Using MODIS data for understanding changes in seagrass meadow health: A case study in the Great Barrier Reef (Australia)

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Abstract

Stretching more than 2,000 km along the Queensland coast, the Great Barrier Reef Marine Park (GBR) shelters over 43,000 square km of seagrass meadows. Despite the status of marine protected area and World Heritage listing of the GBR, local seagrass meadows are under stress from reduced water quality levels; with reduction in the amount of light available for seagrass photosynthesis defined as the primary cause of seagrass loss throughout the GBR. Methods have been developed to map GBR plume water types by using MODIS quasi-true colour (hereafter true colour) images reclassified in function of their dominant colour. These data can be used as an interpretative tool for understanding changes in seagrass meadow health (as defined in this study by the seagrass area and abundance) at different spatial and temporal scales. We tested this method in Cleveland Bay, in the northern GBR, where substantial loss in seagrass area and biomass was detected by annual monitoring from 2007 to 2011. A strong correlation was found between bay-wide seagrass meadow area and biomass and exposure to turbid Primary (sediment-dominated) water type. There was also a strong correlation between the changes of biomass and area of individual meadows and exposure of seagrass ecosystems to Primary water type over the 5-year period. Seagrass meadows were also grouped according to the dominant species within each meadow, irrespective of location within Cleveland Bay. These consolidated community types did not correlate well with the exposure to Primary water type, and this is likely to be due to local environmental conditions with the individual meadows that comprise these groupings. This study proved that remote sensing data provide the synoptic window and repetitivity required to investigate changes in water quality conditions over time. Remote sensing data provide an opportunity to investigate the risk of marine-coastal ecosystems to light limitation due to increased water turbidity when in situ water quality data is not available or is insufficient.

KeywordsSeagrass healthMODISWater clarityEcological consequences

1Introduction

River plumes are the major transport mechanism for sediments, nutrients, and other land-based pollutants and are a major threat to coastal and marine ecosystems worldwide (e.g. Halpern et al., 2008). Identifying the movement, duration, frequency of occurrence and composition of river plumes and associated water quality, is critical to measure the risk of marine ecosystems to reduced water quality such as reduced light availability due to increased water turbidity (e.g., Warrick et al., 2004; Novoa et al., 2012a, b; Petus et al., in press). Satellite sensors provide an effective means for frequent and synoptic water quality observations over large areas. The input of Total Suspended Sediments (TSS), Coloured Dissolved Organic Matters (CDOM) and phytoplankton (measured through the concentrations of chlorophyll-a (chl-a)) by river discharges alter the turbidity, colour and optical properties of the water and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images have been used to monitor river plumes worldwide (e.g., Devlin et al., 2011a,b, 2012a; Petus et al., 2009, 2014; Saldías et al., 2012).

In the Great Barrier Reef Marine Park (hereafter GBR) and World Heritage Area, recent studies have focused on developing innovative MODIS methods to map the spatial extent and frequency of occurrence of the different river plume water types existing within the GBR river plume gradient; as well as the exposure of local ecosystems to land-based pollutants discharged through river plumes (e.g., Álvarez-Romero et al., 2013; Devlin et al., 2013a; Petus et al., in press). Three main river plume water types (Primary, Secondary and Tertiary plume water types) were described from the inshore to the offshore boundary of GBR river plumes (e.g., Devlin et al., 2011b, 2012b; Petus et al., in press). Each plume water type (hereafter water type) is associated with different levels of pollutants and optically active components (OACs), including TSS, chl-a and CDOM levels (Devlin et al., 2012b; Petus et al., in press and Appendix A). TSS, aand CDOM and Kd(PAR) levels in river plume waters decrease from the inshore/Primary to the offshore/Tertiary plume water types (Devlin and Schaffelke, 2009; Devlin et al., 2012a, 2013a, b; Petus et al., in press) and. tThe relative concentrations of these OACs affect the light attenuation properties of the water types (Devlin et al., 2008, 2009) and the diffuse attenuation coefficient of photosynthetically active radiation (Kd(PAR)) decrease from the Primary to the Tertiary plume water types.

Comparisons between GBR water types mapped through MODIS images and in situ TSS (in mg L^{-1}), chl-a (in μg L^{-1}), and diffuse attenuation coefficient of photosynthetically active radiation (Kd(PAR), (in m^{-1}) measurements have validated the use of MODIS true colour images to classify GBR plume water types (Devlin et al., 2013b). TSS and Kd(PAR) in the Primary water type are typically around (mean ± 1SD) 36.8 ± 5.5 mg L^{-1} and 0.73 ± 0.54 m^{-1}, respectively; in the Primary water type (Devlin et al., 2013b and Appendix A). Devlin et al. (2013b) also described higher in-situ TSS measurements (and thus light limiting conditions due to increase of water turbidity) related to areas that were more frequently (greater than 50% of the wet season) exposed to the Primary waters type. Primary waters are thus characterized by high turbidity levels and light attenuation properties (Devlin et al., 2008, 2009), and light reduction is the most likely driver of seagrass loss in the region (Collier et al., 2012a, b).

Seagrasses are marine flowering plants that occur in shallow waters (<50 m) across the globe except in the Polar Regions. There are approximately 70 species arising from three separate lineages, which have convergent biological traits and similar ecological roles (Short et al., 2011; Les et al., 1997; Waycott et al., 2006). Their ecological roles also have high economic value, including nutrient cycling, nursery habitat for commercial fish species, sediment stabilisation, carbon storage and they are a direct source of food for numerous herbivores and their high rates of productivity subsidize adjacent ecosystems such as coral reefs (Costanza et al., 1997; Heck et al., 2008; Cullen-Unsworth and Unsworth, 2013; Fourqurean et al., 2012). In tropical regions, such as the GBR, seagrass meadows support turtles, manatees and dugongs, which are seagrass specialists (Marsh et al., 2011). Seagrass meadows have relatively high light requirements compared to other marine plants such as macroalagae and phytoplankton (Dennison et al., 1993), and so they are often restricted to the shallow waters fringing islands and coasts. This places them at high risk of exposure to plume waters from adjacent watersheds and this is contributing to accelerating loss of seagrass across the globe. This loss has placed them amongst the worlds most threatened ecosystems (Waycott et al., 2009; Hughes et al., 2009).

In the GBR, dugong foraging grounds and dugong protection areas largely occur in coastal seagrass meadows. These meadows have a distinct senescent season, which is initiated in the wet season (McKenzie et al., 2012a). During the wet season, seagrasses are exposed to water types that are detrimental to seagrass productivity because water clarity is reduced in turbid and nutrient-rich waters (Collier et al., 2012b). The close association between runoff and seagrass senescence in the GBR makes seagrasses a good habitat for exploring the relationship between ecological health and plume water types.

Multi-scale studies of seagrass species distributions areis often the starting point for examining environmental drivers and interpreting responses of seagrass meadows to climate change and decreased water quality (Kendrick et al., 2008). The main objective of this study was to test if relationships can be established between the frequency of exposure to Primary water type (used to monitor waters with reduced light levels caused by turbidity) and changes in seagrass health (as defined in this study by the seagrass area and abundance) in the GBR at different spatial and temporal scales. We focused on Cleveland Bay, bordering the city of Townsville (North Queensland, Fig. 1), as a case study. Two local rivers drain the study area: the Ross River and Alligator Creek. Both river catchments are impacted by anthropogenic developments and sediment and nutrient exports have increased since European settlement in the region (Furnas, 2003; Kroon et al., 2012). Substantial seagrass loss has occurred in Cleveland Bay over the period 2007– to 2011 and changes in seagrass area and above-ground biomass (hereafter biomass) have beenwere regularly monitored for selected meadows as part of this study (see references in Rasheed and Taylor, 2008; McKenna and Rasheed, 2012).

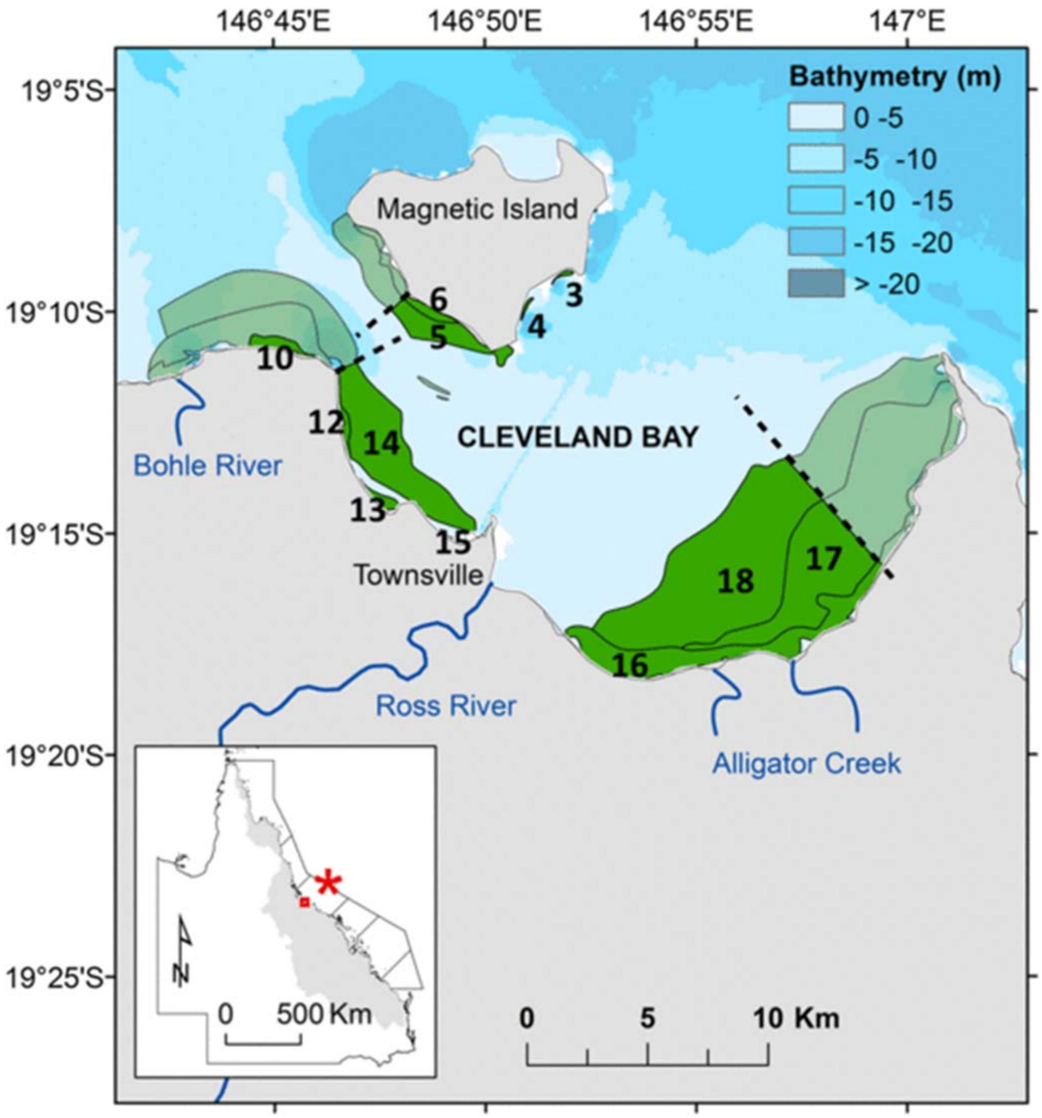

Fig. 1Bathymetry of Cleveland Bay (Bathymetry: © www.deepreef.org) and location of meadows monitored during the 2007 wet season baseline survey. Meadow areas selected for the seagrass health long term monitoring (meadows 3, 4, 5, 6, 10, 12, 13, 14, 15, 16, 17, 18) are indicated with a bright green colour and the location of monitoring survey boundaries with black dashed lines. Red star of the inset map indicate the location of Cleveland Bay within Queensland (in light grey). See Table 1 for description of selected meadows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The seagrass data were coupled with exposure to Primary water type, which was derived from MODIS true colour images and the classification method developed by Álvarez-Romero et al. (2013), in order to test the response of these sensitive ecosystems to Primary water type, characterised by reduced light levels.

