Seagrasses in tropical Australia, productive and abundant for decades decimated overnight

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Seagrass ecosystems provide unique coastal habitats critical to the life cycle of many species. Seagrasses are a major store of organic carbon. While seagrasses are globally threatened and in decline, in Cairns Harbour, Queensland, on the tropical east coast of Australia, they have flourished. We assessed seagrass distribution in Cairns Harbour between 1953 and 2012 from historical aerial photographs, Google map satellite images, existing reports and our own surveys of their distribution. Seasonal seagrass physiology was assessed through gross primary production, respiration and photosynthetic characteristics of three seagrass species, *Cymodocea serrulata*, *Thalassia hemprichii* and *Zostera muelleri*. At the higher water temperatures of summer, respiration rates increased in all three species, as did their maximum rates of photosynthesis. All three seagrasses achieved maximum rates of photosynthesis at low tide and when they were exposed. For nearly six decades there was little change in seagrass distribution in Cairns Harbour. This was most likely because the seagrasses were able to achieve sufficient light for growth during intertidal and low tide periods. With historical data of seagrass distribution and measures of species production and respiration, could seagrass survival in a changing climate be predicted? Based on physiology, our results predicted the continued maintenance of the Cairns Harbour seagrasses, although one species was more susceptible to thermal disturbance. However, in 2011 an unforeseen episodic disturbance – Tropical Cyclone Yasi – and associated floods lead to the complete and catastrophic loss of all the seagrasses in Cairns Harbour.

1. Introduction

As submerged marine flowering plants, seagrass meadows are found in shallow coastal waters around the world. They provide food and shelter for invertebrates and fish, endangered species such as dugongs and turtles, and provide a critical part of the early life cycle of many species that contribute to off-shore fisheries (Greenway 1995; Green and Short 2003; Halpern *et al.* 2008). Recent research has shown that seagrass meadows globally store nearly three times more organic carbon than the carbon stocks of the world's forests (Fourqurean *et al.* 2012). Human activity in coastal areas is limiting the extent of their distribution and with global climate change and increased water temperatures their distribution may be even further limited (Orth *et al.*

2006; Short *et al.* 2007; Waycott *et al.* 2009; Jorda *et al.* 2012; McKenzie *et al.* 2012). There are few places in the world where coastal seagrass ecosystems have not only survived but also flourished amidst increasing anthropogenic influences (Halpern *et al.* 2008). While there are many examples of anthropogenic causes of seagrass loss along the Queensland coast over the past decade (McKenzie *et al.* 2012), in Cairns Harbour they have flourished. The focus of our study in Cairns Harbour was to assess seagrass productivity and record their abundance and distribution over the last sixty years.

Predicting the impact of environmental stresses on coastal seagrass ecosystems that will result from our changing climate is imperative. Measuring seagrass photosynthesis and production is essential to assess the effects of global change

in these coastal marine habitats (Ralph *et al.* 2007; Jorda *et al.* 2012). Light is a principal environmental factor influencing the growth and depth distribution of seagrasses (Iverson and Bittaker 1986). Water temperature is also a key factor: the higher the temperature the more primary production is lost to respiration due to thermal stress (Bulthuis 1983; Campbell *et al.* 2006; 2008). Increases in water temperature also increase the amount of light required to saturate photosynthesis (Collier *et al.* 2011). Today this information coupled with an understanding of the seagrass physiology forms the basis of our ability to predict seagrass survival and distribution (Ralph *et al.* 2007; Bekkby *et al.* 2008; Silva *et al.* 2009; O'Brien *et al.* 2012). There is a minimum amount of light necessary to support seagrass growth; to survive they need a positive carbon balance. Seagrass respiration influences the carbon balance, and the way a plant allocates photosynthate between above- and below-ground biomass (Ralph *et al.* 2007). Hence, in this study we monitored the distribution of seagrasses and their relationship with light, seasonal water temperature, production and respiration.

Across Australia, over the last 30 years there have been many studies of depth distribution and growth of seagrasses in relation to the light regime and the importance of light (Clough and Attiwill 1980; Bulthuis 1983; Larkum *et al.* 1989; Masini *et al.* 1990; Ralph and Gademann 2005; Ralph *et al.* 2007; O'Brien *et al.* 2012). Ecosystem-scale models of the North Queensland coast opposite the Great Barrier Reef found that seagrass exposure and tidal extent are the most constraining influences of seagrasses distribution in these tropical coastal environments (Grech and Coles 2010).

