringodium isoetifolium* and *Halodule uninervis* (Figure 16; Appendix 5). Both *Enhalus acoroides* and *Thalassia hemprichii* showed no significant difference in production rates between quarterly sampling events. These results were surprising given that above-ground biomass was found to be at its peak in summer and lowest in winter (Figure 1). This may suggest that there is a lag time between seagrasses investment in production and a measurable change in above-ground biomass, possibly through an investment in below ground stores in the rhizomes that are depleted during peak growing times.

Investment in below-ground growth was also seasonal for seagrass at Mabuiag Island with the fastest growth rates of rhizomes occurring in winter or spring for all species measured. In July 2011, *Cymodocea serrulata* recorded the fastest growth rate of 0.91 ± 0.47 mm day^{-1} while *Halodule uninervis* was the slowest at 0.66 ± 0.21 mm day^{-1} (Table 7). Growth rates of species in April 2011 and January 2012 were similarly low, slowing to as little as 0.02 mm day^{-1} for *Halodule uninervis* in April 2011.

Cymodocea rotundata

Average daily leaf growth for *Cymodocea rotundata* differed markedly between quarters. Above-ground productivity was 0.84 ± 0.21 mg DW shoot^{-1} day^{-1} at its lowest in April 2011, increasing significantly to 1.66 ± 0.13 mg DW shoot^{-1} day^{-1} in July 2011 and reaching a peak of 3.74 ± 0.52 mg DW shoot^{-1} day^{-1} in October 2011. Productivity rates significantly fell by January 2012 to be at similar levels to both the April and July 2011 rates (Figure 16; Appendix 5). Leaf material added per day was highest in October 2011 (1.1 ± 0.06 cm^{2} day^{-1}) (Figure 16; Table 5).

Productivity measured for the rhizome meristems (above- and below-ground growth of shoots, roots and rhizomes) of *Cymodocea rotundata* showed a slightly different pattern with production peaking at 3.71 ± 0.66 mg DW shoot^{-1} day^{-1} in July 2011 (Table 5). Rhizome growth rates ranged from 0.23 mm day^{-1} in October 2011 to 0.85 ± 0.12 mm day^{-1} in July 2011 (Table 7).

Cymodocea serrulata

Average daily leaf growth for *Cymodocea serrulata* differed markedly between April 2011 and October 2011. Each shoot added an average of 0.58 ± 0.06 cm^{2} day^{-1} in April 2011 and 1.1 ± 0.06 cm^{2} day^{-1} in October 2011. Above-ground productivity was significantly higher in October 2011 (2.69 ± 0.15 mg DW shoot^{-1} day^{-1}) than in April 2011 (1.44 ± 0.15 mg DW shoot^{-1} day^{-1}).

Productivity measured for the rhizome meristems (above- and below-ground growth of shoots, roots and rhizomes) of *Cymodocea serrulata* showed a slightly different pattern with production peaking at 5.75 ± 0.13 mg DW shoot^{-1} day^{-1} in July 2011 (Table 5). Rhizome growth rates ranged from 0.06 ± 0.04 mm day^{-1} in April 2011 to 0.91 ± 0.47 mm day^{-1} in July 2011 (Table 7).

Enhalus acoroides

Average daily leaf growth per shoot for *Enhalus acoroides* was consistent between quarters, ranging from 1.48 cm^{2} day^{-1} in October 2011 to 1.55 ± 0.48 cm^{2} day^{-1} in April 2011 (Table 5). Above-ground productivity had a similarly narrow range, recording 6.03 mg DW shoot^{-1} day^{-1} in October 2011 to 6.28 ± 1.97 mg DW shoot^{-1} day^{-1} in April 2011 (Figure 16; Table 5; Appendix 5).

Due to the great depth at which *Enhalus acoroides* meristems sit below the substratum surface, rhizome tagging techniques were not able to be used on this species at Mabuiag Island.

Halodule uninervis

Average daily leaf growth for *Halodule uninervis* (thin and narrow leaf morphologies) was similar between most quarters. Above-ground productivity ranged from 0.23 mg DW shoot^{-1} day^{-1} in January 2012, to 0.59 ± 0.04 mg DW shoot^{-1} day^{-1} in October 2011 (Figure 16; Table 5). There was a significant difference in productivity rates between April 2011 (0.24 ± 0.05 mg DW shoot^{-1} day^{-1}) and October 2011 (0.59 ± 0.04 mg DW shoot^{-1} day^{-1}) (Figure 16; Appendix 5). Leaf material added per day was highest in October 2011 (0.29 ± 0.02 cm^{2} day^{-1}) (Table 6).

Productivity measured for the rhizome meristems (above- and below-ground growth of shoots, roots and rhizomes) of *Halodule uninervis* followed the same pattern with production peaking at 1.24 ± 0.22 mg DW shoot^{-1} day^{-1} in October 2011. Rhizome growth rates ranged from 0.02 mm day^{-1} in April 2011 to 0.66 ± 0.21 mm day^{-1} in July 2011 (Table 7).

Syringodium isoetifolium

Average daily leaf growth for *Syringodium isoetifolium* differed significantly between April 2011 and October 2011 (Figure 16; Appendix 5). Each shoot added an average of 0.03 ± 0.01 cm^2 day^{-1} in April 2011 and 0.16 ± 0.01 cm^2 day^{-1} in October 2011 (Table 6). Above-ground productivity was significantly higher in October 2011 (0.64 ± 0.18 mg DW $shoot^{-1}$ day^{-1}) than in April 2011 (0.11 ± 0.06 mg DW $shoot^{-1}$ day^{-1})(Table 5; Appendix 5).

Productivity measured for the rhizome meristems (above- and below-ground growth of shoots, roots and rhizomes) of *Syringodium isoetifolium* showed a slightly different pattern with production peaking at 2.52 ± 0.37 mg DW $shoot^{-1}$ day^{-1} in July 2011 (Table 5) and being at its lowest in January 2012 (although no data was available for April 2011). Rhizome growth rates ranged from 0.13 ± 0.02 mm day^{-1} in January 2012 to 0.68 ± 0.19 mm day^{-1} in July 2011 (Table 7).

Thalassia hemprichii

Average daily leaf growth per shoot for *Thalassia hemprichii* was consistent between quarters, ranging from 0.52 ± 0.07 cm^2 day^{-1} in July 2011 to 0.66 ± 0.46 cm^2 day^{-1} in April 2011 (Table 6). Above-ground productivity had a similarly narrow range, recording 1.67 ± 0.22 mg DW $shoot^{-1}$ day^{-1} in July 2011 to 2.12 ± 1.49 mg DW $shoot^{-1}$ day^{-1} in April 2011 (Figure 16; Table 5; Appendix 5).

Due to the great depth at which *Thalassia hemprichii* meristems sit below the substratum surface, rhizome tagging techniques were not able to be used on this species at Mabuiag Island.