2Study area

Cleveland Bay is located on the eastern coast of north Queensland, Australia, 1,359 km kilometres north of Brisbane. Cleveland Bay is located in the dry tropics and experiences a summer wet season

(December– to April) and a winter dry season (May– to November). The average rainfall is about 1120 mm an^{-1}, the majority of which falls during the wet season (Furnas, 2003).

The Bay is bordered to the west by the city of Townsville (Fig. 1) and to the east by Magnetic Island; an inshore continental island of the GBR located about 8 km offshore from Townsville. The Port of Townsville is Queensland's third largest commercial port and has undergone large extensions over the past few years. Cleveland Bay reaches a maximum depth of 15 m at its seaward edge and the bay is protected from the south-easterly trade winds that dominate the dry season by Cape Cleveland. The Ross River and Alligator Creek with catchment areas of 998 km2 and 265 km2, respectively, discharge into the Bay and the average fine sediment discharge in Cleveland Bay has been estimated around 25,900 t y^{-1} (Lambrechts et al., 2010). The bay can also receive fine sediments from the Burdekin River located 100 km to the South (Bainbridge et al., 2012; Lambrechts et al., 2010).

Numerous intertidal and shallow subtidal seagrass meadows, comprised of six seagrass species, are located along Cape Cleveland, from the Bohle River to Ross River, and around Magnetic Island (Fig. 1 and Table 1). The combination of seasonal terrestrial run-off, regular cyclones, strong south-easterly trade winds and large tidal runs creates significant coastal turbidity and reduces light levels available for primary production. To survive this regime seagrasses need to exhibit high vegetative growth rates and prolific seed banks (Waycott et al., 2005). This has led to the predominance of opportunistic species, such as Halodule uninervis and Halophila spinulosa in Cleveland Bay. Other main seagrass species in shallow waters near Townsville are, Zostera muelleri (also known as Zostera capricorni), and Cymodocea serrulata, while the other two species – Halophila ovalis and Halophila decipiens were less dominant at the time of this study, though H. ovalis in particular, is widespread throughout the region.

Table 1Description of meadows selected for long term monitoring (Rasheed and Taylor, 2008), including unique meadow ID, and species composition. Hu: Halodule uninervis; Cs: Cymodocea serrulata, Ho: Halophila ovalis, Zm: Zostera muelleri, Hd: Halophila decipiens, Hs: Halophila spinulosa. Meadows are regrouped into four consolidated communities according to the dominant species within each meadow at the start of the monitoring program: Hu*: Halodule uninervis (thin)-dominated communities, Cs*: Cymodocea serrulata-dominated communities, Zm*: Zostera muelleri-dominated communities, and Hs*: Halophila spinulosa-dominated communities. Int: Intertidal, Sub: subtidal. mix sp.: mixed species.

Meadow ID	Consolidated communities	Location	Habitat type	Community type	Species present
3	Hu*	Magnetic Island	Int/Sub	Dense Hu (thin)	Hu (thin)
4	Hu*		Int/Sub	Moderate Hu (thin)	Hu (thin), Hu (wide), Ho
5a	Cs*		Int/Sub	Moderate Cs with mix sp	Cs, Hu (wide), Hu (thin), Ho, Zm, Hs

Meadow ID	Consolidated communities	Location	Habitat type	Community type	Species present
6	Zm*		Int	Light Zm with mix sp	Zm, Ho, Hu (wide), Hu (thin), Cs
10	Zm*	Bohle River to Ross River	Intl	Light Zm with Hu (thin)	Zm, Hu (thin), Cs, Ho
12	Hu*		Int/Sub	Moderate Hu (thin)	Hu (thin)
13	Hu*		Int/Sub	Dense Hu (thin)	Hu (thin), Hu (wide), Ho
14a	Hs*		Sub	Light Hs with Hu (thin)	Hs, Hu (wide), Hu (thin), Ho, Hd
15	Hu*		Int/Sub	Light Hu (thin)	Hu (thin)
16a	Zm*	Ross River to Cape Cleveland	Int	Moderate Zm	Zm, Cs, Hu (thin), Hu (wide), Ho
17a	Cs*		Sub	Dense Cs	Cs, Hu (wide), Zm, Hs, Hu (thin), Ho
18a	Hu*		Sub	Light Hu (thin) with mix sp	Hs, Hu (wide), Hu (thin), Cs, Ho, Hd

aOnly part of total meadow area monitored.

Cleveland Bay is typical of anthropogenically-modified shallow turbid environments impacted by seasonal terrestrial run-off and it has widespread seagrass meadows. Cleveland Bay was thus selected in this study for testing the response of seagrasses to reduced light levels, as measured by the frequency of exposure to Primary water type.

3Methods

3.1Seagrass surveys in Cleveland Bay

The sampling approach for the seagrass surveys in Cleveland Bay is described in detail in e.g., Rasheed and Taylor (2008), Unsworth et al. (2009) and McKenna and Rasheed (2012, 2013). Two baseline surveys of seagrass distribution and abundance were conducted within port limits of Townsville in the 2007/2008 wet season (November 2007– – February 2008) (Figure 1) and 2008 dry season (June 2008). The surveyed area included intertidal and subtidal areas extending from the Bohle River through to Cape Cleveland, including the southern side of Magnetic Island. A total of 634 and 761 sites were surveyed in the wet season baseline 2007 and dry season baseline 2008. Twelve mixed species meadow types of varying density and eight meadow types were identified and were categorised according to each meadow's dominant species. (Rasheed and Taylor, 2008).

This baseline information was used to select a subset of 12 meadows and design a long-term monitoring program to assess seagrass health from 2007 to 2011 (Table 1 and Fig. 1). These selected meadows represented the range of meadow types found in the area suitable for monitoring and also captured areas of interest and likely water quality impact (including resuspension of sediments and reduction in light levels) related to increased sedimentation from river discharge and Townsville port development. Monitoring meadows included both intertidal and subtidal seagrasses as well as meadows preferred as food by dugong and those likely to support high fisheries productivity (Rasheed and Taylor, 2008). In this study, we reclassified the 12 selected meadows into four consolidated communities (Hu*, Cs*, Zm* and Hs*; Table 1) according to the dominant species within each meadow at the start of the monitoring program.

The monitoring program surveyed seagrass biomass, area, distribution and species composition each spring/summer (October/November) from 2007 to 2011 using methods developed by the James Cook University Seagrass Marine Ecology Group for their network of established seagrass monitoring programs, including Cairns, Mourilyan Harbour, Gladstone, Karumba, and Weipa (McKenna and Rasheed, 2013). The boundary of the seagrass meadow was mapped from aerial (helicopter) surveys conducted at low tide when the seagrass meadows were exposed, or by free diving and underwater camera techniques. Waypoints were recorded around the edge of the meadow using a global positioning system (GPS) and were digitised on to a Geographic Information System (GIS) base map. The GIS base map was constructed from a 1:25,000 vertical aerial photograph rectified and projected to Geodetic Datum of Australia (GDA 94) coordinates. Each seagrass meadow was assigned a mapping precision estimate based on the mapping methodology utilised for that meadow (McKenzie et al., 2001). Mapping precision estimates ranged from 10 m for isolated intertidal seagrass meadows to 500 m for larger subtidal meadows (see Table 3 in Unsworth et al., 2009). The mapping precision estimate was used to calculate a range of meadow area for each meadow and was expressed as a meadow reliability estimate in hectares. Additional sources of mapping error associated with digitising aerial photographs onto basemaps and with GPS fixes for survey sites were embedded within the meadow reliability estimates.

Biomasses were estimated using a modified “visual estimates of biomass” technique described by Mellors (1991). This method has been utilised in surveys throughout Queensland and peer reviewed on several occasions (Rasheed et al., 2008; Rasheed and Unsworth, 2011). The method involves an observer ranking above-ground seagrass biomass within three randomly placed 0.25 m2 quadrats at each site. Measurements for each observer are later calibrated to previously obtained biomass values from seagrass harvested from quadrats and dried in the lab to determine mean above-ground biomass in grams dry weight per square metre at each site.

3.2Mapping MODIS primary water type, representing turbid water

Flood plumes were mapped in this work using the method presented in Álvarez-Romero et al. (2013) and described in Appendix B. In this method, daily MODIS Level-0 data acquired from the NASA Ocean Colour website (http://oceancolour.gsfc.nasa.gov) are converted into true colour images with a spatial resolution of about 500 × 500 m using SeaWiFS Data Analysis System (SeaDAS; Baith et al., 2001). True colour images are then spectrally enhanced (from RGB to HSI colour system) and classified into six colour classes through a supervised classification using spectral signature from river plume waters in the GBR.

The six colour classes are further reclassified into 3 plume water types corresponding to the three GBR water types (Primary, Secondary, Tertiary) defined by e.g., Devlin and Schaffelke (2009) and Devlin et al. (2012a). The turbid sediment-dominated waters or Primary water type is defined as corresponding to colour classes 1– to 4 of Álvarez-Romero et al. (2013), the chl-a dominated waters or Secondary water type is defined as corresponding to the colour class 5 and the Tertiary water type is defined as corresponding to the colour class 6 (Álvarez-Romero et al., 2013; Devlin et al., 2013b) (Appendix A). Satellite/in-situ match-ups analyses were performed by Devlin et al. (2013a, b) and validated plume water type maps produced at the multiannual time scale and GBR spatial scale from the re-classification of the colour classes of Álvarez-Romero et al. (2013).

The supervised classification of Álvarez-Romero et al. (2013) was used to classify 5 years of MODIS images (from 2007 to 2011, focused on the summer wet season i.e., December to April inclusive), and to produce daily Primary water type maps over the 2007 (i.e., December 2006– to April 2007) to 2011(i.e., December 2010– to April 2011) wet seasons. Secondary and Tertiary water type maps were not included in this study as we wanted to focus our study on the potential ecological effects of highly turbid waters on seagrass meadows. Weekly Primary water type composites were created to minimize the amount of area without data per image due to masking of dense cloud cover, common during the wet season (Brodie et al., 2010), and intense sun glint (Álvarez-Romero et al., 2013).

Weekly composites were resampled at the minimum MODIS spatial resolution (250 × 250 m) using the resampling function of ARCGIS 10.1 and a nearest interpolation resampling technique to allow comparison between the MODIS images and the smallest seagrass beds of Cleveland Bay. This technique uses the value of the closest cell to assign a value to the output cell when resampling. Weekly composites were thus overlaid (i.e., presence/absence of Primary water type) and normalized, to compute annual normalised frequency maps of occurrence of Primary water type (hereafter annual Primary water frequency maps). Finally, annual Primary water frequency maps were overlayed in ArcGIS to create multi-annual (2007–-2011) normalised frequency composites of occurrence of Primary water types (hereafter multi-annual Primary water frequency composites). Three composites were created by calculating the median, maximum and standard deviation frequency values of each cell/year. The annual/multi-annual frequency of occurrence of Primary water type represent the number of week the Primary plume water type was present in each MODIS pixel during one/several (2007– to 2011) consecutive wet season(s), respectively.

3.3Using MODIS annual turbid water maps for understanding changes in seagrass meadow health

Relationships in Cleveland Bay were investigated between annual Primary water type maps and seagrass at three different spatial scales, including: (i) the individual meadow scale (i.e., for every respective 12 individual meadows (Table 1); (ii) the consolidated community scale (i.e., for the four consolidated communities: Hu*, Cs*, Zm* and Hs*; Table 1), and; (iii) the bay-wide scale (i.e., for the Cleveland combined 12 monitored meadows; Table 1), respectively. Relationships were investigated by correlating seagrass health measurements with the exposure of seagrasses to Primary water type at these three different scales (Fig. 2). The 12 meadows were consolidated into four communities because we aimed to test if correlation between the turbid waters and the seagrass changes could be explained by the dominant seagrass species (and its specific growth requirements) in each of the seagrass meadows. Methods are further described in Sections 3.3.1 and 3.3.2. Appendix C presents the ranges of scales (in pixel, km2 and Ha) for the individual, the consolidated community and the bay-wide seagrass meadow scales.