An important aspect of our research was to show the seagrass distribution in Cairns Harbour before the devastating loss of 2011. As early as 1967, den Hartog (1970) surveyed the seagrasses of Cairns Harbour. We wanted to collect and describe the history of the seagrass distribution from these early studies of den Hartog. There are few studies on the long-term survival of these tropical species and their light requirements. Our aim was to assess the survival of these seagrasses in the tropics over decades along with knowledge of the seagrasses' physiology. With historical data of seagrass distribution and measures of species production and respiration in Cairns Harbour, we hypothesise that seagrass survival in a changing climate, could be predicted.

2. Materials and methods

2.1 *Site description*

Cairns Harbour has extensive areas of intertidal mudflats between Cairns Marina and Ellie Point to the west of the shipping channel (Western Cairns Harbour) and Trinity Inlet and False Cape east of the shipping channel (Eastern Cairns Harbour). For a detailed description, see figure 1 and other surveys

(Campbell *et al.* 2003; Rasheed *et al.* 2006). Our study site was a 56 ha intertidal area located adjacent to and extending up to 250 m from the Esplanade (figure 1; 16° 53′ 41.22′′ S, 145° 47′ 14.05′′ E).

Within our study site we identified 6 species; *Zostera muelleri, Cymodocea serrulata, Thalassia hemprichii, Halophila ovalis, Halodule uninervis* and *Halodule pinifolia*. Figure 1 shows the species present at sites inspected in 1987 and at the stations sampled on our study transect. *Zostera* and *Halophila* had the greatest range of depth distribution (0.25 m below chart datum (CD) to 0.9 m above CD), whilst *Cymodocea* and *H.uninervis* were restricted to the lower tidal limits (−0.25 m to 0.3 m). *Thalassia* was recorded above the chart datum while *H. pinifolia* was extensively subtidal.

Molecular genetics and morphological analysis has shown that *Zostera capricorni* and *Zostera muelleri* should be considered synonymous (Waycott *et al.* 2004). *Zostera capricorni* is also referred to as *Zostera muelleri* in the Australian Plant Name Index (APNI). *Zostera muelleri* used throughout this manuscript also refers to the many historical surveys and existing published works, which have used the nomenclature *Zostera capricorni*.

2.2 *Monitoring changes in seagrass distribution*

The extent of seagrass within Cairns Harbour was mapped from aerial photographs between 1952 and 2012 every 4 years. Extensive ground-truthing of the seagrass species in Cairns Harbour was conducted between 1987 and 1992. These studies were conducted before GPS instruments were common. To accurately plot the location of the seagrass species and our sampling sites, a registered surveyor was stationed on shore with a theodolite. The ground-truthing survey of seagrass distribution was then compared to the aerial photographs and satellite images. Northern Fisheries Centre, Cairns, also conducted field seagrass surveys before and after 1992 (Lee Long *et al.* 1993; Campbell *et al.* 2003; Rasheed *et al.* 2006) as did Den Hartog (1970) in the late 1960s.

