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Towards Ecologically Relevant Targets: Impact of flow and sediment discharge on seagrass communities in the Great Barrier Reef

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Abstract: Catchment degradation causing increased sediment flow is one of the key stressors facing Great Barrier Reef (GBR) habitats. Ecologically relevant targets (ERTs) for sediment and nutrient loads have been previously proposed based on seagrass light requirements, the next step is to connect these to ecological response. The overarching goal of the present work is to recommend preliminary thresholds that can be used in the development of more refined ERTs. To achieve this, we perform statistical analysis on datasets for catchment flows and sediment loads and condition of the adjacent seagrass habitat, to identify what might be the direct impacts of catchment discharge on seagrass and the associated timescales of ecological response.

Our case study focuses on Cleveland Bay, which is located in the central GBR, and has important seagrass habitat that is affected by discharge from the Burdekin River. Annual monitoring of seagrass biomass and area has been undertaken since 2007. We compare these ecological time-series with data for Burdekin River annual flow and total sediment load from 2005 onwards.

Annual Burdekin River flow varied by nearly 40-fold within the 2005-2018 study period, and declines in biomass and area of both subtidal and intertidal seagrasses were associated with high flows and loads from the Burdekin. Subtidal seagrasses appeared more sensitive to changes in catchment discharges than intertidal seagrasses, exhibiting a 3 year timeframe for recovery, following high annual flows and loads.

Based on our results, a linear model relating change in seagrass biomass to Burdekin River metrics was used to calculate *predicted thresholds* below which seagrass biomass was likely to increase, and above which biomass was likely to decline. For seagrass area, a *growth threshold*, below which seagrass area expanded; and a *decline threshold,* above which seagrass area fell, were defined for annual Burdekin River flow, and sediment load. Overall these thresholds provide the first steps towards refining ERTs based on ecological condition, which can directly inform the management of the GBR to protect its iconic seagrass habitats and associated communities. The next step is to examine whether the relationship between river discharge and sediment load was the primary cause of seagrass decline.

Keywords: *Seagrass, sediment, ecologically relevant target, catchment loads*

1. INTRODUCTION

Catchment runoff presents a major threat to water quality and ecosystem health within the Great Barrier Reef (GBR) (Grech et al. 2011, Bainbridge et al. 2018). Ecologically Relevant Targets (ERTs) for sediment and nutrient loads and pesticide concentrations have been proposed based on seagrass light requirements (Brodie et al. 2017a,b) and incorporated into the 5-year Reef 2050 Water Quality Improvement Plan (The State of Queensland, 2018). This paper extends the work of Brodie et al. (2017a,b), by exmaining how catchment loads related to observed changes in seagrass area and biomass.

Seagrass is a key ecosystem of the GBR (Coles et al. 2015) that provides habitat and food for marine animals, including iconic megafauna such as turtles and dugongs, along with a range of other ecosystem services. Criteria for seagrass persistence are typically represented as a minimum average annual benthic light requirement (Erftemeijer and Lewis 2006); however in practice, light requirements vary between species, and also depend on the duration of light deprivation (Collier et al. 2016). For example, a short-duration (4-12 weeks of low light) light threshold of 6 mol photons m^{-2} d^{-1} has been proposed for the common species *Zostera muelleri* (Chartrand et al. 2016). Small, colonising species decline rapidly under light deprivation, but large, persistent species survive up to 2 years, even under extreme light deprivation (O'Brien et al. 2018). The timescales of seagrass response to changes in benthic light availability have also been quantified (e.g. Adams et al. 2015). However, neither the *sensitivity to or timescale of* seagrass response to changes in catchment runoff from adjacent land (Saunders et al. 2017), which potentially regulates the benthic light availability for seagrass, have been quantified in the GBR from measured data. This is needed so that ERTs over appropriate scales can be developed.

This study investigates how seagrass condition is related to catchment runoff and associated sediment loads, in a step towards defining ecologically relevant targets for catchment remediation. We chose Cleveland Bay within the GBR for our study, as it possesses an ecologically important and well-studied seagrass habitat.