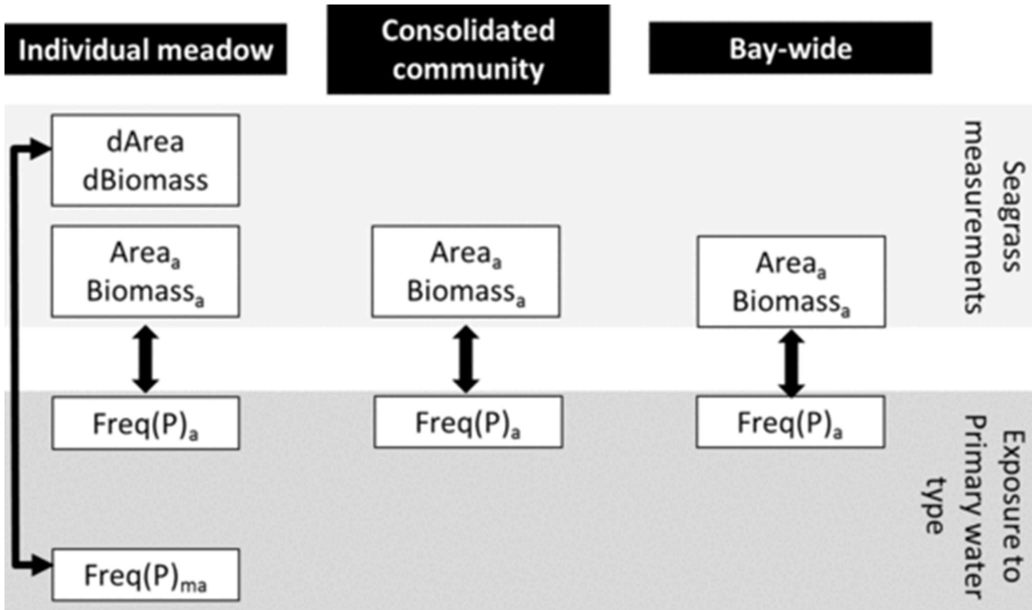

Fig. 2Mmethods used to investigate relationships between seagrass meadow health measurements and the exposure of seagrass beds to Primary water type: a: annual, ma: multiannual; dArea and dBiomass: total changes over the 5-year monitoring in the individual meadow area and biomass and; Freq(P): exposure of seagrasses to Primary water type. Areaa and Biomassa of the consolidated communities and bay-wide seagrasses are calculated by summing the corresponding individual meadow Areaa and Biomassa measured from 2007 to 2011 and Freq(P)a are calculated following methods of Fig. 3 dArea and dBiomass are calculated following Eq. (1) and Freq(P)ma extracted from the multi-annual Primary water frequency composites (median, maximum and standard deviation composites).

3.3.1Measurements of seagrass health

Areas and biomasses were computed annually (Areaa and Biomassa) for the three seagrass scales. Areas of the consolidated communities and bay-wide seagrasses were calculated by summing the corresponding individual meadow areas measured every year from 2007 to 2011. To fully quantify changes in seagrass area and abundance, the biomass recorded for each meadow was multiplied by its respective area to derive an individual meadow estimate. Consolidated community and bay-wide biomasses were calculated by summing the corresponding meadow biomass. Finally, in order to better assess individual meadow area and biomass total changes over the 5-year monitoring period, the difference (d) of seagrass areas and biomasses were estimated following Eq. (1).

(1)

With the difference (d) in %, the Area in hectares (Ha) and the biomass in mgDW (DW: Dry Weight).

3.3.2Exposure to primary water type

The annual and multi-annual Primary water frequency maps and composites were used to inform turbidity changes and exposure of seagrasses to reduced light levels caused by turbidity. Exposure of seagrasses to Primary water type (i.e., to reduced light levels) was estimated by calculating the mean annual Primary water frequency (Freq(P)a) measured over the seagrass, considering the three different seagrass spatial scales. Every pixel (i.e., annual frequency value) located over (i) each individual seagrass meadow (individual meadow scale; Fig. 3.4a); (ii) each of the consolidated communities (consolidated community scale; Fig. 3.4b); and, (iii) the combined 12 monitored meadows (bay-wide scale; Fig. 3.4c) as measured during the 2007 wet season baseline survey, were selected and frequency values were averaged, per year. The objective was to describe how changes in the frequency of high turbidity waters related to changes in seagrass area and biomass. Multi-annual Primary water frequency composites (median, maximum and standard deviation composites) were then used to calculate the multi-annual exposure of every individual meadow to Primary water type (Freq(P)ma). Every pixel (i.e., multi-annual median, maximum and standard deviation frequency value) located over each individual seagrass meadow was selected and averaged. All these exposure measurements to Primary water type were used for correlation analysis with the seagrass health measurements defined in the previous section.

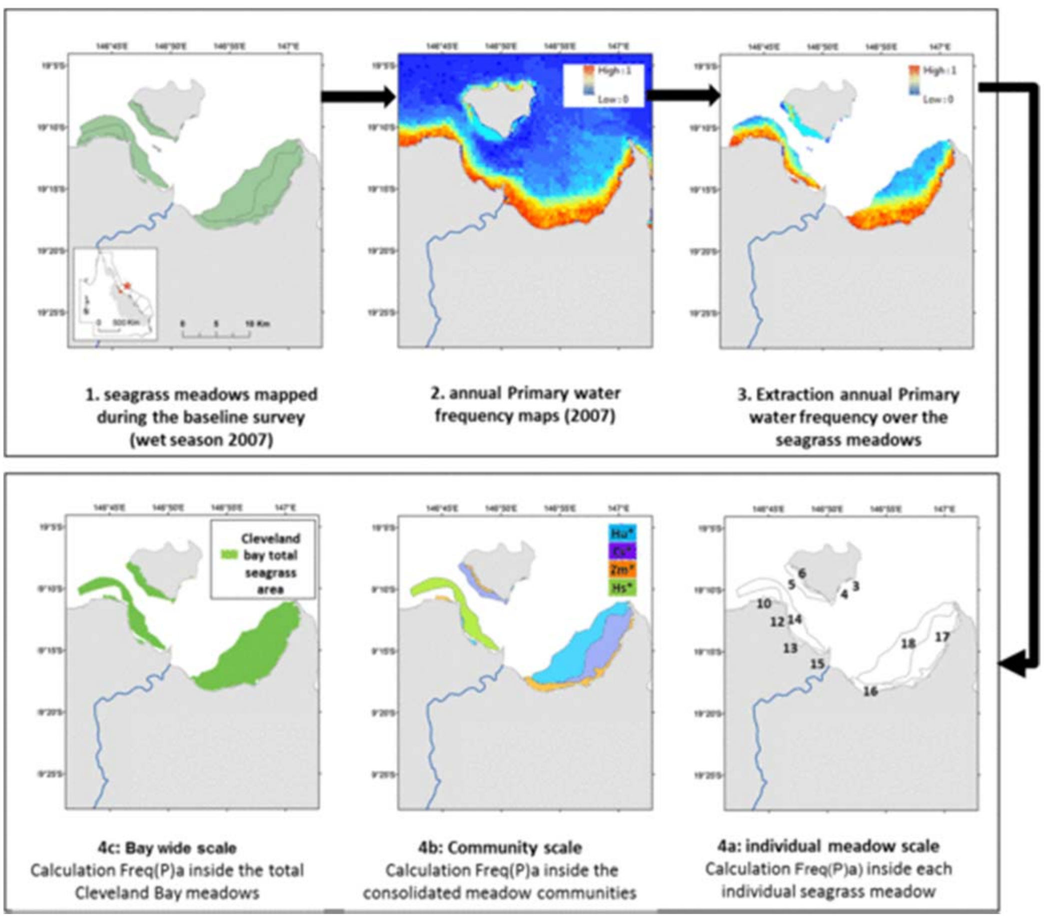

Fig. 3mMethod used to report the mean annual Primary water frequency (Freq(P)a) over the individual (4a), consolidated community (4b) and bay-wide (4c) seagrass meadow areas.

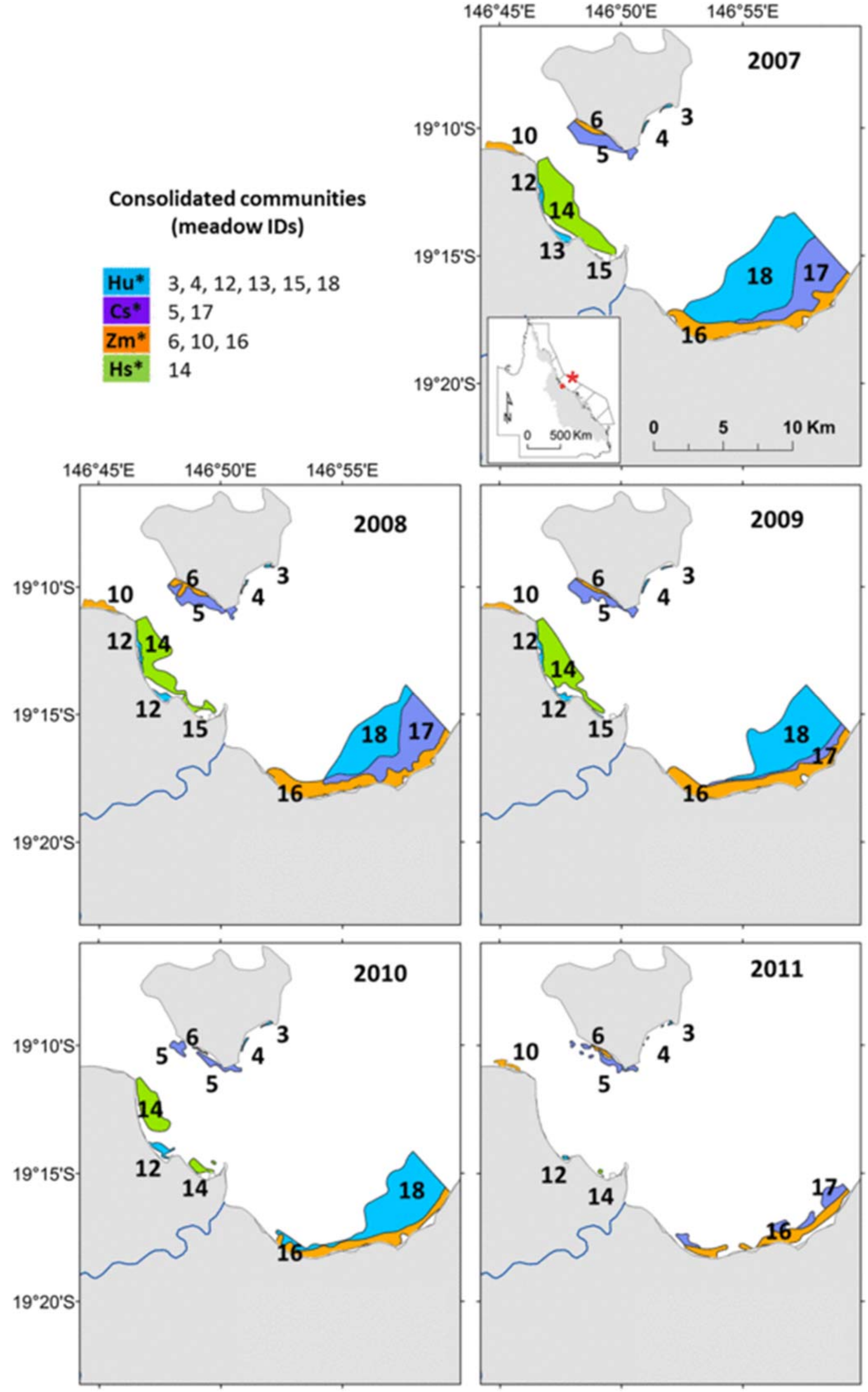

Fig. 4Monitored seagrass meadows: location and spatial extent from October 2007 to October 2011.