2.3 *Measuring rates of photosynthesis*

The most recent methods used to measure seagrass production have been reviewed (Silva *et al.* 2009). They concluded that the newer methods still need calibration and validation. We used a lacunal gas release technique that has been validated (Roberts and Moriarty 1987). We were also able to apply the method at the place and time the seagrass material was collected, an important criteria for measuring seagrass photosynthesis accurately (Silvia *et al.* 2009).
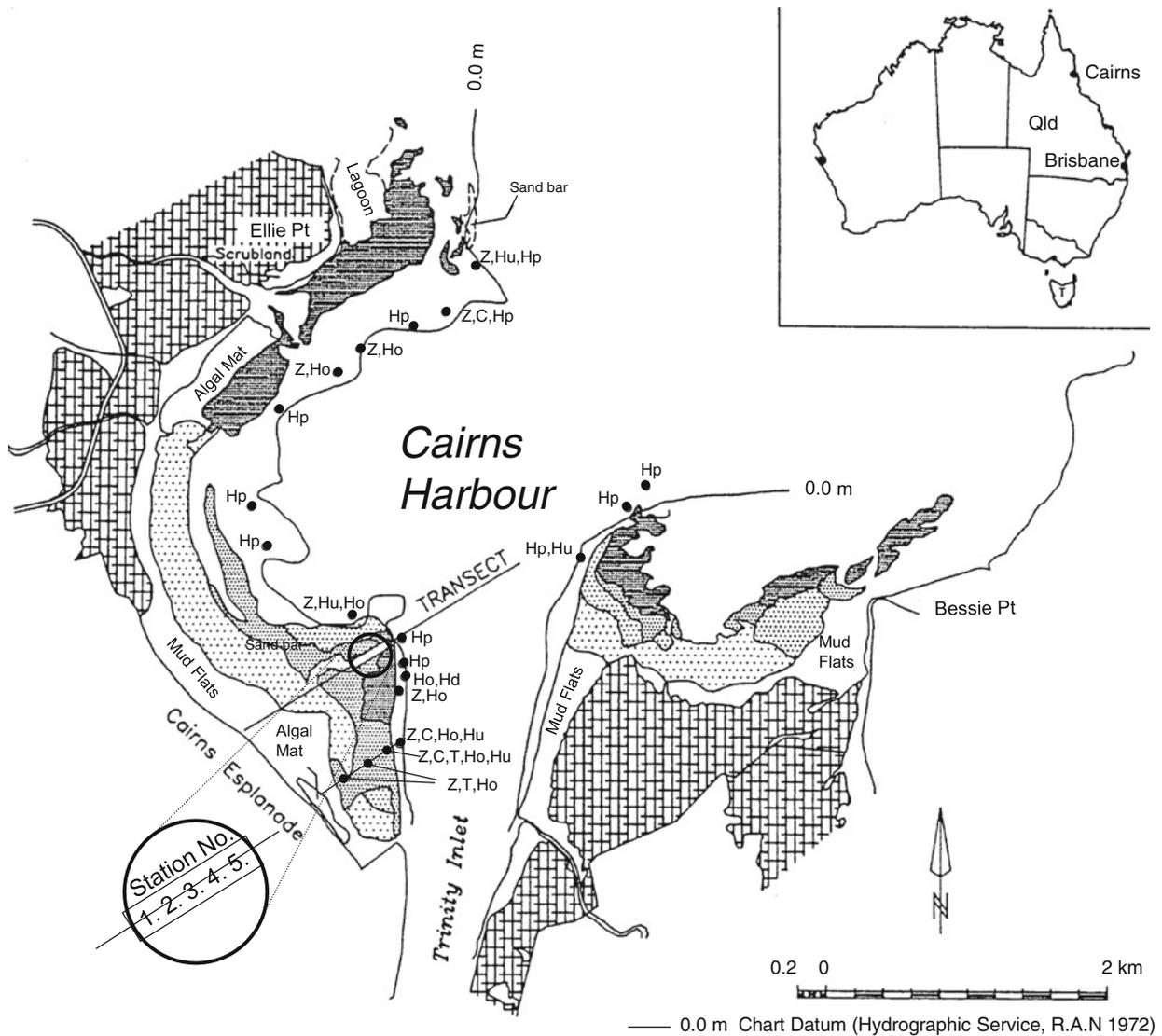
Figure 1. The distribution of the seagrasses in Cairns Harbour in 1987 from ground-truthing. Note: study site is above the zero datum contour.

Shoots (n=12) of three broad leaved species *C. serrulata*, *T. hemprichii* and *Z. muelleri* were collected from different depths above port datum (0.0 m) along our transect (figure 1; Stations 1 (in-shore) to 5 (off-shore)). The rate of photosynthesis of individual shoots was measured using the lacunal-gas technique of Roberts and Moriarty (1987). Sheath material was teased off and the shoot cleanly cut from the rhizome with a new razor blade. The resulting tapered shoot base fit snugly into a silicon sleeve that was then attached to a graduated 1 mL pipette. Particular care was taken not to damage the continuity of the lacunal space. If the shoot tissue was not damaged, the release of gas through the sleeve was immediately obvious. The pipettes, with the attached shoots, were fastened to a wire rack attached to the floor of a plastic basket. The basket was tied beside the boat. Shade cloth was used to vary light intensity to generate the *PI* relationships. Seagrasses shoots were incubated at the time of collection at 34 different light intensities, at least eight of which were below the maximum rates of photosynthesis. One-way ANOVAs were used to compare mean values and determine significance using the p values for the data shown in tables 1 and 2.

Changes to the gas volume released during photosynthesis, as a result of the changes to the light intensity, were measured in the pipette every 15 minutes. The light intensity (μmol m^{-2} s^{-1}) was recorded along with the rate of total lacunal gas release (mL h^{-1} shoot^{-1}). Initially, shoots were exposed to light intensities greater than 100 μmol m^{-2} s^{-1}. After 2 to 3 mL of gas had been released into the pipettes, the seagrass shoot was subject to a new light intensity. The rate of decrease in the volume of gas in the pipette indicated the rate of shoot respiration, i.e. lacunal O_2 gas consumption was greater than the rate of photosynthesis. The lacunal gas released or consumed and the corresponding light intensities were used to generate photosynthesis versus light (*PI*) curves for each seagrass species. A new set of shoots was used each day. After each experiment, the shoots were kept frozen for later measurements of dry weight.