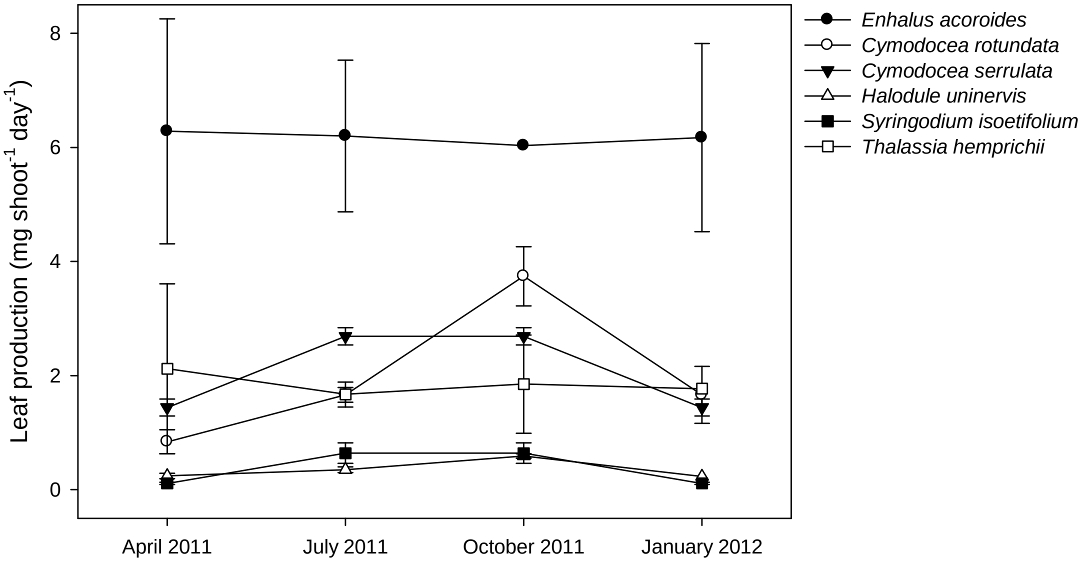


Figure 16. Mean leaf production rates (mg $shoot^{-1}$ day^{-1}, ± standard error) of Mabuiag Island seagrasses, April 2011 – January 2012.

Table 5. Daily rates of new growth (mg) per shoot for leaf marked samples and per meristem for rhizome tagged (includes shoots, roots and rhizomes) seagrasses for each quarter, Mabuiag Island.

Species	Marking Technique	New growth mg DW day^{-1} (# samples)				Source
		Apr-11	Jul-11	Oct-11	Jan-12	
Cymodocea rotundata	Leaf marking	0.84 ± 0.21 (9)	1.66 ± 0.13 (3)	3.74 ± 0.52 (20)	1.66 ± 0.5 (3)	This study
Cymodocea rotundata	Rhizome tagging	1.66 ± NA (1)	3.71 ± .66 (2)	1.83 ± NA (1)	2.22 ± 0.49 (6)	This study
Cymodocea serrulata	Leaf marking	1.44 ± 0.15 (29)	2.69 ± 0.15#	2.69 ± 0.15 (71)	1.44 ± 0.15*	This study
Cymodocea serrulata	Rhizome tagging	2.74 ± 0.77 (3)	5.75 ± 0.13 (8)	3.01 ± 0.43 (16)	4.15 ± 1.43 (6)	This study
Enhalus acoroides	Leaf marking	6.28 ± 1.97 (11)	6.2 ± 1.33 (7)	6.03 ± NA (1)	6.17 ± 1.65^	This study
Halophila ovalis	Rhizome tagging	0.50	0.50	0.50	0.50	Rasheed et al. 2008
Halodule uninervis	Leaf marking	0.24 ± 0.05 (9)	0.35 ± 0.05 (7)	0.59 ± 0.04 (29)	0.23 ± NA (1)	This study
Halodule uninervis	Rhizome tagging	0.31 ± NA (1)	0.77 ± 0.13 (19)	1.24 ± 0.22 (11)	0.21 ± 0.16 (8)	This study
Syringodium isoetifolium	Leaf marking	0.11 ± 0.02 (6)	0.64 ± 0.18#	0.64 ± 0.18 (2)	0.11 ± 0.02*	This study
Syringodium isoetifolium	Rhizome tagging	NA	2.52 ± 0.37 (7)	1.21 ± 0.26 (5)	0.61 ± 0.1 (2)	This study
Thalassia hemprichii	Leaf marking	2.12 ± 1.49 (3)	1.67 ± 0.22 (8)	1.85 ± 0.86^	1.77 ± NA (1)	This study

^ Value averaged from available data
* Value used as per April 2011 result
# Value used as per October 2011 result

Table 6. Mean daily rates of new growth (cm^2 shoot^{-1}, $\pm$ standard error) for Mabuiag Island seagrasses, April 2011 – January 2012.

Species	Shoot growth cm^2 day^{-1}			
	Apr-11	Jul-11	Oct-11	Jan-12
Cymodocea rotundata	0.23 ± 0.06	0.47 ± 0.04	1.12 ± 0.16	0.47 ± 0.14
Cymodocea serrulata	0.58 ± 0.06	NA	1.1 ± 0.06	NA
Enhalus acoroides	1.55 ± 0.48	1.53 ± 0.33	1.48 ± NA	NA
Halodule uninervis	0.11 ± 0.03	0.17 ± 0.03	0.29 ± 0.02	0.11 ± NA
Syringodium isoetifolium	0.03 ± 0.01	NA	0.16 ± 0.01	NA
Thalassia hemprichii	0.66 ± 0.46	0.52 ± 0.07	NA	0.55 ± NA

Table 7. Mean daily rates of new rhizome growth (mm day^{-1}, ± standard error) for Mabuiag Island seagrasses April 2011 – January 2012.

Species	Rhizome growth mm day^{-1}			
	Apr-11	Jul-11	Oct-11	Jan-12
Cymodocea rotundata	0.25 ± NA	0.85 ± 0.12	0.23 ± NA	0.25 ± 0.05
Cymodocea serrulata	0.06 ± 0.04	0.91 ± 0.47	0.14 ± 0.02	0.16 ± 0.06
Enhalus acoroides	NA	NA	NA	NA
Halodule uninervis	0.02 ± NA	0.66 ± 0.21	0.14 ± 0.03	0.03 ± 0.02
Syringodium isoetifolium	NA	0.68 ± 0.19	0.32 ± 0.06	0.13 ± 0.02
Thalassia hemprichii	NA	NA	NA	NA

4.3.2 Above-ground productivity of the intertidal seagrass meadow and meadow turnover

The Mabuiag Island intertidal foreshore seagrass meadow had an estimated total net above-ground productivity of 0.42 tonne dry weight per day at its lowest in April 2011 and reached 1.27 t DW day^{-1} at its peak in October 2011 (Figure 17). The time required for the intertidal seagrass meadow to turn over its above-ground biomass ranged from 15.1 days in October 2011 to 63.8 days in January 2012 (Figure 17). As expected, the quickest meadow turnover time corresponded with the peak in above-ground productivity; however, the inverse was not true. Meadow turnover time was slowest in January 2012 despite above-ground productivity being higher than in April 2011. Seagrass above-ground biomass peaked in February 2012 and thus when productivity rates slowed in January, it was taking longer to turn over the considerable meadow biomass.