3.4Relationship between reduced light levels caused by turbidity and frequency of occurrence of primary water type

Finally, the mean discharge recorded over each monitoring wet seasons at the gauging station of the Bohle River (http://watermonitoring.derm.qld.gov.au/) was compared to the corresponding Freq(P)a in order to illustrate the relationship between reduced light levels caused by turbidity and frequency of occurrence of Primary water type, as described in Devlin et al., 2013b. This comparison is justified as runoff is assumed to be the main parameter influencing the sediment supply and turbidity levels in the coastal waters during the wet season (Fabricius et al., 2012; Logan et al., 2013) and maximum frequency of occurrence to Primary water type over the monitoring period should be correlated to the maximum river discharge recorded.

4Results

4.1Changes in seagrass areas and biomasses

Substantial seagrass loss occurred from 2007 to 2011 with total bay-wide seagrass meadow extent decreasing from 8161 Ha to 1268 Ha (84% loss) (Figs. 4 and 5b and Table 2). Biomass loss also occurred, declining from a bay-wide estimate of 2.13 × 109 to 7.10 × 106 gDW (>99% loss; Fig. 5a and Table 2). This estimated loss in seagrass biomass is due to the loss of extent, as well as large reductions in biomass within the meadows that remain. In the 2010–-2011 wet season the largest relative change in seagrass area occurred, with an 86% loss in area compared to 2010. Earlier losses in area ranged from 7% to 30% per year. In contrast biomass reductions were large in each year, ranging from 70% to 85% per year.

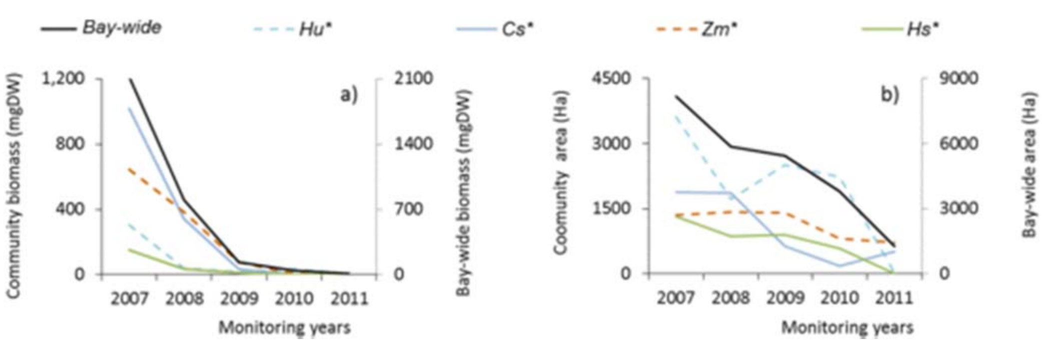

Fig. 5Bay-wide and consolidated community seagrass a) biomass and b) area at the long-term (2007 and 2011, inclusive) monitoring sites in Cleveland Bay. Changes of seagrass community re-grouped following: Hu*: Halodule uninervis (thin)-dominated communities, Cs*: Cymodocea serrulata-dominated communities, Zm*: Zostera muelleri-dominated communities, and Hs*: Halophila spinulosa-dominated communities.

Table 2Bay-wide and consolidated community (Com.) seagrass biomasses and areas measured at the long-term (2007 and 2011, inclusive) monitoring sites in Cleveland Bay.

		2007		2008		2009		2010		2011	
Biomass and error (mgDW)	Bay-wide	2126	±201	800	±80	137	±35	46	±9	7	±1

		2007		2008		2009		2010		2011	
	Com. Hu*	306	±54	39	±7	18	±5	34	±5	0	±0
	Cs*	1020	±77	343	±34	32	±5	2	±1	3	±1
	Zm*	647	±50	383	±36	78	±22	8	±2	4	±1
	Hs*	152	±21	35	±4	9	±3	2	±1	0	±0
Area and error (Ha)	Bay-wide	8161	±581	5858	±776	5443	±464	3786	±446	1268	±246
	Com. Hu*	3605	±223	1721	±320	2503	±254	2234	±341	25	±4
	Cs*	1882	±198	1854	±138	635	±121	178	±25	513	±195
	Zm*	1352	±78	1417	±73	1405	±50	800	±48	723	±41
	Hs*	1321	±82	866	±245	900	±39	573	±32	7	±5

All communities declined in meadow area over the five monitored years; however, the annual change varied among the community groupings (Figs. 4 and 5d and Table 2). H. uninervis–dominated communities declined in area by 99% overall with the greatest declines in 2011 (98%) and 2008 (43%) relative to the area in the previous year. Only 6 Ha of H. uninervis-dominated meadows remained in 2011. Cymodocea serrulata-dominated communities declined relative to the previous year by 65% and 43% in 2009 and 2010, but then increased slightly in 2011, when all other communities declined. In total, C. serrulata-dominated communities declined in area by 73% over the entire monitoring period from 2007 to 2011. Zostera muelleri-dominated meadows were all very shallow, intertidal communities, with the largest area in southern Cleveland Bay. These meadows had the smallest overall decline (46%), with 14% and 40% decline in 2010 and 2011, relative to the previous year. Halophila spinulosa-dominated meadows, which also contained significant amounts of H. uninervis (Table 1), incrementally declined in meadow extent throughout the monitoring period, with a total loss in area of 99%. Only 7 Ha remained in 2011.

4.2Mapping of turbid areas through MODIS primary water type

Annual and multi-annual Primary water frequency maps and composites are presented in Fig. 6a and b.

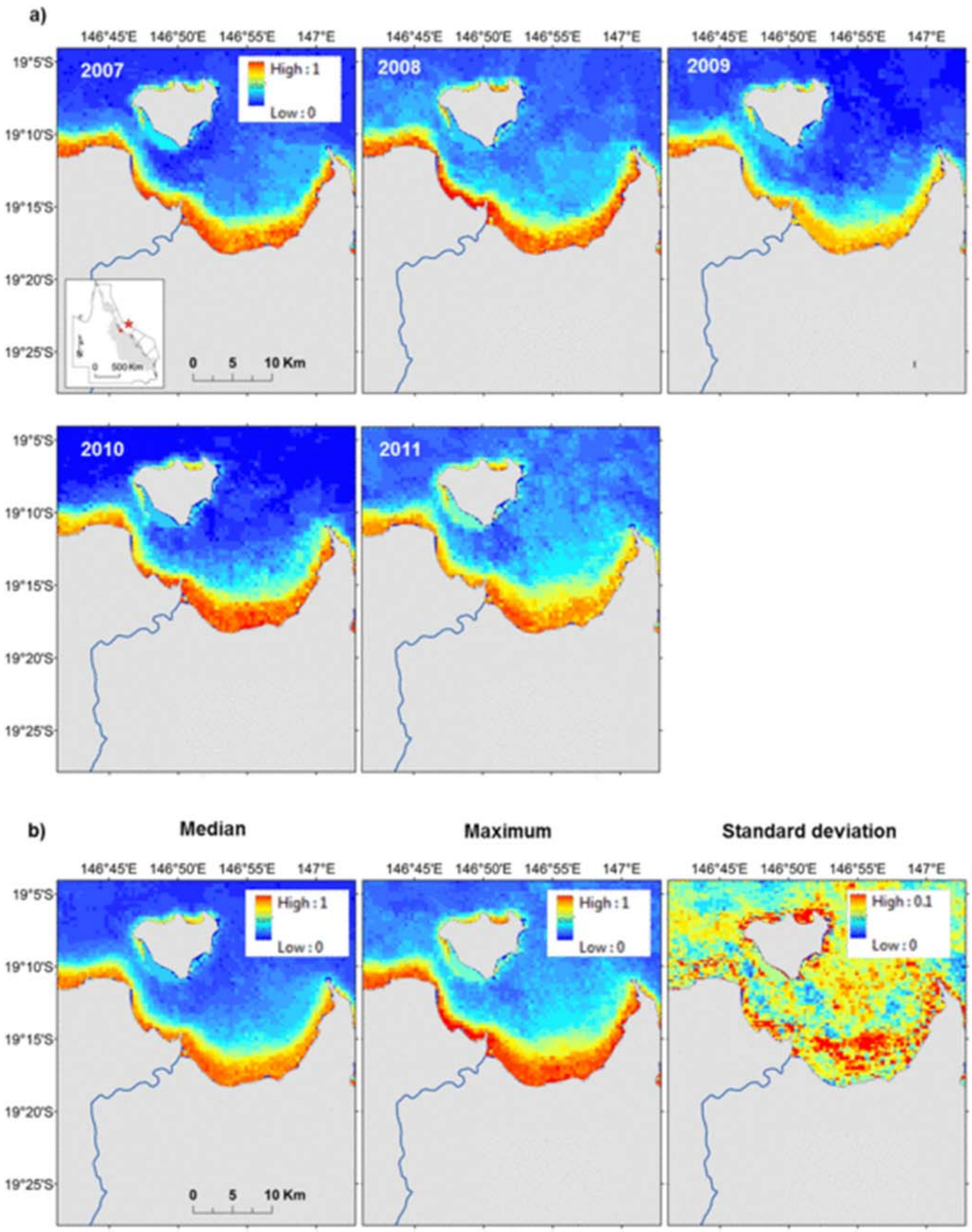

Fig. 6(a) Annual Primary water frequency maps. Frequency values are normalized with a pixel value of 1 indicating that Primary water type was measured, for this pixel, 22 weeks over the 22 weeks of this wet season. (b) Multi-Annual Primary water frequency composites (2007–-2011): median, maximum and standard deviation. Frequency values are normalized with a pixel value of 1 indicating that Primary water type was measured, for this pixel, 110 weeks over the 110 weeks of the 5 combined wet seasons.

Highest frequency of occurrence of Primary water type is located along the Townsville coast, with Primary frequency values reaching close to 100% of the time (Fig. 6a and b (Median, Maximum)). Low variability in the annual frequency of Primary water type (Fig. 6b(iii)) is observed in these inshore waters; i.e., all years during the study period had a relatively high level of exposure to

Primary water. More offshore, coastal waters of Magnetic Island are classified 10– to 40% of the time as Primary water type. Along the south western coast of Magnetic Island, lowest and relatively homogeneous frequency values recorded around meadows 5 and 6 are related to the presence of clear water in Cockle Bay. This shallow bay, south west of Magnetic Island, is protected from the prevailing SE winds by the island, and from the ocean swells by the Great Barrier Reef (Birch and Birch, 1984) and is thus a low-energy bay where sediment resuspension is limited. At the individual meadow scale, Freq(P)a couldn't be calculated for individual meadows 4 and 15 as scales of these seagrass beds were under the minimum detection limit of the MODIS images (i.e., <1 pixel, see Appendix C).

The mean wet season discharge measured at the Bohle River gauging station and the mean Freq(P)a at the bay-wide scale follow the same increasing trend with the exception of the relationship measured in 2009 (Fig. 7). This positive relationship proved that frequency of occurrence to Primary water type recorded in Cleveland Bay over the monitoring period is correlated to the maximum river discharge recorded and validated the method used to classify the plume water types in Cleveland Bay.