Experiments were conducted over 5 days in January 1988 (austral summer) and July 1992 (austral winter). In 1988 seagrass shoots were only collected from 0.85 m, but in 1992 shoots were collected from 5 stations between 1.0 m and 0.1m above datum (figure 1). Ambient seawater temperatures were 29°C in summer (January) and 19°C in winter (July).

2.4 *Measuring light intensity*

Irradiance as photosynthetically active radiation (PAR) was measured with an integrating quantum-scalar Li-Cor biospherical photometer. The photometer was positioned alongside the seagrass shoots. To determine the natural daily changes in PAR in the seagrass bed, a photometer was also set up immediately above the leaf canopy. A third photometer recorded air-surface PAR. PAR was monitored over the tidal cycle for the 5 days of each study.

2.5 *Photosynthesis–Irradiance (PI) curves*

The rate of photosynthesis (P) was plotted against the PAR-irradiance (I_d) for all three species. The irradiance (I_k), was the onset of saturation and the maximum rate of photosynthesis (P_{max}) (Kirk 1986) and R represents the rate of respiration in the dark. The Photosynthesis-Irradiance (*PI*) curves were fit to the lacunal gas data using a nonlinear least-squares procedure with the initial slope (α_t) of the function as per the following equation:

$$P = [P_{max} \alpha_t I_d] \Big/ \left[(P_{max})^2 + \alpha_t^2 (I_d)^2 \right]^{\frac{1}{2}} - R$$

The fitting procedure calculated the asymptotic mean and standard error for the maximum rate of photosynthesis. In the field a minimum of six data points were used to the initial slope of the curve to indicate the efficiency with which the seagrass used light, as in other studies of seagrass light characteristics (Bulthuis 1983; Fourqurean and Zieman 1991). The observed rates of photosynthesis minus the rates that the above model predicted (Residuals) were plotted against the PAR (graph not shown). The respiration data (the negative intercepts in figure 2) fit well with the PI curve model described in the methods as the residual values were

Table 1. The photosynthetic characteristics and respiration of three seagrass species at Station 2 (0.85 m above port datum), Cairns Harbour, are compared between winter and summer. The asymptotic means±s.e. (n=12) for the maximum rate of photosynthesis (P_{max}), respiration rate (R), saturation light intensities (I_k) and compensation light intensities (I_c) are shown. Maximum rates of photosynthesis for *C. serrulata* did not differ between seasons (p=0.56), while there was a four-fold increase in respiration rates in summer. P_{max} rates for the other two species were significantly higher in summer (p<0.01)

Seagrass species Season	P_{max} (mL h^{-1} mg dry wt^{-1})	I_k (μmol m^{-2} s^{-1})	I_c	Respiration rate (mL h^{-1} mg dry wt^{-1})
C. serrulata				
Summer	3.90±0.31	104±10	64.5±17	−2.042
Winter	3.59±2.33	328±10	52.0±15	−0.561
T. hemprichii				
Summer	8.08±0.75	126±23	39.0±32	−2.445
Winter	4.89±0.56	163±23	50.1±21	−1.448
Z. muelleri				
Summer	2.84±0.14	118±10	61.4±24	−1.330
Winter	1.70±0.14	171±10	15.0±14	−0.156

Table 2. The photosynthetic characteristics of three seagrass species (n=12) at five different depths in winter along the study transect shown in figure 1

Station number (Height above zero datum)	1 (m) In-shore	2 (0.85 m)	3 (0.4 m)	4 (0.25 m)	5 (0.10 m) off-shore
C. serrulata					
P_{max} (mL h^{-1} mg dry wt^{-1})	N/P	3.62	N/P	N/P	2.073
I_k (μmol m^{-2} s^{-1})		328			148
I_c (μmol m^{-2} s^{-1})		52			21
T. hemprichii					
P_{max} (mL h^{-1} mg dry wt^{-1})	7.32	4.89	1.62	N/P	N/P
I_k (μmol m^{-2} s^{-1})	194	163	123		
I_c (μmol m^{-2} s^{-1})	42.8	50.12	80.12		
Z. muelleri					
P_{max} (mL h^{-1} mg dry wt^{-1})	4.33	1.76	2.30	2.60	2.03
I_k (μmol m^{-2} s^{-1})	380	171	270	305	143
I_c (μmol m^{-2} s^{-1})	11.10	15	37.0	22.5	15.5

The maximum rate of photosynthesis (P_{max}), saturation light intensities (I_k) and compensation light intensities (I_c) are shown for each depth. Site 1 was the shallowest site while Site 5 was the deepest. N/P = Not Present.

randomly spread either side of zero. This demonstrated that the model fit the field observed relationship between light and lacuna gas release without bias.