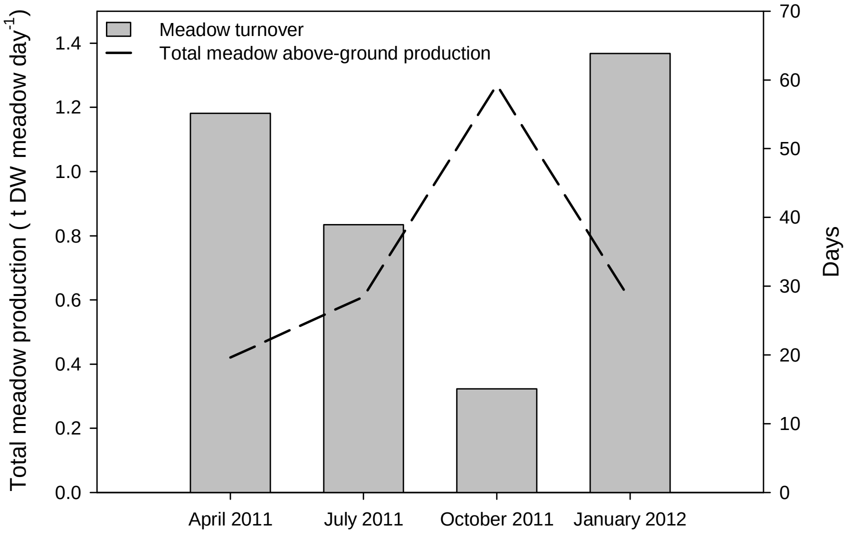


Figure 17. Total meadow above-ground production (t DW meadow day^{-1}) and meadow turnover time of Mabuiag Island intertidal seagrasses for each quarterly sample.

It is estimated that the Mabuiag Island intertidal foreshore seagrass meadow incorporated from 0.14 (April 2011) to 0.43 (October 2011) tonnes of carbon per day into its above-ground biomass. The rate of production per unit area similarly peaked in October 2011 at 0.72 g C m^{-2} day^{-1} (Table 8). Using the quarterly results to calculate annual productivity resulted in a value of 148g C m^{-2} $year^{-1}$.

Table 8. Above-ground carbon production for the Mabuiag Island intertidal seagrass meadow.

Time	Total meadow carbon production (t C meadow day^{-1})	Mean carbon production (g C m^{-2} day^{-1})
Apr-11	0.14	0.23
Jul-11	0.21	0.34
Oct-11	0.43	0.72
Jan-12	0.20	0.33

4.4 Discussion

Compared with other shallow aquatic environments seagrasses are generally considered to be one of the most productive habitats (Duarte and Chiscano 1999) and Mabuiag Island seagrasses appear to compare highly with other globally important ecosystems (Table 9). The net primary productivity of the intertidal study meadow at Mabuiag Island at its peak in October was higher than that of tropical coastal seagrasses studied at Abbot Point, Queensland (0.65 g C m^{-2} day^{-1}) (Unsworth et al. 2010), and far above terrestrial grassland systems (0.50 g C m^{-2} day^{-1})(Duarte and Chiscano 1999). This provides evidence that intertidal seagrasses at Mabuiag Island make a major contribution to local productivity that would be available for consumption by dugong and turtle.

Table 9. Net daily primary production of a range of different plant communities (g C m^{-2} day^{-1}).

Ecosystem	Location	Study	Production (g C m^{-2} day^{-1})
Grasslands	Global	Duarte and Chiscano 1999	0.50
Tropical Mangrove	Global	Lugo et al. 1988	0.92
Temperate Forest	Europe	Luyssaert et al. 2010	1.22
Tropical Rainforest	Amazon	Malhi et al. 2009	3.15
Tropical Reef Seagrass	Torres Strait	Rasheed et al. 2008	1.19
Seagrass Average	Global	Duarte and Chiscano 1999	0.94
Tropical Coastal Seagrass	Abbot Point	Unsworth et al. 2010	0.65
Tropical Island Reef Seagrass	Mabuiag Island	Present study	0.72

Above-ground productivity and carbon assimilated by Mabuiag Island intertidal seagrass meadows were strongly influenced by intra- and inter-annual changes to above-ground biomass changes, species composition and shoot density. Results of our study indicate that production was likely to be substantially higher around October than throughout the rest of the year.

The above-ground growth rates we measured for species at Mabuiag Island were generally within the range of values recorded for the same species in other tropical locations. The leaf productivity rate for the most productive species in our study, *Enhalus acoroides* (approx. 0.006 g DW shoot^{-1} day^{-1}) was double than that measured for an intertidal meadow at the nearby Orman Reefs, Torres Strait, (0.003 g DW shoot^{-1} day^{-1}; Rasheed et al. 2008) but much lower than that recorded for the species growing in similar substrates to Mabuiag Island in Philippines (0.04 to 0.07 g DW shoot^{-1} day^{-1}; Terrados et al. 1999). The above-ground productivity we measured for all other species were similar to other studies that have examined these species (Vermaat et al. 1995; Udy et al. 1999; Uku and Bjork 2005; Rasheed et al. 2008).

The Mabuiag Island intertidal seagrass meadow was less productive than seagrass meadows of similar species composition at the nearby Orman Reefs. The mean above-ground production of the meadow from our study in April was substantially lower than values recorded by Rasheed et al. (2008) for March 2004 (0.69 g DW m^{-2} day^{-1} compared with five meadows ranging from 1.0 to 2.63 g DW m^{-2} day^{-1}). The values recorded for October at Mabuiag Island, however, were towards the high end of the range at Orman Reefs (2.11 g DW m^{-2} day^{-1}). The high productivity at Orman Reefs in March was remarkable given that the mean above-ground biomass (and presumably shoot density) of the meadows were substantially lower than for Mabuiag Island (38.01 g DW m^{-2} (April) compared with 10.39 to 26.09 g DW m^{-2}) indicating that seagrass shoots may be much more productive at Orman Reefs at that time of year, but not necessarily throughout the entire year. Alternatively, this may simply be a reflection of more favourable conditions for seagrass growth being present in 2004 than during this study in 2011.

For species capable of replacing their leaves, production at the rhizome meristem (growing tip; new leaf plus rhizome growth) was generally much higher than for production in the leaf shoot. This production would likely have added significantly to the total production and carbon assimilated by Mabuiag Island seagrasses. Other studies have found that below ground production accounts for more than 32% of the total seagrass production (Duarte and Chiscano 1999) and this may be even higher when root production is included (up to 50 %, Duarte et al. 1998). A study in Papua New Guinea reported strong differences in the contribution to productivity made by below-ground structures between many of the species that were also found at Mabuiag Island (Brouns 1987) (17% for *Thalassia hemprichii*, 34% for *Cymodocea serrulata*, 50% for *Cymodocea rotundata* and 69% for *Syringodium isoetifolium*).