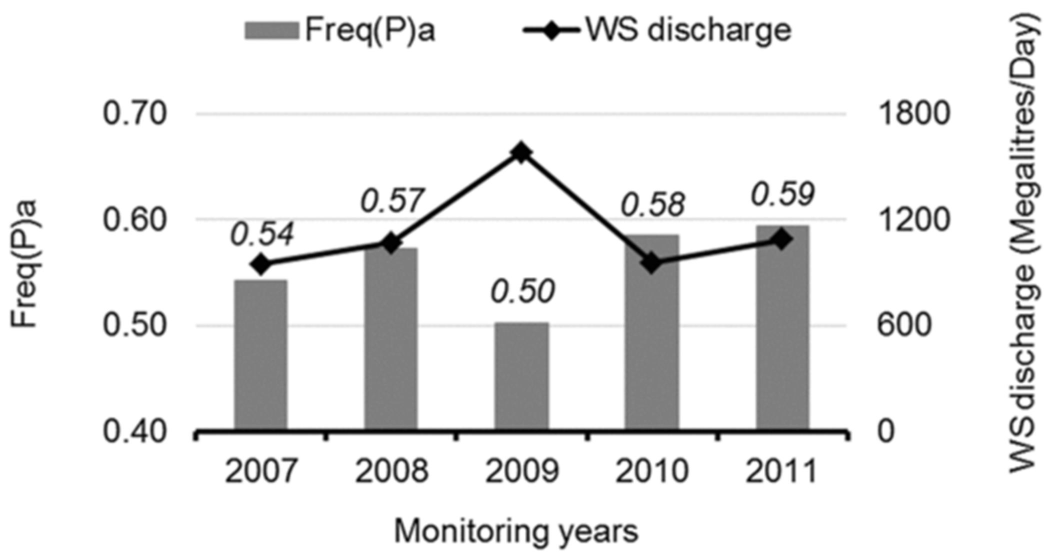

Fig. 7Comparison between the mean wet season (WS) discharges (calculated as the average of the mean monthly discharge values recorded every respective monitored year between December and April inclusive) at the gauging station of the Bohle River and the mean annual frequency of Primary water type (Freq(P)a). (Freq(P)a) values are indicated in italic.

4.3Using MODIS primary water type for understanding changes in seagrass meadow health

4.3.1Bay-wide scale

At the Bay-wide scale, negative relationships between annual seagrass health measurements and Freq(P)a (Fig. 8) are observed with lowest biomass and area measurements associated with the highest exposure to Primary water type.

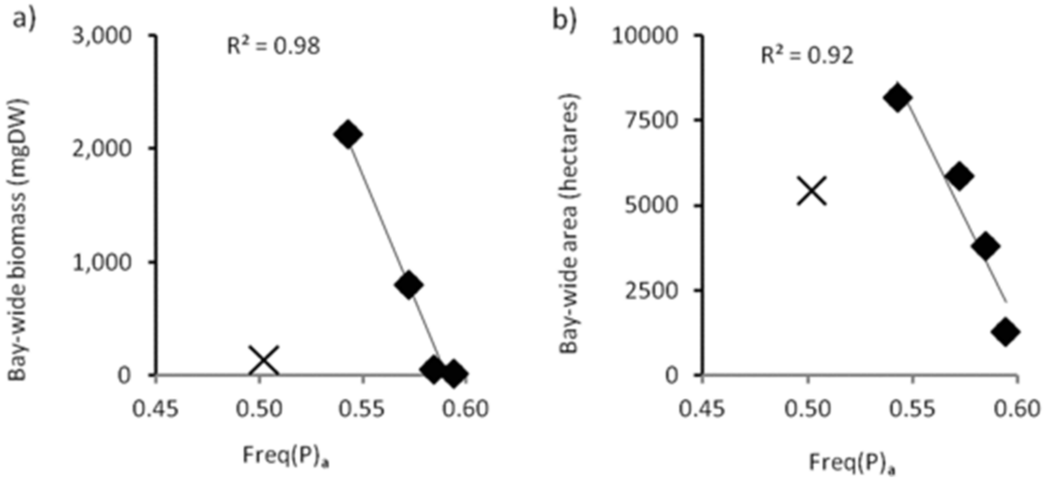

Fig. 8Correlation between annual total seagrass a) biomasses and b) areas and the mean annual frequencies of Primary water type. Trendlines and determination coefficient are computed without considering the year 2009 (cross symbol).

Annual biomasses and areas of seagrass are generally well predicted by the annual frequency of primary water type, with again the exception of data collected in 2009. Excluding 2009, 98% of variance in total biomass can be explained by changes in mean Primary water type frequency (Fig. 8a, R2 = 0.98, $p < 0.05$) and 92% of variance in total seagrass area can be explained by changes in mean Primary water type frequency (Fig. 8b, R2 = 0.92, $p < 0.05$).

4.3.2Consolidated community scale

At the community scale, data plotted for each community demonstrated non-significant responses within the community assemblages (Appendix D). The annual biomass and area of each consolidated seagrass communities (Hu*, Cs*, Zm* and Hs; Table 1) could not be predicted by Freq(P)a. Negative relationships between annual seagrass health measurements and Freq(P)a were nevertheless observed, similarly to the Bay-wide scale, for the Hu* and Cs* consolidated communities, respectively.

4.3.3Individual meadow scale

At the individual meadow scale, the loss of seagrass biomass over the 5-year period correlated well with the median and maximum multi-annual exposure values to Primary water (Fig. 9b). Loss of seagrass area also correlated with the median and maximum exposure to Primary water (Fig. 9a), with exceptions of meadows 10 and 16, which are both Z. muelleri –dominated meadows in intertidal habitats.

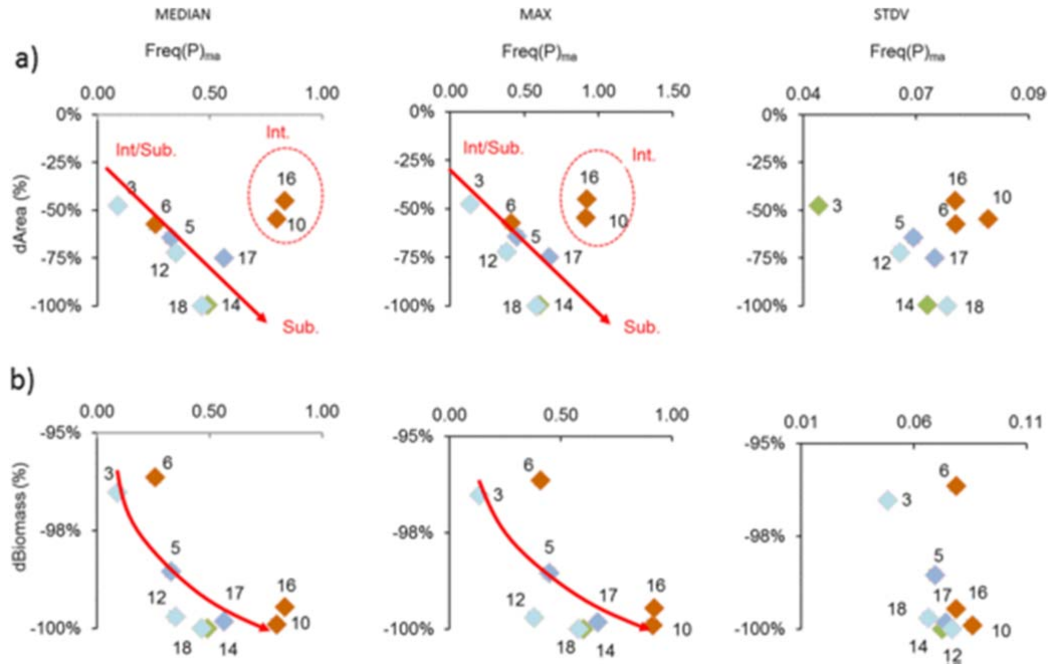

Fig. 9Correlation between total (5-year: 2007–-2011) loss in seagrass calculated following Eq. (1a) area and b) biomass and the multi-annual mean frequency of Primary waters type extracted from the mean median, maximum and standard deviation combined maps (Fig. 6b). Colour scale used is the same as Figure 5 i.e., blue: Hu*; violet: Cs*; Brown: Zm* and green Hs* communities. Int: Intertidal, Sub: subtidal (see Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5Discussion

Changes in areas and biomasses of seagrass in Cleveland Bay have been documented in McKenna and Rasheed (2012). However, this study did not include collection of water quality or other environmental data, making interpretation of seagrass changes speculative and based largely on climate information. Repeated and extended above average wet seasons were monitored in the GBR between 2007 and 2011. Nearly all of the GBR rivers experienced a high degree of flooding during the 2010–-2011 wet season due to the very strong 'La Nina' beginning early in the season in mid-2010 and three cyclones (Tasha in December 2010, Anthony in January 2011 and the most damaging: Yasi in February 2011) that crossed the North Queensland coast over a period of three months (Devlin et al., 2012b; Logan et al., 2013). The present study, which combines MODIS measurements and ecological information across years, provided further information about interactions between seagrass health (as measured by the area and biomass of seagrasses) and reduced light levels caused by turbidity (as measured by the frequency of exposure to Primary water type); as well as recovery and resilience of these inshore ecosystems in a context of extreme weather conditions.

5.1Changes in seagrass abundance and area

The decline in meadow area in Cleveland Bay from 2007 to 2011 was unprecedented and striking (Fig. 4), as meadow loss indicates an advanced state of exposure to stressful conditions. The loss in meadow area in Cleveland Bay from 2007 to 2011 was far in excess of global seagrass losses

(Waycott et al., 2009) and of that reported, for example, for Cockburn Sound in Western Australia (Cambridge and McComb, 1984), and suggests that earlier estimates of seagrass decline may have underestimated their losses at a global scale.

Biomass loss also occurred and was quantitatively higher than reductions in area (>99% biomass loss). Biomass loss can be attributed to plant death, thinning of shoots (fewer shoots per plant), reductions in the number of leaves per shoot and even changes to morphology (Collier et al., 2012a; Ralph et al., 2007); however, these meadow and plant attributes were not documented as part of the long-term monitoring program (McKenna and Rasheed, 2012). In addition, loss of seagrass biomass occurred faster than loss in area (Fig. 5). This result is consistent with our current understanding of meadow-scale responses to reductions in light availability, whereby, for example, seagrass meadows which occur in reduced light conditions, have lower biomass and as light reduces further meadows disappear i.e., biomass loss followed by loss in area (Collier et al., 2007; Ralph et al., 2007).

The substantial impacts to seagrass meadow area and abundance were not restricted to Cleveland Bay, but occurred throughout the GBR from 2007 to 2011 (McKenzie et al., 2012a, b; Collier et al., 2012b; Pollard and Greenway, 2013; Rasheed et al., 2014). These widespread impacts can be attributed largely to the extreme weather conditions occurring during the monitoring years in which above-average rainfall exposed meadows to turbid plume waters that reduce light penetration: an impact that occurred throughout the central and southern Great Barrier Reef. Seagrass meadows of the GBR typically undergo a period of senescence in the wet season when meadow abundance and productivity is reduced (Collier et al., 2012b; McKenzie et al., 2012a). The meadows then recover during the dry season as water warms and light increases. However, during the study period, the repeated and extended above average wet seasons were followed by shortened dry season recovery periods (McKenzie et al., 2012a).

5.2Using MODIS primary water type for understanding changes in seagrass meadow health

Declines in seagrass meadow area and biomass from 2007 to 2011 in Cleveland Bay were compared with the frequency of exposure of the Cleveland bay seagrass meadows to Primary water type, at different spatial scales (bay-wide, community and individual meadow scales). Relationships were found between bay-wide seagrass meadow area and biomass and exposure to Primary water type (Fig. 8) as well as changes of biomass and area of individual meadows and exposure of seagrass ecosystems to Primary water type over the 5-year studied period (Fig. 9). These results confirmed that MODIS data can be used to explain changes in seagrass health at different spatial scales and indicated that declines in seagrass areas and biomasses over the 2007–-2011 period were linked to increased exposure to Primary water type, i.e., reduced light levels caused by increase in water turbidity. These results are in agreement with an increase in sediment loads reported in the region (Kroon et al., 2012; Waterhouse et al., 2012). The relationships confirmed correlations previously observed in-situ between light availability and seagrass abundance at the site level (Collier et al., 2012b; McKenzie et al., 2012a) and indicate that these correlations are also relevant at a bay-wide scale.