The compensation light intensity (I_c) was calculated from the above equation after solving for α_t and the constant. Then P_{max} and α_t were used to estimate the light intensity (I_k) at which the onset of saturation occurred: $I_k = P_{max}/\alpha_t$ (figure 3).

The maximum rates of photosynthesis (P_{max}) were calculated from the asymptotic mean of the rate of lacunal-gas release at higher than saturating light intensities. The saturating (I_k) and compensating (I_c) light intensities, and the initial slopes (α_t) of the response curves were calculated from the light-dependent portion of the curves at light intensities between 100 and 190 μmol m^{-2} s^{-1}. The rate of shoot respiration was calculated from the rate the shoot consumed lacunal gas at less than compensating light intensities – the negative intercept on the irradiance axis (figure 2). Whole plant gross primary production could be approximated with the sum of the maximum rates of production plus that lost through shoot respiration but does not take into account that lost through below-ground respiration.

3. Results

3.1 *In situ light environment*

Figure 3 shows PAR on the falling tide immediately above the seagrass at Station 2 (0.85 m) under sunny conditions during a winter extreme spring tide on 31 July 1992 (height low tide; 16:02 hours). A similar pattern occurred during a summer neap

tide on 20 January 1988 (height low tide; 16:20 hours). Table 3 shows the monthly mean hours of sunshine over Cairns Harbour. The Austral winter/spring (June to Nov) has the longest hours of sunshine which coincides with the dry season. During the extreme winter spring tide the seagrasses at Station 2 (0.85 m) were inter-tidally exposed for 5 h, whereas during the summer neap tide they were only exposed for 1 h. PAR at
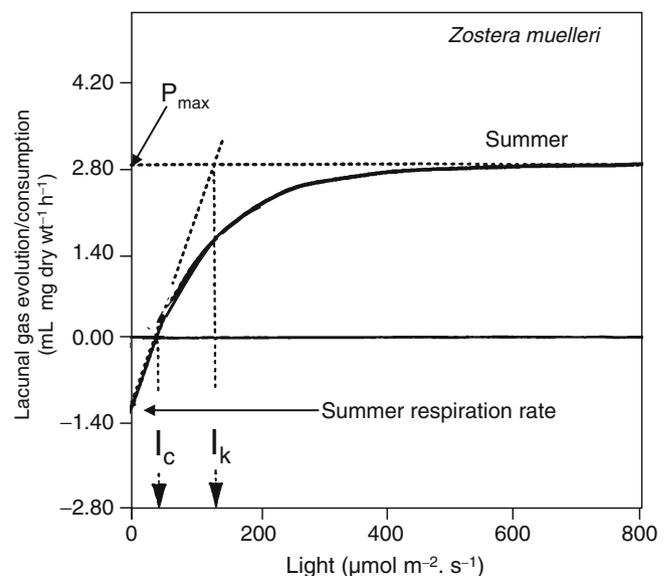

Figure 2. *Zostera muelleri* photosynthesis versus Irradiance curve shows the model parameters; maximum rate of photosynthesis (P_{max}), respiration rate (R), saturation light intensity (I_k) and compensation light intensity (I_c). Station 2 (0.85 m above datum) for summer.
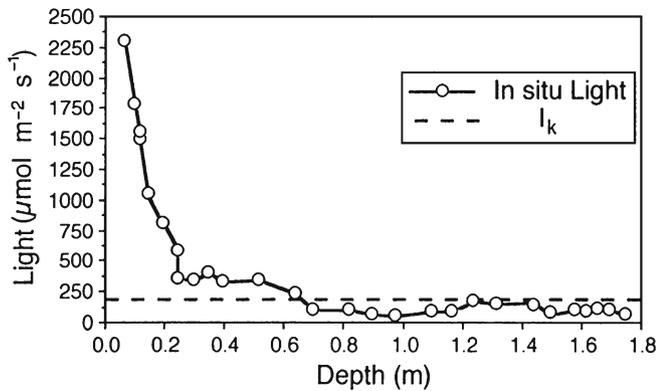
Figure 3. Light (PAR) on a falling tide above the seagrass meadow at Site 2 (0.85 m above datum) during winter spring tide. The dashed line represents the mean saturation light intensity (I_k) for the seagrasses of this study.