The intertidal seagrass meadow at Mabuiag Island had a relatively rapid turnover time with the meadow able to replace its above-ground biomass from as little as 15 days. Meadow turnover time was affected seasonally, however, with turnover taking up to 63 days in January when productivity was lowest. Turnover time was a reflection of the species composition with the meadow's most dominant species (by biomass) having very long reported turnover times in literature. *Cymodocea serrulata* is typically a slow species to turnover its biomass taking up to 37 days at the Orman Reefs (Rasheed et al. 2008), 60 days in the Philippines (Vermaat et al. 1995) and up to 100 days in our study. Similarly, two further species which form dominant components of the meadow, *Cymodocea rotundata* and *Syringodium isoetifolium,* also have slow turn over times (Vermaat et al. 1995; Uku and Bjork 2005; Rasheed et al. 2008). The slow turnover for these three species was offset somewhat at Mabuiag Island due to the presence of faster turnover species within the meadows such as *Thalassia hemprichii, Halophila ovalis* and *Halodule uninervis* which turned over their above-ground biomass in as quickly as every 7 days.

Net carbon productivity at Mabuiag Island (ranging from 0.23 to 0.72 g C m^{-2} day^{-1}) was similar to other tropical seagrass meadows that have been studied (e.g. Lindeboom and Sandee 1989; Kenworthy et al. 1989; Moriarty 1990; Rasheed et al. 2008). Measurements of mixed species seagrass meadows similar in species composition to our site in Indonesia had a net carbon production of 0.06 to 1.06 g C m^{-2} day^{-1} (Lindeboom and Sandee 1989). While production at Mabuiag Island was typical compared with other tropical locations, net carbon production in some dense temperate seagrass meadows can be much higher such as for *Zostera marina* which can range from 1.7 to 10.3 g C m^{-2} day^{-1} (Stevenson 1988).

This study provides an initial assessment of the above-ground production and carbon assimilated by Mabuiag Island seagrasses. It is likely that the productivity and carbon assimilated could vary from the estimated figures due to the inter-annual changes in factors that influence seagrass growth, and because meadow size is not constant and was likely to have varied seasonally. The net primary production of the reef platform seagrasses at Mabuiag Island is likely to be an important source of carbon for marine ecosystems in the Torres Strait region. Sources of marine autotrophic production are of critical importance in the area due to the general lack of terrestrial sources of carbon. The large area of intertidal seagrass at Mabuiag Island (2,190 ha; see Taylor et al. 2010) represented a substantial proportion of the available shallow seagrass habitat of the central Torres Strait. Carbon stable isotope analysis in Torres Strait food webs has also demonstrated that seagrasses are a key source of carbon for animals in intertidal areas compared with other primary producers such as macro algae, phytoplankton and epiphytic algae (Fry et al. 1983).

5 GENERAL DISCUSSION

The Torres Strait supports some of the largest and most diverse seagrass communities in the world. For the most part seagrasses in the Torres Strait remain in extremely good condition and have to date been insulated from the declines noted in many other parts of the world. Seagrass meadows are being rapidly lost globally by around 5% per year, and at least a third of the global seagrass area has been lost since World War II (Waycott et al. 2009). In the future seagrasses of the Torres Strait region are likely to be under increasing pressure from the predicted effects of climate change as well as the increasing risks posed by substantial increases in shipping through the region. This study provides an assessment of Torres Strait seagrass resilience, capacity for recovery, and the response of seagrasses to climate that can form the basis of understanding what the implications may be of these future pressures and by extension the implications for species such as dugong and turtle that rely on them.

5.1 Effects of predicted climate change

Although there has been considerable debate among scientists regarding the magnitude of predicted climate change (Schneider 1990), there is a consensus that an accelerated warming of the Earth's surface has begun and will continue (Schneider 1990; Kerr 1992; Watson et al. 1996). The impacts of increased atmospheric carbon dioxide, elevated land and sea temperatures, increasing sea level, increasing UV radiation and a host of secondary changes will alter the conditions for growth of aquatic plants (Watson et al. 1996). At Mabuiag Island the local climate factors that most impacted seagrasses were tidal exposure, water temperature and salinity. It is important to note, however, that these factors may not always be the most important climate drivers in the future. Seagrasses at Mabuiag Island may currently be living in their optimal light and pH ranges which are why changes in these factors over the 12 months period did not seem to alter seagrass abundance. Nevertheless as local climate regimes change this may no longer be the case.

Pacific Ocean mean sea-surface temperatures are expected to rise 1.4- to 2.6°C by the end of the century (Australian Bureau of Meteorology and CSIRO 2011). Increasing water temperature will directly affect seagrass metabolism and the maintenance of a positive carbon balance (Evans et al. 1986; Marsh et al. 1986; Bulthuis 1987; Zimmerman et al. 1989), which may result in changes in seasonal and geographic patterns of species abundance and distribution (McMillan 1984; Walker 1991). The direct effects of increased temperature will depend on the individual species thermal tolerances and their optimum temperatures for photosynthesis, respiration and growth. For intertidal seagrasses as a whole at Mabuiag Island, we found a positive relationship between water temperature and above-ground biomass indicating that seagrasses are currently within their optimal range, even at peak summer water temperatures. However, evidence suggests there is a critical temperature limit for seagrasses, above which it is expected there would be a decrease in productivity and distribution (Short and Neckles 1999).

Tropical seagrasses are typically living at the edge of their salinity thresholds (Walker 1985; Koch et al. 2007). Predicted reductions to ocean salinity levels (up to 0.34 ppt by 2090) as a result of climate change in the Pacific (Australian Bureau of Meteorology and CSIRO 2011) may provide a small buffer for Mabuiag Island seagrasses. Little research has been conducted as to how tropical seagrasses would react in the face of a gradual decline in salinity, with most work focusing on salinity increases caused by brine discharge in the Mediterranean (Short and Neckles 1999; Koch et al. 2007) or freshwater pulse events from flooding (Campbell and McKenzie 2004). Evidence suggests, however, that photosynthesis and respiration are often inhibited in aquatic plants exposed to extreme hypo-osmotic conditions (Touchette 2007). Diminished photosynthesis in seagrasses under hyposaline conditions have been observed in *Halophila ovalis* and *Zostera muelleri* under 25ppt, which is far below the predicted salinity levels for the Pacific under climate change scenarios (Kerr and Strother, 1985; Ralph, 1998).

Projections for sea level rise in the Torres Strait indicate a rise of 0.84m by 2100 is possible (Suppiah et al. 2007). Sea level rise is expected to cause a change in the magnitude of tidal range: depending on coastal geomorphology and degree of tidal restriction already existing at a given location, expansion or lessening of tidal range may occur (De Jonge and De Jong, 1992). Increased tidal range would impact seagrasses most at Mabuiag Island by increasing the amount of intertidal exposure at low tide. At the shallow edge of the meadow, seagrass stress due to exposure at low tide would be increased. Results from this study indicate that seagrasses in the intertidal are already being impacted by high levels of exposure, particularly during the summer months, and therefore the result of further stress may see a loss of seagrass area. It is unlikely that successful seaward movement of intertidal seagrass meadows would occur as the geomorphology of the island and surrounding channels would impede movement.