Although bay-wide and individual meadow-scales analysis did show a strong correlation with water type, no significant relationship was found between the biomass and area of consolidated communities and the exposure of Primary water (Appendix D). Trends in both area and biomass reduction differed amongst the four main seagrass community types (Fig. 5). Z. muelleri and H. spinulosa are the most vulnerable to reductions in light availability most likely due to their low overall storage capacity (Collier et al., 2012a). However, Z. muelleri occurs in very shallow intertidal meadows (Fig. 4 and Table 1) which receive light before, during, and immediately after low tide (Petrou et al., 2013) which meant that losses in area of this species were actually lower than the other species (overall decline of 46%, see Fig. 5a). This is also well illustrated by Fig. 9a, where the Z. muelleri-dominated meadows 16 and 10 are outliers in the meadow area vs. exposure analysis. In contrast, H. spinulosa, which only occurs in subtidal meadows and therefore does not get reprieve from low light conditions at low tide, were highly sensitive and had lowest survival rates (total loss in area of 99%, see Figs. 5a and 9a.). These observations, indicating that subtidal seagrasses are more sensitive to light depletion, are consistent with other cases of seagrass responses to short-term light reduction, typically associated with changes in water quality (Collier et al., 2012a). Other studies worldwide nevertheless reported impact from reduced water clarity for both subtidal and intertidal seagrasses species; with loss in seagrass areas affecting first subtidal then intertidal species (Plus et al., 2010).

C. serrulata-dominated communities were impacted strongly in 2008 and 2009 and lost quantitatively less area and biomass in later years when exposure was even greater due to the consecutive lowering of annual measurements of area and biomass in 2008 and 2009. Of the subtidal meadows, C. serrulata has relatively high light requirements (summarised in Collier and Waycott, 2009) and it also has more above ground biomass (i.e., leaves) to support, relative to the below-ground storage of reserves. The largest of the C. serrulata meadows (17) was subtidal (Table 1 and Fig. 4), and therefore light penetration to the meadow was reduced under turbid conditions making it more vulnerable to Primary waters compared to the adjacent, shallow, intertidal meadows (McKenzie et al., 2012a). Cs* meadows showed the strongest (though not significant) relationship between changes in area and biomass and the frequency of exposure to primary water.

In addition to specific resilience characteristics of the four main seagrass community types, the consolidated communities considered in this study were also spread out amongst different meadows (Fig. 4) and, most certainly, amongst different physical (e.g., temperature, salinity, bathymetry and sediment type), chemical (e.g., nutrients and specific pollutant concentrations like PSII) and hydrological (e.g., local tidal currents and wave exposure) conditions. Seagrass require light, nutrients, and tolerable salinity, temperature and pH to survive. Photosystem II inhibiting herbicide (PSII) diuron commonly found in inshore GBR waters also adversely affects seagrass productivity and physical factors, such as tidal variation, sediment type and wave exposure also influence seagrass distribution (see references in Schaffelke et al., 2013). The environmental conditions within seagrass meadows influence the response of meadows within the community groupings and further explain the non-significant relationships obtained between the biomass and area of consolidated communities and the exposure of Primary water. Finally, meadows were defined according to the dominant species present at the start of the monitoring, but generally they were comprised of multiple species (Table 1), which may respond differently to exposure to reduced light levels and local environmental conditions.

These observations underline the complexity of coastal ecosystems such as seagrass meadows, where changes in health are linked to a combination of human-induced and environmental stressors as well as to the natural resilience of species to these combined stressors. Environmental and biological components can also interact and Ganthy et al. (2013) showed that presence of meadows modifies the balance between particle trapping and protection against erosion processes, depending upon the seasonal growth stage of seagrass. Decline of seagrass meadows facilitates the resuspension of sediment, leading to reduction in the amount of light available for seagrass photosynthesis and thus to further impact on seagrass ecosystem health. Remote sensing models are in development to try to incorporate the cumulative effects of pollutants using MODIS data (Petus et al., in press). In the meantime, this study focused on light as reduction in the amount of light available for seagrass photosynthesis was defined as the primary cause of seagrass loss throughout the GBR.

Loss and recovery are a natural part of the seagrass dynamics in the Great Barrier Reef (Birch and Birch, 1984; Waycott et al., 2005), but whether Cleveland Bay can fully recover from this series of extreme events that led to loss of more than 99% of seagrass biomass will depend on availability of recruits (e.g. seed bank) (Rasheed et al., 2014; Waycott et al., 2005), and the occurrence of additional stressors such as further runoff events or cyclones, during the recovery period. Underground parts (roots, rhizomes) were not considered in the monitoring and we thus have no information about the possibility for a rapid recolonisation of Cleveland Bay seagrass meadows; however the extreme level of loss indicates a high likelihood of rhizome mortality. A number of these species, such as H. uninervis form persistent seed banks and these are likely to be important in during recovery (Inglis, 2000).

5.3Technical limitations

The size of seagrass meadows presented a challenge in this study as some of the seagrass mapping units are under or just in the satellite detection limit. For example, Freq(P)a couldn't be calculated for meadows 4 and 15 as scales of these meadows were less than one MODIS pixel (Appendix C); and these seagrass beds were thus not included in the individual meadow analyses (Fig. 9). Nevertheless, results obtained in this study were coherent with correlations previously observed in-situ between light availability and seagrass health measurements and support the use of the MODIS data for monitoring of relative changes in water clarity over multi-annual time frame. MODIS data provides an effective means for frequent and synoptic water clarity observations over Cleveland Bay; information not available in this study area through more classical in-situ measurements.

Primary water type is characterised through the mapping of river plumes by MODIS true colour images recorded during the wet season (December to April inclusive; Álvarez-Romero et al., 2013), as it is typically during these periods of high flow when water quality conditions can be across a gradient of high turbidity waters (Devlin et al., 2012a; Petus et al., in press). At the whole GBR scale, restricting the analysis to wet season months also minimizes the occurrence of “false” river plume areas associated with wind-driven re-suspension of sediments during the strong trade winds typical of the dry season (Álvarez-Romero et al., 2013). However in the shallow coastal areas of Cleveland Bay and Magnetic Island (Fig. 1), muddy sediments can be resuspended (Lambrechts et al., 2010), and it is likely that resuspension of sediment by wind, waves and tidal currents also affect the turbidity levels in the coastal waters classified as Primary water type.

The mapping of exposure to water types depends on the frequency and availability of the MODIS imagery. Cloud contamination preventing ocean colour observations and the description of the water types through optical satellites images influence the number of images available to compute the annual frequency maps, and alter some of the existing water quality/seagrass correlations. Significant breaks in relationships between the Bohle river discharge, the bay-wide biomass, the bay-wide area and Freq(P)a measured in 2009, respectively (Figs. 7 and 8), seems to underline a problem in the frequency maps of Primary water produced for 2009.

Number of MODIS cloud free images available for a specific study area is inversely proportional to the local River discharge conditions (Petus et al., 2014a). More frequent cloud cover over Cleveland Bay associated with stormy condition and high Boyle River discharge could be a possible explanation for underestimated Freq(P)a values in 2009 (Figs. 7 and 8). These observations underline the climatic limitations of our satellite-based methodology. Similar limitations nevertheless apply when using in-situ measurements as shipboard surveys and sampling data quality are highly dependent of the wind and sea conditions. Satellite images offer the most extensive spatial and temporal coverage available to monitor reduced light levels caused by turbidity over large scale and temporal periods.

Mapping seagrass cover using remote sensing is impossible in turbid waters (Lyons et al., 2012) and in situ seagrass health measurements are still essential in shallow turbid environments such as Cleveland Bay. Furthermore, the degree of variability (Iinter- and multi-annual) and the timing issues between satellite water quality measurements and corresponding seagrass impacts can make it difficult to align the water quality pressure with the seagrass response. The correlative measures explored in this report require more investigation. However, these are encouraging preliminary results, and further work on other statistical measures and models may provide better explanation of the water quality–-seagrass relationship.

5.4Future direction

MODIS satellite data are available since 2000, offering potentially more than a decade of synoptic water turbidity information; and expansion of the temporal scale would be useful. Indeed, the seagrass exposure history possibly affects their vulnerability (Kendrick et al., 2008); and a critical component in seagrass changes might be previous year exposures e.g., how was the community exposed to Primary water type pre-2007. Information on the number of continuous days or weeks seagrass beds were in contact with water types, and the maximum TSS concentrations or turbidity levels associated with each event could be extracted from the MODIS true colour images and through the processing of MODIS Level 2 data (Petus et al., in press). This study tested sensitivity of seagrasses to turbid water exposure over an entire wet season but recovery intervals in between periods of acute light limitation can enhance seagrass survival, and furthermore the duration of the recovery is a key predictor of survival (Biber et al., 2009). Work on persistence of Primary water would thus help to clarify drivers of change in seagrass meadow health. Furthermore, documenting maximum concentrations of TSS or maximum turbidity levels associated with the exposure would help describing thresholds of acceptable changes for the seagrass ecosystems.

This study was focussed on an anthropogenically-modified shallow turbid region impacted by seasonal terrestrial run-off and with high frequency of exposure to Primary water type. The relationship between water type and seagrass meadow health needs to be validated for a greater range of physical, chemical and hydrological environmental conditions, water types (including Secondary and Tertiary water types), and frequency of occurrence levels. This could be explored in the GBR using long-term monitoring data (seagrass health, as well as MODIS water type data) that ranges from relatively low impact through to heavily impacted such as Cleveland Bay (Collier et al., in preparation). Repeating this work at the whole GBR scale or through the comparison of this data with reference areas (non/low impacted by anthropogenic developments) would more clearly show the links between satellite water quality outputs and seagrass community measures. A similar methodology could also be applied for regions outside of the GBR marine park, including the Torres Strait region where extensive seagrass beds (Coles et al., 2003) shelter a large population of endangered dugongs (Marsh and Kwan, 2008); if long-term seagrass health data were available for this region. Nevertheless, spectral signatures used to classify the MODIS true colour data into 6-colour (and resulting 3 water types), should be adjusted as they were created using specific spectral/colour characteristics of the GBR region (see Appendix B and Álvarez-Romero et al., 2013).

Finally, and more particularly at the community scale, satellite data should be associated with physico-chemical and hydrological measurements (temperature, salinity, nutrient and specific pollutants concentrations) for a better understanding of seagrass community changes. MODIS data used in this study could be combined with other satellite synoptic products, such as the MODIS sea surface temperature and load of nutrients from GBR rivers derived from MODIS true colour images (Álvarez-Romero et al., 2013), as well as with numerical hydrodynamic outputs into more complex seagrass productivity models to encompass combined stressors affecting the seagrass health. In the near future, these productivity models should help predict seagrasses health changes.

6Conclusions

This study looked at innovative remote sensing methods to test if relationships can be established between the frequency of exposure to Primary water type (used to monitor waters with reduced light levels caused by turbidity) and changes in seagrass health (defined in this study by the seagrass biomasses and areas). This study demonstrated that exposure to Primary water is strongly linked to seagrass area and biomass changes in Cleveland Bay at the bay-wide and individual meadow scale and reaffirmed that turbidity is a priority concern for seagrass meadow health in the northern GBR (e.g., Collier et al., 2012b). Despite limitations, this case study has demonstrated that water quality information derived from remote sensing data can be used to interpret ecological change. This study opened a suite of possibilities for exploring historical ecological data where environmental in-situ data are not available.

Uncited reference

Brodie and Waterhouse, 2012; Lee Long et al., 1998; Preen et al., 1995; Waycott et al, 2011.

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Appendix APlume water types as described in Devlin et al. (2012a) and Álvarez-Romero et al. (2013), detailing the water quality and optical properties (e.g., Clarke et al., 1970; Morel and Prieur, 1977; Froidefond et al., 2002; McClain, 2009), and the mean TSS, chl-a and Kd(PAR) which define the plume characteristics within each plume type concentrations (modified from Devlin et al., 2013b).