Station 2 on the rising tide for both summer and winter did not exceed 20 $\mu mol\,m^{-2}\,s^{-1}$ as physical wave action of the rising tide increased turbidity. For the most part seagrasses above the datum received saturating light intensities when they were exposed or the depth was less than 0.2 m yet these periods are some of the most physiologically stressful for these seagrasses (Campbell *et al.* 2006, 2008). However, it appears that these high light intensities during exposed periods were actually crucial for the survival of the seagrasses in Cairns Harbour, as it made them independent of the highly turbid and low-light water column.

3.2 *Photosynthetic characteristics*

The photosynthetic characteristics were determined for *C. serrulata*, *T. hemprichii* and *Z. muelleri* for summer and winter (table 1), and for different depths in the same year

(table 2). All three species exhibited the typical relationship between photosynthesis and light (figure 2). At low light intensities there was a rapid increase in the rate of photosynthesis that asymptotically came to a maximum rate of photosynthesis without any sign of photo-inhibition, even when seagrasses were exposed to full sunlight at low tide. In summer the water temperature was 10°C higher than in winter and all three species showed a significant increase in the rates of respiration compared to the winter months (table 1).

Saturation irradiance (I_k) is the light intensity at which maximum rates of photosynthesis are achieved, while compensation irradiance (I_c) is the light intensity at which photosynthesis equals respiration. We found, as have others, that I_k and I_c values vary for seagrass species growing at different depths (Drew 1978; Dennison and Alberte 1986; Libes 1986; Pirc 1986; Dawes and Tomasko 1988; Ralph and Gademann 2005; Ralph *et al.* 2007; Sharon *et al.* 2009). However, values also appear to depend on the method used to determine these constants (Silva *et al.* 2009). Most I_k values fall within the range of 70–230 $\mu mol\,m^{-2}\,s^{-1}$, whilst I_c values range between 9 and 55 $\mu mol\,m^{-2}\,s^{-1}$. The values for both parameters generally were within those reported ranges (tables 1 and 2), further validating the use of the lacuna gas method used to measure seagrass production.

3.3 *Photosynthesis vs Respiration*

Maximum rates of photosynthesis were 60% higher in summer than in winter for shoots of *T. hemprichii* and *Z. muelleri*; however, the increase was minor for *C. serrulata*. The respiration rates were also higher in summer for all three species. In Cairns Harbour the ambient seawater temperatures were 19°C during the winter experimental period and 29°C during the summer period. Mean annual air

Table 3. Mean annual air temperature, rainfall and sunshine hours over Cairns Harbour

Month	Jan	Feb	Mar	Apr	Ma	Jun	Jul	Au	Sep	Oct	Nov	Dec	Annual	years
Temperature														
Mean (n =70) maximum temperature (°C)	31	31	31	29	28	26	26	27	28	30	31	31	29	1942 2012
Mean (n=70) minimum temperature (°C)	24	24	23	22	20	18	17	17	19	21	22	23	20.8	1942 2012
Rainfall														
Mean (n=70) rainfall (mm)	396	455	428	197	90	46	29	27	34	47	95	181	2024	1942 2012
Daily Sunshine hours														
Mean daily (n=39) sunshine (hours)	6.8	6.1	6.4	6.7	6.8	7.3	7.4	8	8.6	8.8	8.4	7.7	7.4	1973 2012

Data courtesy of Australian Government Bureau of Meteorology.

temperatures are shown in table 3 and ranged between 17 and 26°C in the winter and 24 and 31°C in the summer.

Maximum rates of photosynthesis for *C. serrulata* did not differ between seasons (p=0.56, n=20), while there was a 4-fold increase in respiration rates in summer. However, the P_{max} rates for the other two species were significantly higher in summer (p<0.01, n=20) but also with increases in respiration rates in the warmer summer months. A 10- and 2-fold increase was seen for *Z. muelleri* and *T. hemprichii* respectively (table 1). Because of the several-fold increases in respiration ANOVA was not done here.

4. Discussion

Seagrasses are considered biological indicators of coastal ecosystem health because they respond to environmental change. Understanding seagrass physiology, monitoring their abundance and distribution over long periods can tell us much about human activities and climate change that may adversely impact seagrass ecosystems.

As early as 1929 Setchell suggested that seasonal temperature controls the growth of seagrasses and since then there have been confirming reports (Campbell *et al.* 2006; Orth *et al.* 2006). However seasonal temperature is not the sole controlling environmental factor. Both light and temperature together produce another more complex level of control of seagrass production (Bulthuis 1987).

While increases in respiration was seen for *C. serrulata* and *T. hemprichii*, the order of magnitude increase for *Z. muelleri* suggests that of the three species, *Z. muelleri* might not respond well to warmer water temperatures in these tropical waters, especially if less light was available, e.g., due to increased turbidity. Saturation light intensities (I_k) were lower in summer than winter for all three seagrasses (table 1) when they were achieving higher rates of photosynthesis with less light.