The implications of climate change for seagrasses in the Torres Strait are complex. However what our study to date indicates is that many seagrasses have a good capacity for recovery from impacts and a reasonable level of resilience, providing a local source of propagules remains viable. These attributes mean that acute and short lived impacts such as those associated with shipping accidents have a good prognosis for recovery. However chronic shifts in climate that push seagrass species beyond their tolerance limits have the potential to cause fundamental shifts in the seagrass community.

5.2 Implications for dugong and turtle management

Potential changes in distribution and structure of Torres Strait seagrass communities may have profound implications for local and regional biota, particularly dugong, turtle and economically important fisheries. The spatial distribution of quality food strongly influences the movement patterns and foraging behaviours of dugong (Sheppard et al. 2007). Seagrass areas in Torres Strait have undergone ‘diebacks’, or large-scale episodic losses and changes in distribution on temporal scales of up to decades (Williams 1994). Torres Strait Islanders widely reported such a dieback event in the mid-1970s and in the early 1980s (Johannes and MacFarlane 1991; Williams 1994). Although the reasons behind these diebacks remain unclear, local dugong mortality rates increased dramatically following these events (Marsh et al. 2004). A similar pattern of large-scale seagrass loss across the east coast of Queensland in 2011 resulted in an 215% and 176% increase in dugong and turtle deaths respectively (compared to 2010) primarily as a result of starvation (DERM 2011). These statistics are alarming in the face of predicted climate change scenarios and the potential negative effect on seagrasses.

While there is little to be done locally in the Torres Strait to prevent climate-related change, the management of seagrass resources should be focused on reducing any anthropogenic impacts and risks to ensure resilience levels of local seagrass populations remain high. Repeated pulse impact events on the east coast of Queensland have resulted in reduced resilience of seagrass in some areas and reduced recovery capacity following losses, despite general climate conditions being favourable for growth (i.e. Mourilyan Harbour; Reason et al. 2012). At present, the seagrass species most favoured as food for dugong in the Torres Strait, *Halodule uninervis* and *Halophila ovalis*, have high levels of resilience with dense seed banks established and their ability to rapidly re-colonise disturbed areas through both sexual and asexual means. Many other species found in the Torres Strait that form more minor components of the diet of dugongs and turtles have moderate levels of resilience as they rely more heavily on asexual reproduction and have the potential to take in excess of a year to recover from large-scale loss.

This research program is ongoing with continued assessment of seagrass changes against water quality and climate parameters in the coming years likely to further strengthen and resolve some of the key relationships that we have begun to establish. This will place us in a better position to examine potential implications of climate shifts to seagrass communities as well as to dugong and turtle feeding opportunities.

5.3 Recommendations

Continuation of the monitoring and research program at Mabuiag Island will provide much-needed information on how natural climate variability, and future scenarios of climate change, may impact seagrass meadows and therefore dugong and turtle feeding opportunities. These relationships require data to be collected over several seasons and years. We recommend:

1. Continue monitoring intertidal and subtidal seagrass meadows and climate variables to further assess the relationship between seagrass biomass with water quality and climate. A long term data set will allow for more accurate estimates of the strength of these relationships and provide the ability to predict how seagrasses may respond to climatic variation.

2. New experimental research should focus on how seagrasses in Torres Strait respond to some of the predicted effects of climate change, and may include the effect of decreased salinity on seagrass photosynthesis and respiration, increased water temperature, and increased exposure of intertidal seagrasses.

3. Information that is collected can be incorporated into modelling of the consequences of climate change on Torres Strait seagrass distribution to develop appropriate dugong and turtle management strategies that respond to potential shifts in seagrass distribution and communities.

4. Information collected in the program form part of considerations for future dugong and turtle management plans in the Torres Strait.

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A APPENDICES

A.1 Statistical Analysis

Table 1. Results of one-way ANOVA tests for mean above-ground biomass versus time (months), Mabuiag Island, March 2011 – June 2012.

Intertidal	DF	SS	MS	F	P
Between Months	11	9888.062	898.915	2.957	0.002
Within Months	96	29185.58	304.016		
Total	107	39073.65			

Results of Behrens Fisher Test (unequal variances) comparisons of mean above-ground biomass versus month for intertidal seagrass, Mabuiag Island, March 2011 – June 2012. Shaded cells indicate a significant difference of $p < 0.01$.

Intertidal	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12
Apr-11															
May-11	NO														
Jun-11	NO	NO													
Jul-11	NO	NO	NO												
Aug-11	NO	NO	NO	NO											
Sep-11	NO	NO	NO	NO	NO										
Oct-11	NO	NO	NO	NO	NO	NO									
Nov-11	NO	NO	YES	NO	YES	YES	YES								
Dec-11	NO	NO	YES	NO	NO	NO	NO	NO							
Jan-12	NO	YES	YES	YES	NO	NO	YES	NO	NO						
Feb-12	NO	YES	YES	YES	NO	NO	YES	NO	NO	NO					
Mar-12	NO	YES	YES	YES	NO	NO	YES	NO	NO	NO	NO				
Apr-12	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO			
May-12	NO	NO	YES	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO		
Jun-12	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	

Table 2. Results of one-way ANOVA tests for mean subtidal above-ground biomass versus time (months), Mabuiag Island, March 2011 – June 2012.

Subtidal	DF	SS	MS	F	P
Between Groups	4	31101.09	7775.273	29.149	<0.001
Residual	40	10669.6	266.74		
Total	44	41770.69			

Results of Least Significant Difference (LSD; equal variances) pair-wise comparisons of subtidal mean above-ground biomass versus month, Mabuiag Island, March 2011 – June 2012. Means that share a common letter for each month are not significantly different.

Subtidal	
Month	**Mean Biomass**
Apr-11	48.38 a
Aug-11	29.58 a
Oct-11	82.73 b
Dec-11	102.64 b
Apr-12	50.13 a

A.2 Statistical Analysis

Table 3. Comparison of relationships between mean daily salinity, water temperature, daily rainfall, total rainfall and total daytime tidal exposure with seagrass meadow above-ground biomass in intertidal meadows, using environmental data collected over five time periods leading up to seagrass sampling. Slopes or intercepts that share a common letter between time periods are not significantly different. Rows in bold indicate time period that was the strongest predictor for each environmental variable with seagrass biomass.