Colour classes	Water type	Description	Colour properties	Mean concentrations (Devlin et al., 2013b; see Figure 10)
1–4	Primary	Sediment-dominated waters: characterised by high values of coloured dissolved organic matters (CDOM) and total suspended sediment (TSS), with TSS concentrations dropping out rapidly as the heavier particulate material flocculates and settles to the sea floor (Devlin and Brodie, 2005; Brodie and Waterhouse, 2009). Turbidity levels limit the light (KdPAR) in these lower salinity waters, inhibiting production by primary producers and limiting chl-a concentrations.	Greenish-brown to beige waters: Sediment particles are highly reflective in the red to infra-red wavelengths of the light spectrum. Sediment-dominated waters have a distinctive brown/beige colour, depending upon the concentration and mineral composition of the sediments.	TSS: 36.8 ± 5.5 mg L−1 chl-a: 0.98 ± 0.2 μg L−1 Kd(PAR): 0.73 ± 0.54 m−1
5	Secondary	Chlorophyll-a-dominated waters: characterised by a region where CDOM is elevated with reduced TSS concentrations due to sedimentation. In this region, the	Bluish-green waters: Due to this green pigment, chlorophyll/phytoplankton preferentially absorb the red and blue portions of the light spectrum (for photosynthesis) and reflect green light. Chl-a-dominated waters will appear as	TSS:8.9 ± 18.1 mg l−1 chl-a: 1.3 ± 0.6 μg L−1 Kd(PAR): 0.39 ± 0.20 m−1

Colour classes	Water type	Description	Colour properties	Mean concentrations (Devlin et al., 2013b; see Figure 10)
		increased light in comparison to primary water type condition (but still under marine ambient conditions) and nutrient availability prompt phytoplankton growth measured by elevated chl-a concentrations.	certain shades, from blue-green to green, depending upon the type and density of the phytoplankton population.	
6	Tertiary	CDOM-dominated waters: offshore region of the plume that exhibits no or low TSS that has originated from the flood plume and above ambient concentrations of chl-a and CDOM. This region can be described as being the transition between secondary water type and marine ambient conditions.	Dark yellow waters: CDOM are highly absorbing in the blue spectral domain. CDOM-dominated waters have a distinctive dark yellow colour.	TSS:2.9 ± 3.2 mg l−1 chl-a: 0.7 ± 0.3 μg L−1 Kd(PAR): 0.24 ± 0.02 m−1

Appendix Bmethod and techniques used to classify the true colour images (modified from Alvarez-Romero et al., 2013; Devlin et al., 2013a,b) into 6 colour classes and Primary, Secondary, Tertiary water types.

The method used to classify the MODIS true colour images into 6 colour classes and is detailed in Álvarez-Romero et al., 2013, Section 2.1.1 and summarize on Fig. 1-step 1 (Classify daily true colour satellite images) below. This methods involve converting true colour images from Red-Green-Blue (RGB) to Intensity-Hue-Saturation (HIS) colour schemes, the definition of 6 colour classes corresponding to plume areas and that describe a gradient in the river borne pollutants as well as 2 classes corresponding to non-plume areas (cloud and sun glint signatures), the creation of spectral signatures for these respective areas, and the utilization of the created spectral signature to map the full extent of the plume.

Colour classes (and their respective spectral signature) corresponding to plume and dense clouds and sun glint, were created using a MODIS true colour image with large plumes occurring along the whole GBR coast to ensure that colour variations within plumes along the latitudinal gradient were incorporated into the spectral signature. The selected image included large areas with no plumes, varied atmospheric conditions (light to dense clouds, haze and sun glint), and sections with no data (not covered by satellite swath). To create the spectral signatures, we used the ArcMap Spatial Analyst (ESRI, 2010) isodata clustering tool to perform an unsupervised classification of the selected image. The resulting structure allowed characterization of the natural groupings of cells (i.e., pixels within an image) in multidimensional attribute space, i.e. IHS and RGB spaces for plumes and clouds/sun glint, respectively.

Plume maps produced were assessed using different number of classes based on two criteria: how well the mapped classes identified the river plume boundary (we assessed the classified images against visually interpreted true-colour imagery); and whether the variation of selected L2 parameters among the colour classes showed the expected gradient (as described by Devlin et al., 2012a; see Section 3.1.1). For each classification the mean value of the two L2 parameters for each colour class was plotted. Due to reflectance similarities between land and very turbid plumes occurring in the mouth of the rivers, the full image, was classified without masking out land. This allowed to map very turbid/high TSS plume areas commonly found near river mouths, which are frequently flagged incorrectly as land or very dense clouds. The classification was selected based on 6 colour classes as the most appropriate for plume mapping. These classes represent a gradient in exposure to pollutants, from highest in class 1 to lowest in class 6.

Finally, a supervised classification was used to map the full extent of plumes and to create a mask representing dense clouds and intense sun glint. Supervised classification uses labelled training data (i.e., the colour classes defined in the previous step) to create a spectral signature for each class, which is then used to classify all of the daily input imagery into 6-colour classes. The ArcMap Spatial Analyst maximum-likelihood classification tool (ESRI, 2010) was used to produce: (1) daily 6-class plume maps representing variations in L2 parameters (also used to identify the plume boundary) and (2) masks representing dense clouds and intense sun glint, used to eliminate areas with insufficient information to map plumes. A number of images covering different years, regions and months was selected to confirm the plume extent and overall congruence of our classified plume maps against plume maps produced using the method proposed by Devlin et al. (2012b), and to visually validate the clouds/sun glint masks.

Weekly 6-classes composites were thus created to minimize the amount of area without data per image due to masking of dense cloud cover, common during the wet season (Brodie et al., 2010), and intense sun glint (Álvarez-Romero et al., 2013). The six colour classes were further reclassified into 3 plume water types corresponding to the three GBR water types (Primary, Secondary, Tertiary) defined by e.g., Devlin and Schaffelke (2009) and Devlin et al. (2012a) (see Fig. 1 below; step 2: Create weekly 3-class plume maps). The turbid sediment-dominated waters or Primary water type is defined as corresponding to colour classes 1 to 4 of Álvarez-Romero et al. (2013), the chl-a dominated waters or Secondary water type is defined as corresponding to the colour class 5 and the Tertiary water type is defined as corresponding to the colour class 6 (Álvarez-Romero et al., 2013; Devlin et al., 2013b). Land is thus removed using a shapefile of the Great Barrier Reef (GBR) marine National Resource Management (NRM) boundaries (source: GBRMPA, GBR: Features) and by assigning 'No Data' values to any pixels outside of the shapefile boundaries (including land and offshore areas outside of the GBR marine park). Satellite/in-situ match-ups analyses were performed by Devlin et al. (2013a, b) and validated plume water type maps produced from the re-classification of the colour classes of Álvarez-Romero et al. (2013).

Weekly composites were thus resampled at the minimum MODIS spatial resolution (250 × 250 m) using the resampling function of ARCGIS 10.1 and a nearest interpolation resampling technique. This technique uses the value of the closest cell to assign a value to the output cell when resampling ArcGIS., Weekly composites were thus overlaid (i.e., presence/absence of Primary water type) and normalized, to compute annual normalised frequency maps of occurrence of Primary water type (hereafter annual Primary water frequency maps) (see Fig. 1 below, step 3: Create annual 3-class plume maps). Multi-annual (2007–-2011) normalised frequency composites of occurrence of Primary water types (hereafter multi-annual Primary water frequency composites) are created by overlaying the weekly composites in Arcgis and calculating the median, maximum and standard deviation frequency values of each cell/year.

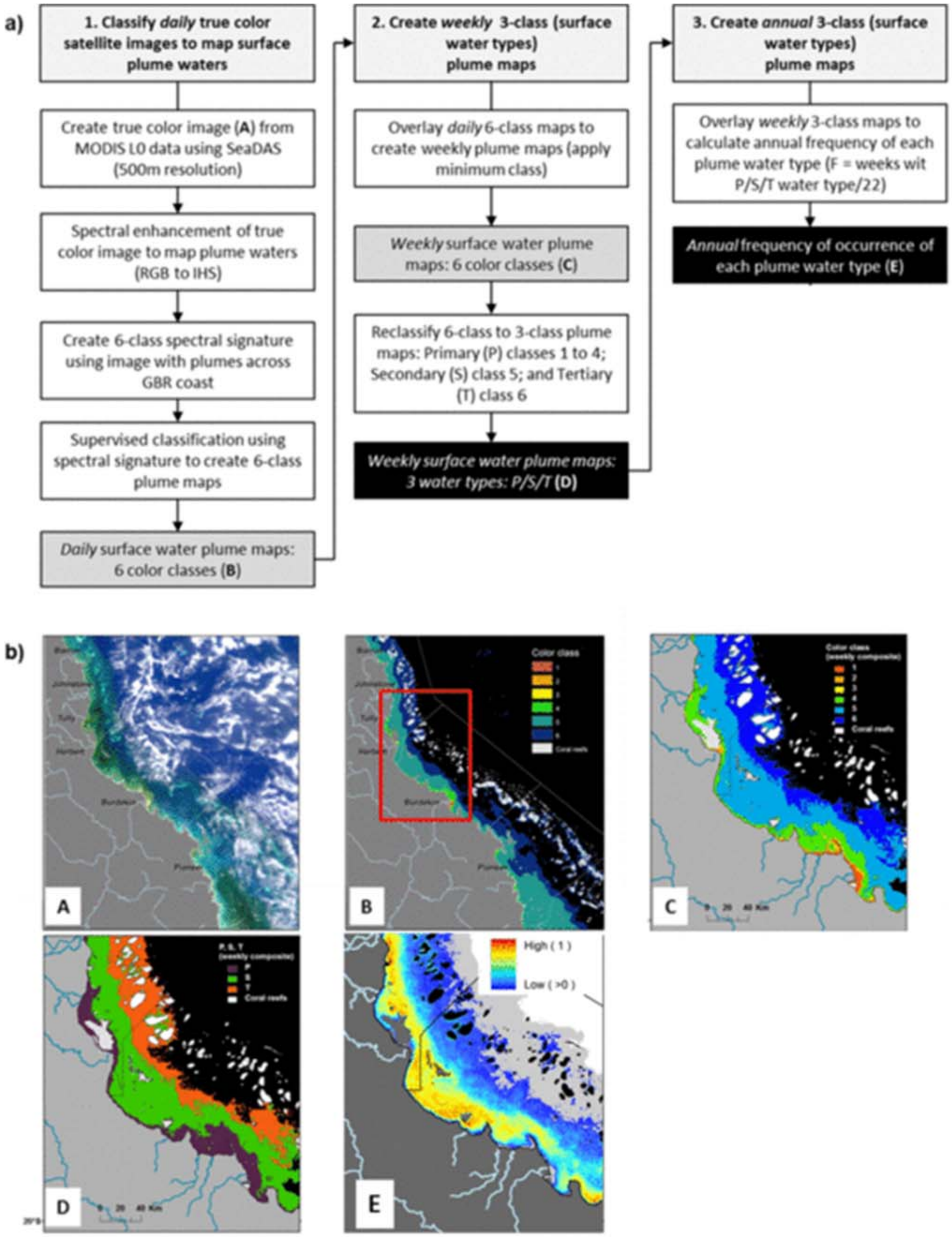
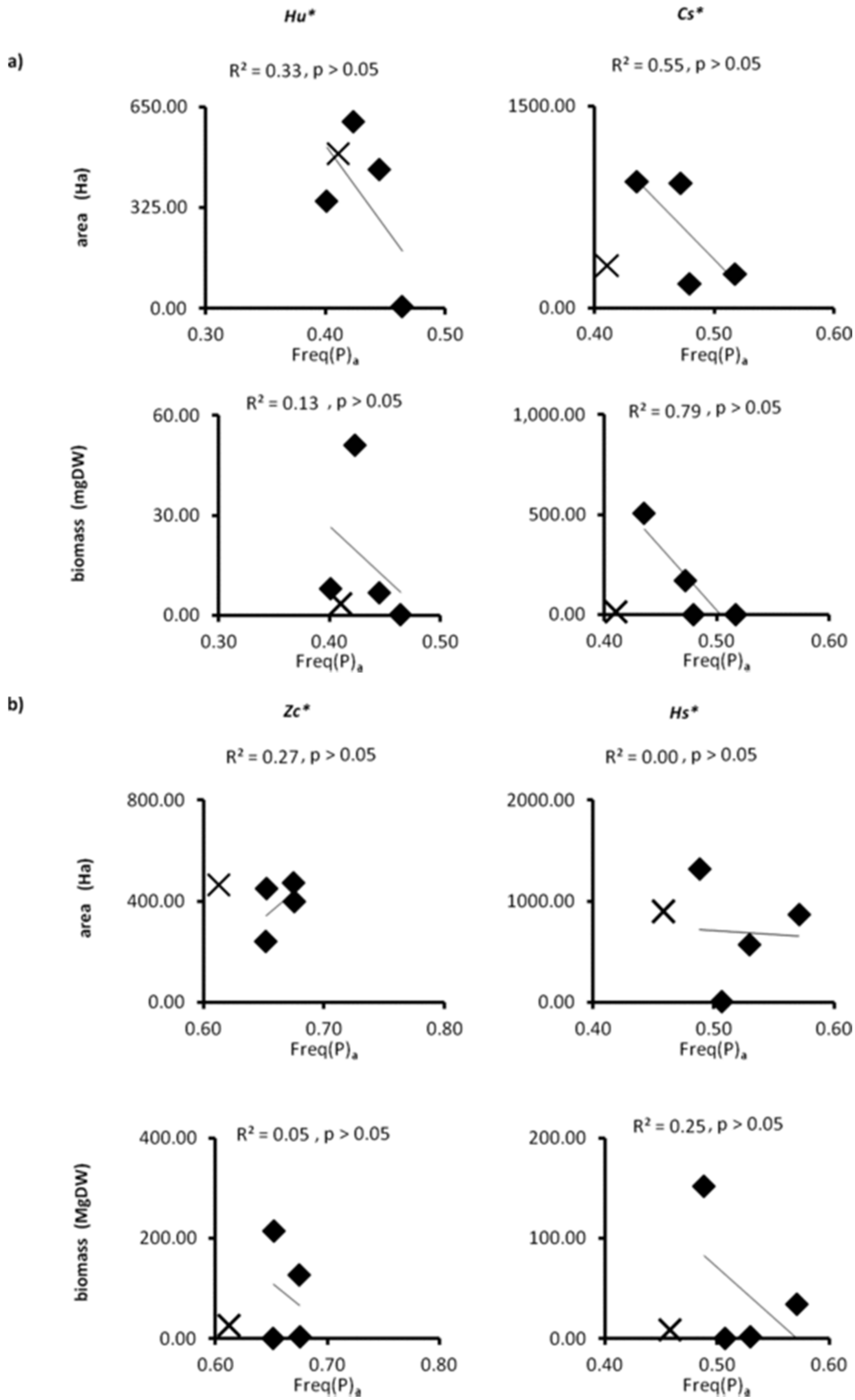