2. METHOD

Annual surveys of seagrass biomass and extent from Cleveland Bay were compared with discharge and sediment loads from the Burdekin River to investigate the relationship between riverine discharge and seagrass state. The study period (2005-2018) captured several large discharge events from 2007-2012 including flooding caused by a monsoonal low (2008), tropical cyclones Charlotte and Ellie (2009), Tasha (2010/2011) and Yasi (2011). Low flows were recorded in other years.

2.1. Study site

The Burdekin River, located over 80 km south-east of Cleveland Bay, has one of the largest catchments in Australia (133,432 km^2, see Figure 1), and has a large influence on the GBR. It has extremely variable flow, with high flow and discharge of sediment and nutrients following high rainfall, often associated with tropical cyclones.

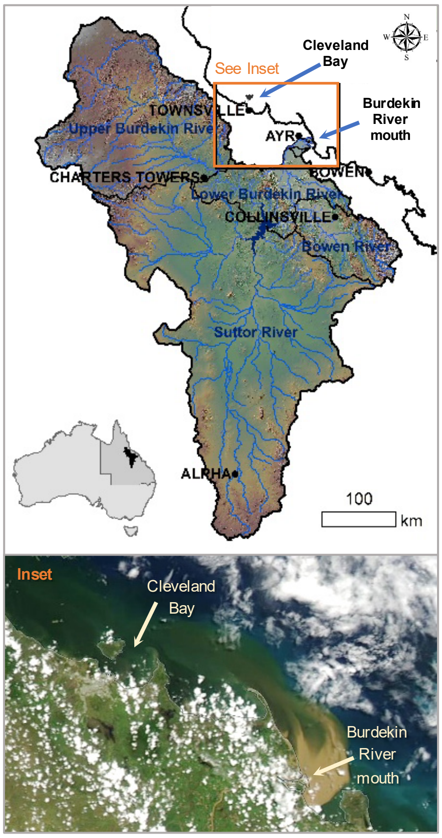

Figure 1. Burdekin River catchment. Inset: Sediment from the Burdekin River flood plume dispersing towards Cleveland Bay (NASA Worldview 9 February 2019). White areas are clouds.

2.2. Cleveland Bay seagrass

In Cleveland Bay, turbidity and hence the light climate is governed by resuspension of fine sediment flocs in periods of high wind. The flocs are delivered to the Bay in Burdekin River discharge flood plumes as shown clearly in satellite images (Figure 1 inset, Bainbridge et al. 2012; Fabricius et al. 2014; Schroeder et al. 2012). Records of turbidity from the Bay show the relationship between turbidity (and benthic light) and wind speed and direction (McDonald et al. 2013). Seagrass surveys have been conducted annually during peak growing season (September to December) since 2007 as part of the Port of Townsville monitoring program, assessing above-ground biomass and species composition (Bryant et al 2018). There are many potential indicators for seagrass condition (McMahon et al. 2013): here we used biomass as a measure of density of the plants, and area to describe spatial extent. This follows on from the work of Collier and others (submitted), who categorised Cleveland Bay seagrasses into two subtidal (deep and shallow) and five intertidal seagrass community types, depending on species composition, depth/intertidal exposure, sediment type and water quality. They quantified mean biomass and spatial extent for each community type, with the exception of the deep subtidal community where area estimates are not available as it is not sampled as frequently (Collier et al. submitted).

For our analysis, seagrass area for all five intertidal community types was added together to obtain a total intertidal area for each year, and seagrass area across the shallow subtidal community was added together to obtain a total shallow subtidal area for each year. Total seagrass area for each year was equal to shallow subtidal and intertidal area combined. Similarly, we estimated mean biomass for the total intertidal, shallow subtidal and deep subtidal seagrasses by first averaging the mean biomass values across each community type. Subsequently for intertidal seagrasses we averaged the five mean biomass values associated with the five intertidal community types, for each year. The mean biomass across all seagrass communities for each year was also calculated by averaging the mean biomass for each seagrass community. Hence our data for seagrasses consisted of time series for seven different types of seagrass condition: intertidal area, shallow subtidal area, total seagrass area, mean intertidal biomass, mean shallow subtidal biomass, mean deep subtidal biomass, and mean seagrass biomass.