Environmental variable	Time period	R^2	*P*-value	ANCOVA	
				slopes	intercepts
Mean daily salinity	7 days	R^2=0.51	<0.05	a	a
	14 days	R^2=0.54	<0.05	a	a
	1 month	**R^2=0.55**	**<0.01**	a	a
	2 months	R^2=0.43	<0.05	a	a
	3 months		>0.05		
Mean daily water temperature	7 days		>0.05		
	14 days		>0.05		
	1 month	R^2=0.46	<0.05	a	a
	2 months	R^2=0.59	<0.01	a	a
	3 month	**R^2=0.63**	**<0.05**	a	a
Mean daily rainfall	**7 days**	**R^2=0.51**	**<0.01**	a	a
	14 days	R^2=0.37	<0.05	a	a
	1 month		>0.05		
	2 months		>0.05		
	3 months		>0.05		
Total rainfall	**7 days**	**R^2=0.47**	**<0.05**		
	14 days		>0.05		
	1 month		>0.05		
	2 months		>0.05		
	3 months		>0.05		
Total daytime tidal exposure	7 days		>0.05		
	14 days		>0.05		
	1 month	**R^2=0.55**	**<0.01**	a	a
	2 months	**R^2=0.55**	**<0.01**	a	a,b
	3 months	R^2=0.24	<0.05	a	b

A.3 Statistical Analysis

Table 4. Results of nested two-way ANOVA tests for "Round 1" mean above-ground biomass versus treatment for each block and time (months since clearing), Mabuiag Island.

Source of variation	**Time 0**			**Time 1**			**Time 2**			**Time 3**			**Time 4 & 4.5 (Subtidal)**		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	1058.92	0.1770	2	142.95	0.3240	2	34.76	0.0890	2	107.17	0.4480	2	304.15	0.0750
Treatment	3	5411.79	**<0.001**	3	2818.33	**<0.001**	3	2090.90	**<0.001**	3	1725.8	**<0.001**	3	2932.01	**<0.001**
Block x Treatment	6	452.13	0.5820	6	64.66	0.7760	6	28.60	0.0780	6	59.73	0.8290	6	305.83	0.0280
Residual	24	567.64		24	120.86		24	12.97		24	128.97		24	105.29	
Total	35	991.12		35	343.7		35	195.00		35	252.73		35	393.32	
Subtidal	**DF**	**MS**	**P**										**DF**	**MS**	**P**
Block	2	164.014	0.1000										2	43.6	0.5910
Treatment	3	6606.53	**<0.001**										3	1425.26	**<0.001**
Block x Treatment	6	92.62	0.2430										6	93.82	0.3620
Residual	24	64.57											24	81.17	
Total	35	635.8											35	196.4	

Source of variation	**Time 5.5**			**Time 6.5 & 6 (Subtidal)**			**Time 7.5**			**Time 8.5 & 8 (Subtidal)**			**Time 10**		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	335.11	0.0940	2	227.51	0.3600	2	20.723	0.5960	2	28.518	0.8150	2	942.818	0.0920
Treatment	3	2827.37	**<0.001**	3	1962.106	**<0.001**	3	3570.924	**<0.001**	3	3935.209	**<0.001**	3	6493.075	**<0.001**
Block x Treatment	6	159.77	0.3200	6	194.034	0.5050	6	111.42	0.0310	6	140.797	0.4390	6	223.894	0.7060
Residual	24	128.43		24	213.441		24	39.229		24	138.612		24	356.629	
Total	35	376.95		35	360.803		35	353.264		35	458.118		35	893.352	
Subtidal				**DF**	**MS**	**P**				**DF**	**MS**	**P**			
Block				2	1494.762	0.0410				2	1716.879	0.0020			
Treatment				3	4874.798	<0.001				3	12021.97	<0.001			
Block x Treatment				6	258.015	0.7040				6	423.149	0.1120			
Residual				24	409.012					24	215.721				
Total				35	827.951					35	1349.025				

Source of variation	Time 11			Time 12			Time 13			Time 14			Time 15		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	1591.186	**0.0430**	2	500.554	0.0580	2	369.983	0.1080	2	42.811	0.5410	2	56.329	0.6120
Treatment	3	3316.194	**0.0010**	3	3861.076	**<0.001**	3	2952.698	**<0.001**	3	1489.35	**<0.001**	3	1968.417	**<0.001**
Block x Treatment	6	801.795	0.1380	6	201.346	0.2970	6	113.069	0.6160	6	76.628	0.3770	6	80.53	0.6400
Residual	24	441.151		24	155.497		24	150.97		24	68.001		24	112.402	
Total	35	815.125		35	500.696		35	397.136		35	189.871		35	262.821	
Subtidal				**DF**	**MS**	**P**									
Block				2	759.282	0.0550									
Treatment				3	1924.583	**<0.001**									
Block x Treatment				6	382.663	0.1770									
Residual				24	231.909										
Total				35	432.975										

Results of nested two-way ANOVA tests for “Round 1” mean shoot count versus treatment for each block and time (months since clearing), Mabuiag Island.

Source of variation	Time 0			Time 1			Time 2			Time 3			Time 4 & 4.5 (Subtidal)		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	176318.1	**0.03**	2	1171698	0.131	2	257113	**0.028**	2	9249.361	0.836	2	668123.6	**0.005**
Treatment	3	3861555	**<0.001**	3	5725226	**<0.001**	3	1879914	**<0.001**	3	1403397	**<0.001**	3	2754376	**<0.001**
Block x Treatment	6	96254.24	0.076	6	300504.1	0.752	6	113018.6	0.134	6	9078.991	0.981	6	238971.7	0.06
Residual	23	43115.94		24	529567.9		24	61507.08		24	51424.19		24	100145.4	
Total	34	401740.5		35	972335.1		35	237378.5		35	157638.4		35	383905.6	
Subtidal	**DF**	**MS**	**P**										**DF**	**MS**	**P**
Block	2	85277.78	0.122										2	2650090	**<0.001**
Treatment	3	10252101	**<0.001**										3	7947809	**<0.001**
Block x Treatment	6	33194.44	0.513										6	315717	**0.009**
Residual	24	37013.89											24	83544.97	
Total	35	914695.9											35	944085.3	

Source of variation	Time 5.5			Time 6.5 & 6 (Subtidal)			Time 7.5			Time 8.5 & 8 (Subtidal)			Time 10		
Intertidal	DF	MS	P	DF	MS	P	DF	MS	P	DF	MS	P	DF	MS	P
Block	2	1816857	**0.012**	2	817727.1	**0.014**	2	701406.3	**0.004**	2	390954.9	0.073	2	1040721	**0.008**
Treatment	3	5743477	**<0.001**	3	3226325	**<0.001**	3	2102060	**<0.001**	3	3635851	**<0.001**	3	1329412	**0.001**
Block x Treatment	6	542997.1	0.184	6	375731.7	0.061	6	101383.1	0.435	6	128941	0.468	6	248858.7	0.252
Residual	21	329812.8		24	158343.8		24	99201.39		24	133368.1		24	176590.4	
Total	32	948499.9		35	496259.1		35	305660.7		35	447541.2		35	337171.4	
Subtidal				DF	MS	P				DF	MS	P			
Block				2	5768489	**<0.001**				2	6211120	**<0.001**			
Treatment				3	9350278	**<0.001**				3	7212097	**<0.001**			
Block x Treatment				6	178399.4	0.717				6	1355613	0.022			
Residual				24	290701.7					24	438842.6				
Total				35	1361001					35	1506412				