Zostera muelleri has been shown to be intolerant to increases in water temperatures due to chronic inhibition of photosynthesis (Campbell *et al.* 2006). In the same study they showed that *C. serrulata* and *T. hemprichii* were more tolerant to thermal stress than *Z. muelleri*. Collier *et al.* (2011) also showed that when the optimum water temperature threshold for *Zostera* was exceeded it resulted in critical metabolic imbalances. This resulted in large reductions in photosynthesis and increases in leaf respiration that led to substantially lower seagrass growth rates. Despite the high temperatures and respiration rates of Cairns Harbour, *Zostera* was able to compensate with higher photosynthesis rates at low tide.

Thus, the seagrass species most likely to be lost from this tropical environment if there were increases in water depth and temperature due to climate change, in order of their thermal intolerance, would be *Zostera, Cymodocea* then

Thalassia. A combination of lower light and longer periods of higher rates of respiration would have meant a more negative carbon balance – lower survival rates. Our results, for Cairns Harbour, predict that these tropical seagrasses could not tolerate a combination of low light and higher water temperatures. McKenzie *et al.* (2012) report anthropogenic-influenced environmental changes to water quality from agricultural, urban/industrial runoff and dredging as major contributing factors to the decline in seagrass in tropical Queensland. Others have predicted major losses of seagrasses in the Mediterranean simply based on local temperature increases (Jorda *et al.* 2012). So, what has happened to the seagrass distribution in Cairns Harbour since 1990 and over the last six decades?

The earliest surveys of *Zostera, Cymodocea* and *Thalassia* distribution in tropical Queensland were those of den Hartog in 1967 (den Hartog 1970). The northern most record for *Zostera* was from Thursday Island, 'a few plants at low tide'. den Hartog also recorded *Zostera* on the Cairns Harbour mudflats. The presence of seagrasses on the mudflat is also evident from the earliest aerial photographs in 1952. Despite anthropogenic impacts such as the removal of mangroves, dredging, agricultural and urban runoff and climatic effects of cyclones, the distribution of the *Zostera* in Cairns Harbour has remained fairly constant for 60 years (1953 to 2011).

den Hartog found *Cymodocea* at nearby Double Island 'very numerous in the lower part of the intertidal belt on sandy and muddy bottom'. These conditions were similar to where we found *Cymodocea* growing in Cairns Harbour (figure 1). Regarding *Thalassia*, den Hartog comments that *Thalassia* occurred mainly in the sublittoral zone or if found in the eulittoral zone it was mainly restricted to shallow pools. At Low Island den Hartog found dense *Thalassia* extending from the sublittoral zone into the mangroves. However during his 1967 survey den Hartog notes, 'I did not find one specimen of *Thalassia* on the mainland coast of Queensland', which he attributed to the influence of freshwater runoff.

Aerial photographs between 1953 and 2010 indicate very little change in the pattern of seagrass distribution and density in Cairns Harbour similar to that observed in the late 80s and are described in detail in figure 1. This is also consistent with previous surveys (Campbell *et al.* 2003; Rasheed *et al.* 2006). Both these studies reported the extensive distribution of *Zostera* on the intertidal mud flats.

Satellite images from 2006 and 2008 (Google Earth images at low tide) also show seagrass presence on the landward side of the datum with little if any change in their distribution. The three seagrasses we studies here were far more tolerant of human anthropogenic influences than we had originally expected at least until 2011. This is in stark contrast to the global disappearance of seagrasses due to human impact (Orth *et al.* 2006; Halpern *et al.* 2008). We have shown here that the photosynthetic characteristics of

the seagrasses of Cairns Harbour are much the same as those reported for similar latitudes elsewhere. One reason they survived so well over the last six decades here is that most of the seagrasses are found above datum where they are exposed to full sunlight at low tide. Thus, light was not a limiting factor. All three species showed highest P$_{max}$ values at the shallowest (in-shore) stations (table 2) achieving maximum rates of photosynthesis independently of the water quality. Even in the low light environment of summer with the increase in turbidity that comes with summer monsoonal rains exposure at low tide allowed maximum rates of photosynthesis to be achieved.