2.3. Burdekin River discharges and suspended sediment data

Burdekin River annual flow (2002 to 2018) and total sediment load data (1949 to 2018) were sourced from collated data from many published sources (Stephen Lewis, pers. comm.). Historical river flow data also came from various sources, including the Bureau of Meteorology (1922-1957 Home Hill gauging station 120001A data), Reef CRC (1966-1995 data from King, 2002) as well as Source Catchment Model predictions (1996-2001). Data was summarized annually using a “water year” from October to September. Whilst it is acknowledged that the light climate (i.e. water clarity) in Cleveland Bay is also influenced by riverine nutrient loads (Bainbridge et al. 2018, Fabricius et al. 2014), this preliminary study focuses only on river discharge and sediment loads as predictor variables.

2.4. Modelling approach

For each year of seagrass monitoring data, the seven metrics of seagrass condition (see Section 2.2) were compared against Burdekin River metrics (annual flow, total suspended sediment load; see Section 2.3) for both the preceding water year and multiple years (by summing the preceding three years of flow or load) to assess temporally-cumulative impacts. To account for prior state of seagrass, annual change in area and biomass were also compared against annual flow and sediment load for the preceding year. Separate linear models for each pair of predictor (Burdekin River) and response (Cleveland Bay seagrass) variables were fitted using the R function `lm` (*stats* package). Correlation coefficients (R^2) and p-values associated with these models were computed to investigate the strength of the relationships.

The linear model relating change in seagrass biomass to Burdekin River metrics was used to calculate *predicted thresholds* below which seagrass biomass was more likely to expand and above which it was more likely to decline. For seagrass area, two thresholds were observed for each Burdekin River metric: a *growth threshold*, below which seagrass area expanded; and a *decline threshold,* above which seagrass area fell.

3. RESULTS AND DISCUSSION

3.1. Flow, sediment and seagrass variation over time is high

Annual Burdekin River flow varied by nearly 40-fold within the 2005-2018 study period, with a minimum observed value of 881 GL in 2015 and a maximum observed value of 34,834 GL in 2011 (Figure 2). Sediment loads generally increased with flow; however, the highest annual load (2008) did not correspond to the highest annual flow (2011), which has been attributed to the influence of drought-breaking flood years (i.e. 2008) and the availability of sediment supply across this large catchment (Bainbridge et al. 2014).

Annual seagrass sampling commenced in 2007 just prior to several years of high flows (2008-2012); during this wet period, both seagrass biomass and area substantially declined. Seagrass biomass fell sharply during the periods of high flows and recovered slowly after 2011 (Figure 2a), while seagrass area declined gradually during the periods of high flows then rebounded rapidly in 2012 (Figure 2b).