Source of variation	Time 11			Time 12			Time 13			Time 14			Time 15		
Intertidal	DF	MS	P	DF	MS	P	DF	MS	P	DF	MS	P	DF	MS	P
Block	2	1052278	**0.014**	2	260892.5	0.266	2	228064.8	0.426	2	45461.19	0.591	2	40915.44	0.926
Treatment	3	1363185	**0.002**	3	1162589	**0.003**	3	1360830	**0.006**	3	857289.8	**<0.001**	3	616997.7	0.344
Block x Treatment	6	298954.6	0.231	6	78429.57	0.858	6	146226.8	0.752	6	44223.23	0.785	6	322639.5	0.721
Residual	24	203406.5		24	186276.1		24	257824.5		24	84545.14		24	530153.9	
Total	35	367702.7		35	255735.9		35	331536.2		35	141634.7		35	474067.3	
Subtidal				DF	MS	P									
Block				2	1421892	**0.026**									
Treatment				3	5119120	**<0.001**									
Block x Treatment				6	252540.5	0.611									
Residual				24	334062.5										
Total				35	792396.8										

Table 5. Results of Least Significant Difference (LSD) pair-wise comparisons of “Round 1” mean above-ground biomass versus treatment by month for intertidal and subtidal experimental blocks, Mabuiag Island March 2011 – June 2012. Means that share a common letter for each meadow are not significantly different.

Intertidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	38.01 a	46.15 a	0.0 b	0.0 b
1	30.61 a	35.84 a	4.41 b	1.34 b
2	27.85 a	31.19 a	7.55 b	0.0 c
3	27.31 a	28.23 a	7.62 b	0.91 b
4	39.04 a	37.44 a	19.21 b	0.6 c
5.5	41.38 a	37.97 a	32.15 a	2.55 b
6.5	31.77 a	25.76 a	35.59 a	2.64 b
7.5	41.53 a	40.22 a	43.81 a	2.13 b
8.5	46.21 a	40.37 a	46.21 a	2.8 b
10	62.9 a	56.94 a	70.08 a	10.67 b
11	51.98 a	46.02 a	55.1 a	13.39 b
12	53.81 a	41.18 b	49.38 ab	8.04c
13	48.62 a	38.26 a	45.12 a	8.81 b
14	38.51 a	33.11 a	37.58 a	11.11 b
15	44.1 a	34.98 a	38.6 a	10.61 b

Subtidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	48.38 a	45.38 a	0.0 b	0.0 b
4.5	29.58 a	31.21 a	12.42 b	5.84 b
6	82.73 a	64.28 ab	49.61 b	27.7 c
8	102.64 a	97.18 a	83.18 b	23.1 c
12	50.15 a	44.81 a	48.66 a	18.97 b

Results of Least Significant Difference (LSD) pair-wise comparisons of “Round 1” mean shoot counts versus treatment by month for intertidal and subtidal experimental blocks, Mabuiag Island March 2011 – June 2012. Means that share a common letter for each meadow are not significantly different.

Intertidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	1030.6 a	1258.3 b	0.0 c	0.0 c
1	1696.3 a	1407.4 a	444.4 b	0.0 b
2	961.1 a	877.8 a	331.1 b	0.0 c
3	894.4 a	800 a	480.6 b	19.1 c
4	1263.9 a	1086.1 b	688.9 c	16.4 d
5.5	1518.2 a	1656.9 a	2091.7 a	191.7 b
6.5	1408.3 a	1266.7 a	1444.4 a	185.6 b
7.5	1188.9 a	1177.8 a	1291.7 a	258.3 b
8.5	1502.8 a	1405.6 a	1711.1 a	294.4 b
10	1202.8 a	980.6 a	1244.4 a	409.7 b
11	1072 a	1225 a	1308 a	448.4 b
12	1217 a	930.6 a	1239 a	467 b
13	1377.8 a	1119.4 a	1413.9 a	571.6 b
14	905.6 a	841.7 a	983.3 a	303.9 b
15	1491.7 a	1297.2 a	1544.4 a	965.9 a

Subtidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	1850 a	1847.2 a	0.0 b	0.0 b
4.5	2322.2 a	2325 a	1822.2 b	337.4 c
6	2763.8 a	3050 ab	2469.4 a	778.4 c
8	2205.6 a	2911.1 b	2717 ab	922.6 c
12	2025 a	2411.1 a	2161.1 a	725 b

A.4 Statistical Analysis

Results of nested two-way ANOVA tests for “Round 2” mean above-ground biomass versus treatment for each block and month, intertidal experimental blocks (August 2011 – June 2012) and subtidal experimental blocks (November 2011 – June 2012), Mabuiag Island.

Source of variation	**Time 0**			**Time 1.5 & 1.0 (Subtidal)**			**Time 2.5**			**Time 3.5**			**Time 5 & 5.5 (Subtidal)**		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	82.561	**0.0410**	2	94.085	0.4350	2	135.35	0.2240	2	243.854	0.2520	2	65.34	0.6220
Treatment	3	2950.805	**<0.001**	3	1221.755	**<0.001**	3	3088.21	**<0.001**	3	5497.331	**<0.001**	3	7647.228	**<0.001**
Block x Treatment	6	56.004	0.0520	6	54.121	0.8050	6	125.99	0.2260	6	133.498	0.5790	6	64.527	0.8180
Residual	24	22.623		24	109.245		24	84.98		24	166.711		24	134.867	
Total	35	282.757		35	194.287		35	352.31		35	622.336		35	762.753	
Subtidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**						*	**DF**	**MS**	**P**
Block	2	39.94	0.4480	2	934.595	**0.0110**						Between Treatment	3	683.129	**<0.001**
Treatment	3	13963.38	**<0.001**	3	30607.52	**<0.001**									
Block x Treatment	6	19.625	0.8670	6	313.737	0.1310						Within Treatment	8	20.929	
Residual	24	48.154		24	169.195										
Total	35	1235.528		35	2846.71							Total	11		

Source of variation	**Time 6**			**Time7**			**Time 8**			**Time 9**			**Time 10**		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	149.742	0.6860	2	1551.31	**<0.001**	2	664.203	**0.0130**	2	12.306	0.7110	2	196.276	0.3330
Treatment	3	5211.848	**<0.001**	3	6373.683	**<0.001**	3	2851.407	**<0.001**	3	1101.324	**<0.001**	3	1770.487	**<0.001**
Block x Treatment	6	150.261	0.8820	6	247.995	**0.0360**	6	187.702	0.2250	6	14.983	0.8580	6	56.855	0.9120
Residual	24	391.138		24	90.403		24	126.291		24	35.617		24	170.43	
Total	35	749.254		35	739.466		35	401.138		35	122.094		35	289.585	

* Only 1 of 3 subtidal blocks surveyed. One-way ANOVA conducted.

Results of nested two-way ANOVA tests for “Round 2” mean shoot counts versus treatment for each block and month, intertidal experimental blocks (August 2011 – June 2012) and subtidal experimental blocks (November 2011 – June 2012), Mabuiag Island.