There is an unusual pattern in the P$_{max}$, I$_k$ and I$_c$ for *Z. muelleri* down the depth gradient (table 2) in that this species has the highest P$_{max}$ at the shallowest site where water temperatures were highest. We see that increases in seasonal water temperature also increase respiration rates for *Zostera* (table 1). *Zostera's* highest P$_{max}$ at the shallowest site suggests that this species is compensating for increased respiration rates in the shallow water with an increased P$_{max}$ to compensate for the higher water temperature and associated higher respiration rates at the shallow site. What is also interesting is that *Cymodocea* was not found at this shallow site. This was most likely because *Cymodocea* was unable to compensate for the high water temperatures and respiration as *Thallasia* and *Zostera* have done. Of the three species studied here, *Thalassia* appeared most tolerant of water temperature increases. Both *Thalassia and Zosteria* were found at the shallow site (figure 1).

In relation to climate change and increased water temperatures, table 2 suggest that *Thalassia* could best tolerate increases in respiration rates associated with increases in water temperature. *Z. muelleri* would follow as it can compensate for increased respiration rates with increased water temperature by increasing the P$_{max}$ (table 2; in-shore site). However, *Cymodocea* appeared least able to tolerate increased water temperatures and would explain why it was not found inshore at the shallow sites where water temperatures were highest at low tide.

In February 2011, Tropical Cyclone Yasi (the most powerful since records started, with a 500 km wide front) and associated floodwaters lead to the total loss of all seagrasses in Cairns Harbour as shown on the Google Earth images taken at low tide in April 2011.

Significant seagrass losses occurred elsewhere along the north Queensland coast especially between Cairns and Townsville the region most heavily impacted by Tropical Cyclone Yasi (McKenzie *et al.* 2012).

Figure 4 shows the Cairns annual rainfall from 1943 to 2012, most of which falls in January, February and March (table 3). Before 2011 there were at least 10 years in which the annual rainfall exceeded that of 2011, the last being

1974. However, the seagrass in Cairns Harbour survived each of these major rainfall events.

Since the major flood of 1974 there has been considerable urban and industrial development in the catchment (Cairns Regional Council data), which inevitably would contribute towards deterioration in water quality, e.g. increased turbidity and nutrients in runoff, especially during storms and floods. Yet, 2011 is the first record of seagrass loss on such a massive scale that none remain. Hence, it is likely that a combination of anthropogenic factors and the rare extremely high rainfall event associated with Tropical Cyclone Yasi has lead to the loss of the seagrass in Cairns Harbour.

This is supported by McKenzie *et al.* (2012), who believe that the seagrass meadows in the Great Barrier Reef region were already vulnerable and in decline and that the impacts of Cyclone Yasi exacerbated the stressed seagrass. McKenzie *et al.* (2012) noted a huge decline in seagrass abundance in all their monitoring sites south of Cooktown after the 'monsoon' of 2011.

In this article we have reported seagrass survival in Cairns Harbour over a 60 year period (since the first aerial photographs were available) through several major rainfall/flood events, then its complete loss in February 2011. The most likely cause of seagrass loss was a combination of human activities in the catchment causing increased erosion potential, increased turbidity, increased sediment and nutrient loads coupled with major flooding (turbid freshwater plumes) and turbulent seas (wind and wave action). Poor catchment management in the first place could have stressed this seagrass ecosystem making it less resilient to natural 'disasters' such as tropical cyclones. When we started this project in the late 80s we aimed to predict the seagrasses that could best tolerate the vagaries of global climate change. However,
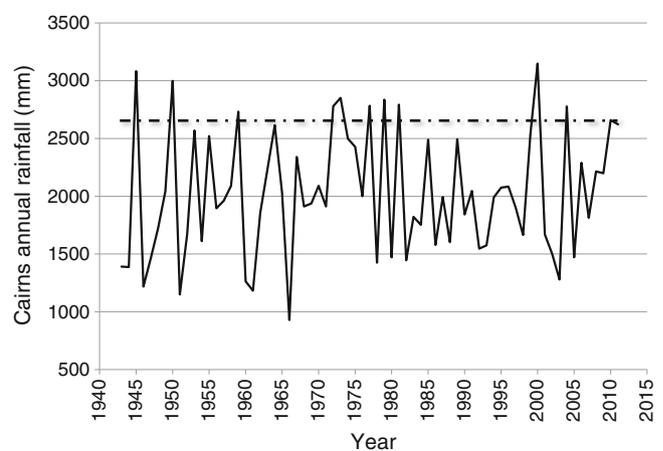

Figure 4. Cairns annual rainfall between 1943 and 2011, courtesy of the Australian Government Bureau of Meteorology. The dashed line represents the mean peak fall in 2011. The rainfall gauge was at the Cairns Airport (latitude 16.8736; longitude 145.7458).

our predictions could not be realised beyond 2010 with the decimating cyclonic event of 2011.

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