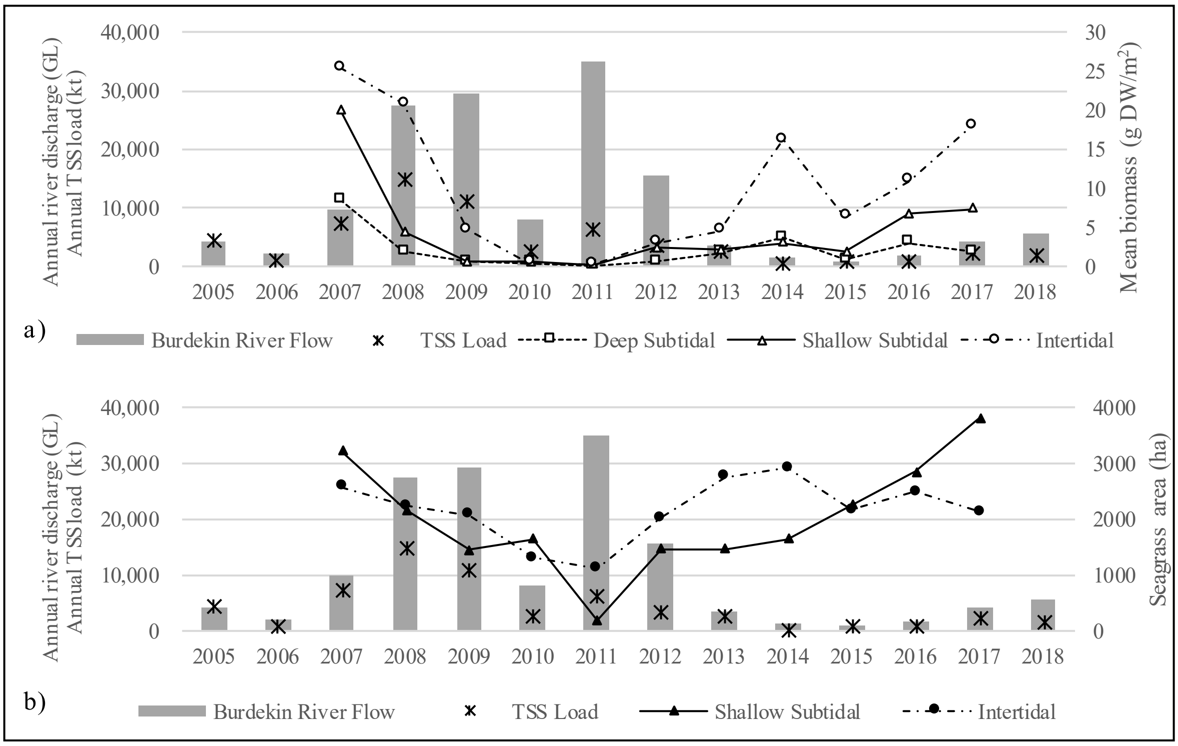

Figure 2. Time series showing variation in a) seagrass biomass, and b) seagrass area in Cleveland Bay with measured annual Burdekin River discharge and annual Total Suspended Sediment (TSS) load.

3.2. Cleveland Bay seagrass health is correlated to Burdekin River discharges

All metrics of Burdekin River discharge were either negatively correlated or not correlated with Cleveland Bay seagrass condition. The strength of all tested correlations are shown in Table 1. Sensitivity to inflows from the Burdekin River was lower in the communities that are exposed to high light during low tide (i.e. intertidal communities), compared to the subtidal seagrass which could be more strongly impacted by light attenuation. For example, the number of statistically significant relationships between shallow subtidal area/biomass and various river discharge metrics (5 out of 16) was higher than the equivalent for intertidal seagrass (2 out of 16). Since subtidal seagrass appeared to be more sensitive to river discharge than intertidal seagrass, and data for deep subtidal seagrass area was not available, the remainder of this paper focuses on observed relationships between the sensitive shallow subtidal community and different discharge metrics.

Table 1. Results of linear models (R^2) for different predictor (Burdekin River) and response (Cleveland Bay seagrass) variables. Significance indicated by * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Cleveland Bay Seagrass			**Burdekin River Predictor Variables**			
Community	**Metric**	**Response Variable**	**Flow**		**TSS Load**	
			Annual	**3 year**	**Annual**	**3 year**
Deep Subtidal	Biomass	Average	0.10	0.28	0.00	0.10
		Annual Change	0.20	0.00	**0.54***	0.12
Shallow Subtidal	Area	Total	0.30	**0.66****	0.02	0.25
		Annual Change	**0.59****	0.27	**0.50***	**0.40***
	Biomass	Average	0.06	0.29	0.02	0.09
		Annual Change	0.29	0.03	**0.76****	0.25
Intertidal	Area	Total	0.30	0.34	0.02	0.27
		Annual Change	0.01	0.02	0.03	0.07
	Biomass	Average	0.04	**0.44***	0.07	0.11
		Annual Change	0.22	0.14	0.30	**0.42***
All Seagrass Communities	Area	Total	**0.41***	**0.72****	0.03	0.35
		Annual Change	0.39	0.11	0.38	0.37
	Biomass	Average	0.05	**0.44***	0.06	0.11
		Annual Change	0.26	0.13	**0.42***	**0.45***

3.3. Seagrass area declines with cumulative flow

Although annual flow from the Burdekin River was not correlated with shallow subtidal seagrass area, cumulative flow (3 yr summed values) was (Table 1). As the sum of the annual flow from the previous 3 years increased, seagrass area in Cleveland Bay declined (Figure 3). This timeframe corresponds to the successive years of above-average rainfall and discharge (Bainbridge et al. 2012) that were associated with the decline, and suggests that 3 years is the approximate timeframe for recovery. This recovery period may include both benthic light recovery, followed by seagrass recovery: Fabricius et al. (2014) suggest recovery of photic depth following a big discharge event takes around 1.5 years, with continued low photic depth following sequential high flows.