Source of variation	Time 0			Time 1.5 & 1.0 (Subtidal)			Time 2.5			Time 3.5			Time 5		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	481458.3	**0.003**	2	396304.5	**0.012**	2	191494.4	0.193	2	708463	**0.01**	2	195388.1	0.253
Treatment	3	9314925	**<0.001**	3	9297672	**<0.001**	3	5407492	**<0.001**	3	4939167	**<0.001**	3	3511318	**<0.001**
Block x Treatment	6	203588	**0.022**	6	287339.7	**0.008**	6	205540.7	0.124	6	125363	0.448	6	93081.6	0.657
Residual	24	66250		24	74710.42		24	108775.9		24	125449.1		24	134087.8	
Total	35	906263.4		35	920077.5		35	584266.6		35	571353.8		35	420038	
Subtidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**			*****	**DF**	**MS**	**P**
Block	2	13489.58	0.748	2	811216.8	**0.016**	2	567390.3	**0.007**			Between Treatment	3	3059318	**<0.001**
Treatment	3	11419352	**<0.001**	3	12858817	**<0.001**	3	2857104	**<0.001**						
Block x Treatment	6	9924.769	0.968	6	467515.4	**0.03**	6	437838.4	**0.003**			Within Treatment	8	126087	
Residual	24	45850.69		24	163306.6		24	92729.67							
Total	35	1012714		35	1340667		35	415961				Total	11		

Source of variation	Time 6			Time7			Time 8			Time 9			Time 10		
Intertidal	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**	**DF**	**MS**	**P**
Block	2	502080.3	0.063	2	120408.7	0.394	3	736986.8	**0.012**	2	44034.11	0.716	2	1068249	**0.004**
Treatment	3	3732660	**<0.001**	3	2382240	**<0.001**	3	5747370	**<0.001**	3	1603947	**<0.001**	3	2210039	**<0.001**
Block x Treatment	6	222543.2	0.263	6	166464.3	0.279	9	355078.9	0.065	6	87781.33	0.67	6	487098.6	**0.018**
Residual	24	161340		24	124341.9		32	172482.7		24	129787.3		24	151465.9	
Total	35	497416		35	324872.2		47	599324		35	244042.6		35	437839.6	

Results of Least Significant Difference (LSD) pair-wise comparisons of “Round 2” mean above-ground biomass versus treatment by month for intertidal experimental blocks (August 2011 – June 2012) and subtidal experimental blocks (November 2011 – June 2012), Mabuiag Island. Means that share a common letter for each meadow are not significantly different.

Intertidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	30.54 a	32.15 a	0.0 b	0.0 b
1.5	26.1 a	22.97 a	7.73 b	2.03 b
2.5	34.93 a	38.11 a	6.35 b	2.89 b
3.5	47.4 a	51.74 a	15.55 b	0.79 c
5	64.89 a	71.15 a	42.8 b	6.63 c
6	52.63 a	52.7 a	25.27 b	2.93 c
7	53.25 a	63.44 a	38.0 b	1.97 c
8	41.67 a	48.95 ab	35.98 a	8.22 c
9	30.69 a	34.04 ab	26.77 a	9.19 c
10	33.44 a	37.43 ab	21.8 a	6.17 c

Subtidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	66.86 a	69.53 a	0.0 b	0.0 b
1	103.18 a	99.91 a	1.0 b	0.13 b
2.5*	NA	NA	NA	NA
5.5^	30.11 a	28.87 a	6.32 b	0.97 b

* Shoot counts only

^ Only 1 of 3 blocks surveyed

Results of Least Significant Difference (LSD) pair-wise comparisons of “Round 2” mean shoot counts biomass versus treatment by month for intertidal experimental blocks (August 2011 – June 2012) and subtidal experimental blocks (November 2011 – June 2012), Mabuiag Island. Means that share a common letter for each meadow are not significantly different.

Intertidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	1872.2 a	1636.1 a	0.0 b	0.0 b
1.5	1955.6 a	1952.8 a	408.3 b	21.8 c
2.5	1725 a	1480.6 a	602.8 b	55.1 c
3.5	1744.4 a	1561.1 a	1127.8 b	89.3 c
5	1594.4 a	1422.2 a	975 b	195.7 c
6	1713.9 a	1308.3 b	1136.1 b	192.7 c
7	1555.6 a	1150 b	1217 ab	341.7 c
8	1941.7 a	1745.8 b	1402.1 b	386.3 c
9	1280.6 a	1041.7 a	1150 a	336 b
10	1472.2 a	797.2 b	1133 ab	310.6 c

Subtidal

Months	Treatment			
	Control, no border	Control, border	Cleared, no border	Cleared, border
0	1905.6 a	1994.4 a	0.0 b	0.0 b
1	2491.7 a	1936.1 b	334 c	48.4 c
2.5	1002.8 a	1227.8 a	366.8 b	6.7 c
5.5*	1933.3 a	2467 ab	1075 a	162.3 c

A.5 Statistical Analysis

Results of one-way ANOVA tests for mean seagrass species leaf production rates (g shoot^{-1} day^{-1}) versus quarterly sampling event Mabuiag Island.

Tested April 2011, July 2011 and October 2011.

Enhalus acoroides*	**DF**	**SS**	**MS**	**F**	**P**
Between Quarters	1	0.000141	0.000141	0.133	0.7200
Residual	16	0.017	0.00106		
Total	17	0.0171			

* Data were square-root transformed to meet the assumption of normality

Tested April 2011, July 2011, October 2011 and January 2012

Cymodocea rotundata	**DF**	**SS**	**MS**	**F**	**P**
Between Quarters	3	0.0000849	0.0000283	8.543	<0.001
Residual	20	0.0000663	0.00000331		
Total	23	0.000151			

Tested April 2011, July 2011, October 2011 and January 2012

Halodule uninervis	**DF**	**SS**	**MS**	**F**	**P**
Between Quarters	2	0.00000107	0.000000536	16.834	<0.001
Residual	42	0.00000134	0.000000032		
Total	44	0.00000241			

Tested April 2011, July 2011 and January 2012

Thalassia hemprichii	**DF**	**SS**	**MS**	**F**	**P**
Between Quarters	1	0.00000044	0.00000044	0.247	0.6310
Residual	9	0.000016	0.000016		
Total	10	0.000017	0.000017		

Results of Least Significant Difference (LSD; equal variances) or Behrens Fisher (unequal variances) pair-wise comparisons mean seagrass species leaf production rates (g shoot^{-1} day^{-1}) versus quarterly sampling event (April 2011, July 2011, October 2011 and January 2011), Mabuiag Island. Means that share a common letter for each month are not significantly different.

Quarter	***C. rotundata****	***H. uninervis***
Apr-11	0.000836 a	0.000238 a
Jul-11	0.001657 b	0.000349 ab
Oct-11	0.004994 c	0.000592 b
Jan-12	0.001661 ab	0.000231 ab

* Behrens Fisher comparison used.

Results of t-test for seagrass species leaf production rates (g shoot^{-1} day^{-1}) In April and October 2011, Mabuiag Island.

Cymodocea serrulata*	**DF**	**t**	**P**
Between Quarters	98	-5.606	<0.001

* Data were square-root transformed to meet the assumptions of normality

Syringodium isoetifolium	**DF**	**t**	**P**
Between Quarters	6	-5.816	0.0010