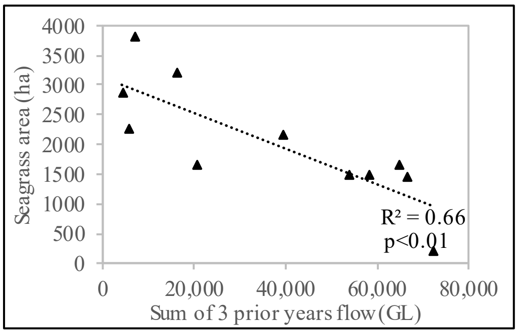

Figure 3. Impact of cumulative Burdekin River flow (sum of previous 3 years) on shallow subtidal seagrass area in Cleveland Bay.

3.4. Annual change in seagrass area and biomass is negatively correlated to sediment load

Annual sediment load from the Burdekin River did not correlate with seagrass biomass or area in Cleveland Bay for any of the seagrass community types (Table 1). The poor correlation may be affected by data from recovering communities that have low biomass and area but are on an improving trajectory. In contrast, *annual change* in seagrass biomass and area correlated well with annual TSS loads, with biomass more strongly correlated than area (Table 1, Figure 4). For each Burdekin River metric in Figure 4a, the *predicted threshold* represents the flow or load below which seagrass is more likely to grow, and above which seagrass is more likely to decline.

For seagrass area, each data point in Figure 4b (representing an individual year) fell into one of two categories: (1) seagrass area increased, and flows or loads were below a certain value which we called the *growth threshold*, or (2) seagrass area declined, and flows or loads exceeded a certain value which we called the *decline threshold* (Table 2).

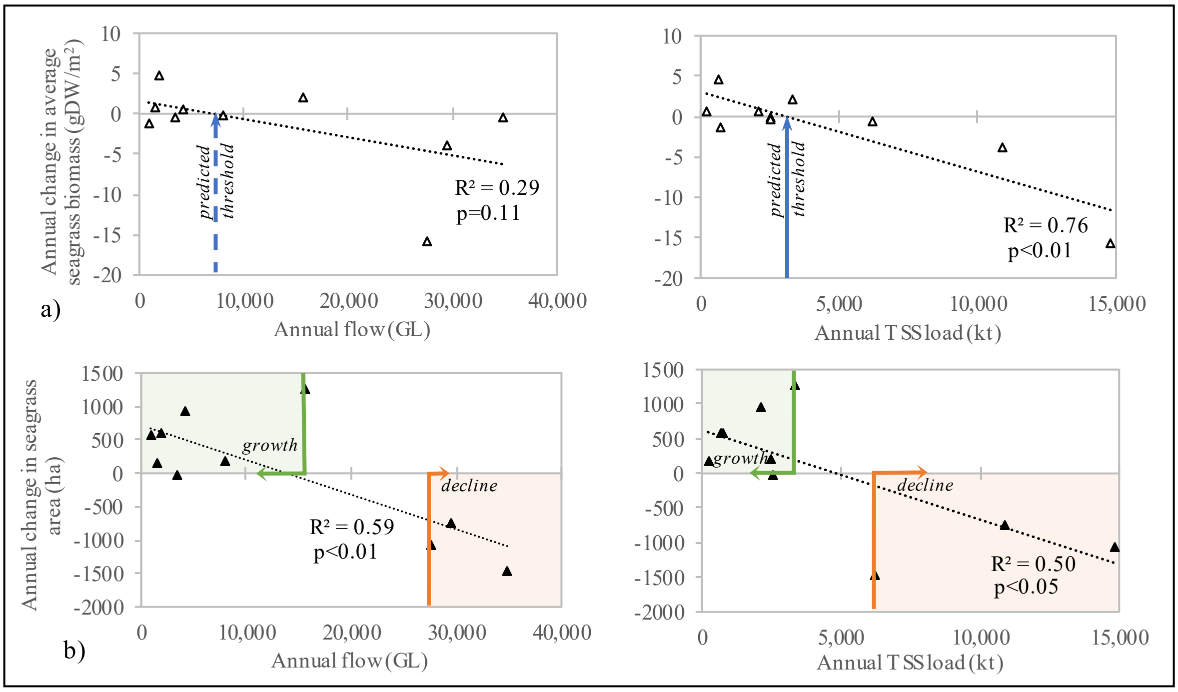

Figure 4. The effect of annual flow and sediment load from the Burdekin River at Home Hill on annual change in Cleveland Bay shallow subtidal seagrass: a) mean biomass; and b) area. Indicated thresholds include a) predicted thresholds (blue arrow) based on the model intercept when change in biomass (y-axis) is zero; and b) observed thresholds for i) growth (green), below which area was observed to increase, and ii) decline (orange), above which seagrass area was observed to decline.

For seagrass biomass, thresholds distinguishing between seagrass growth and decline could not be as clearly defined as for area. Rather, a *predicted threshold* in flow or load, above which seagrass is more likely to decline and below which seagrass is more likely to grow, could be estimated from the *x*-intercept of the linear relationship between biomass and flow or load (Table 2 and Figure 4a).

Table 2. Predicted and observed thresholds for Burdekin River flow and sediment load based on Cleveland Bay shallow subtidal seagrass health (biomass and area, respectively).

Cleveland Bay		**Burdekin River**	
Shallow Subtidal Seagrass Thresholds		**Flow (10^3 GL/yr)**	**Load (Mt/yr)**
Predicted Biomass		8.0[1]	3.0
Observed Area	Growth	15.6	3.3
	Decline	27.5	6.2
Historic data percentiles[2]	25th	2.2	1.1
	50th	6.2	3.2
	75th	11.6	6.5

[1] Correlation not significant (R^2=0.29, p=0.11).
[2] Collated data from several sources.

All three threshold types (predicted, growth and decline) shown in Table 2 could be used to derive potential ERTs (with the exception of biomass-flow as this correlation was not significant at p=0.05 level). Since predicted thresholds (based on biomass) are lower than the observed thresholds derived from seagrass area, ERTs based on the predicted thresholds are more conservative. Predicted thresholds are also advantageous because they possess similar values to the median value of flows and loads seen from historic data (Table 2). On the other hand, ERTs based on the area-derived growth and decline thresholds are easier to interpret but are separated by a region of uncertainty.

For development of potential ERTs, we caution that the relatively short study period (2005-2018) contains three of the six largest discharge years on record. Extending the analysis to include seagrass monitoring results for the most recent wet years (2017-2018, 2018-2019), once available, may add greater resolution to the analysis. It is also possible that other factors associated with large Burdekin River discharges also affect seagrass in Cleveland Bay, e.g. nutrients or other contaminants, sediment size distribution or resuspension. Distinguishing impacts from the Burdekin River and smaller local rivers also requires further study.

4. CONCLUSIONS AND RECOMMENDATIONS

Seagrass biomass and area in Cleveland Bay declined with increased multi-year flows and sediment load from the Burdekin River. Seagrass *area* and annual change in area correlated with river flow for the shallow subtidal communities, while annual change in seagrass *biomass* was more strongly related to sediment load. There were also differences in the strength of correlations depending on the community: the subtidal communities were more highly correlated with flow and sediment loads than intertidal communities, and may therefore be appropriate sentinel communities against which to set ERTs. Future work could investigate whether the five intertidal communities (Collier et al. submitted) are also more sensitive to sediment loads, than the intertidal community as a whole.

Future research is needed to investigate the effect of the sediment load that reaches Cleveland Bay, rather than the entire load coming from the Burdekin River, especially since the former will include a larger proportion of fine sediments preferentially transported in flood plumes. The time-lags for seagrass to react to and recover from large flows and sediment loads, that we observed, are longer than those observed in previous short-term experimental studies. Confirming the cause-effect pathway linking sediment loads to seagrass changes also requires examination of changes in light levels, which are expected to be the intermediate link between catchment load changes and their impacts on seagrass condition.

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