Figure B-1(from Devlin et al., 2012a; Modified from Álvarez-Romero et al., 2013; Devin et al., 2013a,b) : Summary of the process followed to build plume water maps with examples of inputs and outputs: (a) Plume mapping process: different shadings represent steps (light greay), analyses within steps (white), intermediate outputs (dark greay), and final outputs (black); (b) A: MODIS-Aqua true colour image used to create the spectral signature defining 6 colour classes for GBR plumes (25/01/2011), B and C: daily 6-colour class map (25/01/2011) and weekly composite (19– to 25/01/2011) of 6-class map. D: reclassified map into weekly P, S, T composite (19– to 25/01/2011); E: Frequency of occurrence of the secondary water type in 2011; Figure C to E are zoomed in the Tully-Burdekin area (see red box on panel B).

Appendix CRanges of scale (in pixel, km2 and Ha) for the individual, the consolidated community and the bay-wide seagrass meadows.

			Number of pixels		
			Individual	Community	Bay-wide
3	Hu*	Bay-wide	3	774	2130
4			<1		
12			7		
13			10		
15			<1		
18			754		
5	Cs*		127	674	
17			547		
6	Zm*		29	271	
10			20		
16			222		
14	Hs*		411	411	
			Corresponding scales (km2 and Ha)		
			0.1– -100 km2	10– - 100 km2	≈100 km2
			10– - 10000 Ha	1000– - 10000 Ha	≈ 10000 Ha

Appendix DCorrelation between annual seagrass a) biomasses and b) areas of the four consolidated community and the mean annual frequencies of Primary water type. Trendlines and determination coefficient are computed without considering the year 2009 (cross symbol).


a)
Hu*
Cs*
R² = 0.33 , p > 0.05
R² = 0.55 , p > 0.05
area (Ha)
650.00
325.00
0.00
1500.00
0.30
0.40
0.50
0.60
Freq(P)a
R² = 0.13 , p > 0.05
R² = 0.79 , p > 0.05
biomass (mgDW)
60.00
30.00
1,000.00
500.00
b)
Zc*
Hs*
R² = 0.27 , p > 0.05
R² = 0.00 , p > 0.05
800.00
400.00
2000.00
1000.00
0.70
0.80
R² = 0.05 , p > 0.05
R² = 0.25 , p > 0.05
biomass (MgDW)
400.00
200.00
100.00

References

Álvarez-RomeroJ.G.DevlinM.Teixeira da SilvaE.PetusC.BanN.C.PresseyR.L.KoolJ.RobertsJ.CerdeiraS.WengerA.BrodieJ.Following the flow: a combined remote sensing-GIS approach to model exposure of marine ecosystems to riverine flood plumeJ. Environ. Manag.1192013194207

BainbridgeZ.WolanskiE.Álvarez-RomeroJ.LewisS.BrodieJ.Fine sediment and nutrient dynamics related to particle size and floc formation in a Burdekin River flood plume, AustraliaMar. Pollut. Bull.652012236248

Baith, K., Lindsay, R., Fu, G., McClain, C.R., 2001. SeaDAS, a data analysis system for ocean color satellite sensors. Eos Trans. Am. Geophys. Union 82, 202. BiberP.D.KenworthyW.J.PaerlH.W.Experimental analysis of the response and recovery of Zostera marina (L.) and Halodule wrightii (Ascher.) to repeated light-limitation stressJ. Exp. Mar. Biol. Ecol.3692009110117

BirchW.R.BirchM.Succession and pattern of tropical intertidal seagrases in Cockle Bay, Queensland, Australia: a decade of observationsAquat. Bot.191984343367

BrodieJ.SchroederThRohdeK.FaithfulJ.MastersB.DekkerA.BrandoV.MaughanM.Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river discharge events: conclusions from satellite remote sensing and concurrent flood plume samplingMar. Freshw. Res.6162010651664

BrodieJ.E.WaterhouseJ.A critical review of environmental management of the 'not so Great' Barrier ReefEstuar. Coast. Shelf Sci.104–1052012122Brodie, J.E., Waterhouse, J., 2009. Assessment of the relative risk of impacts of broad-scale agriculture on the Great Barrier Reef and priorities for investment under the Reef Protection Package. In: Stage 1 Report: April 2009. ACTFR technical report 09/17. Australian Centre for Tropical Freshwater Research, Townsville

CambridgeM.L.McCombA.J.The loss of seagrass in Cockburn Sound, Western Australia. I the time course and magnitude of seagrass decline in relation to industrial developmentAquat. Bot.201984229243

ClarkeG.L.EwingG.C.LorenzenC.J.Spectra of backscattered light from sea obtained from aircraft as a measure of chlorophyll concentrationScience16197011191121

ColesR.G.McKenzieL.J.CampbellS.J.The seagrasses of eastern AustraliaGreenE.P.ShortF.T.SpaldingM.D.The World Atlas of Seagrasses2003

CollierC.J.LaveryP.S.MasiniR.J.RalphP.J.Morphological, growth and meadow characteristics of the seagrass Posidonia sinuosa along a depth-related gradient of light availabilityMar. Ecol. Prog. Ser.3372007103115

CollierC.J.WaycottM.Drivers of Change to Seagrass Distributions and Communities on the Great Barrier Reef: Literature Review and Gaps Analysis2009Reef and Rainforest Research Centre LimitedCairns

CollierC.J.WaycottM.Giraldo-OspinaA.Responses of four Indo-West Pacific seagrass species to shadingMar. Pollut. Bull.654–92012342354

CollierC.J.WaycottM.MckenzieL.J.Light thresholds derived from seagrass loss in the coastal zone of the Great Barrier ReefEcol. Indic.232012211219

CollierC.DevlinM.WaycottM.LangloisL.PetusC.McKenzieL.Vulnerability of Seagrass Habitats in the GBR to Flood Plume Impacts: Light, Nutrients, SalinityReport to the National Environmental Research Program2014Reef and Rainforest Research Centre LimitedCairns(in preparation)Collier, C., Devlin, M., Langlois, L., Petus, C., da Silva, E., McKenzie, L., Waycott, M., 2014. Thresholds and indicators of declining water quality as tools for tropical seagrass management. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns, 93 pp. (in review)

CostanzaR.D'argeR.De GrootR.FarberS.GrassoM.HannonB.LimburgK.NaeemS.O'neillR.V.ParueloJ.RaskinR.G.SuttonP.Van Den BeltM.The value of the worlds ecosystem services and natural capitalNature3871997253260

Cullen-UnsworthL.UnsworthR.Seagrass meadows, ecosystem services, and sustainabilityEnviron. Sci. Policy Sustain. Dev.5520131428

DennisonW.C.OrthR.J.MooreK.A.StevensonC.CarterV.KollarS.BergstromP.W.BatiukR.A.Assessing water quality with submersed aquatic vegetation: habitat requirements as barometers of Chesapeake Bay healthBioScience4319938694

DevlinM.BrodieJ.Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal watersMar. Pollut. Bull.512005922

DevlinM.J.FodenJ.SivyerD.MillsD.GowenR.TettP.Relationships between suspended particulate material, light attenuation and Secchi depth in waters around the UKEstuar. Coast. Shelf Sci.792008429439

DevlinM.J.BarryJ.MillsD.K.GowenJ.FodenJ.SivyerD.GreenwoodN.PearceD.TettP.Estimating the diffuse attenuation coefficient from optically active constituents in UK marine watersEstuar. Coast. Shelf Sci.8220097383

DevlinM.SchaffelkeB.Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully coastal region, Great Barrier ReefMar. Freshw. Res.60200911091122

Devlin, M., Schroeder, T., McKinna, L., Brodie, J., Brando, V., Dekker, A., 2011a. Monitoring and mapping of flood plumes in the Great Barrier Reef based on insitu and remote sensing observations. In: Chang, N. (Ed.), EnvironmentalRemote Sensing and Systems Analysis. Taylor and Frances Group e the CRC Press, Australia, pp. 147–190. DevlinM.HarknessP.McKinnaL.WaterhouseJ.Mapping the Surface Exposure of Terrestrial Pollutants in the Great Barrier ReefReport to the Great Barrier Reef Marine Park Authority, August 20102011bAustralian Centre for Tropical Freshwater ResearchReport Number 10/12

DevlinM.J.McKinnaL.W.Álvarez-RomeroJ.G.PetusC.AbottB.HarknessP.BrodieJ.Mapping the pollutants in surface riverine flood plume waters in the Great Barrier Reef, AustraliaMar. Pollut. Bull.654–92012224235

DevlinM.J.BrodieJ.WengerA.McKinnaL.W.da SilvaE.Álvarez-RomeroJ.G.WaterhouseJ.McKenzieL.Extreme weather conditions in the Great Barrier Reef: Drivers of change?Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9–13 July 20122012

DevlinM.PetusC.CollierC.ZehD.McKenzieL.Chapter 6: Seagrass and water quality impacts including a case study linking annual measurements of seagrass change against satellite water clarity data (Cleveland Bay)A Report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, AustraliaAssessment of the Relative Risk of Water Quality to Ecosystems of the Great Barrier Reef: Supporting Studies2013

DevlinM.J.Teixeira da SilvaE.PetusC.WengerA.ZehD.TraceyD.Álvarez-RomeroJ.BrodieJ.Combining water quality and remote sensed data across spatial and temporal scales to measure wet season chlorophyll-a variability: Great Barrier Reef lagoon (Queensland, Australia)Ecol. Proces.220133110.1186/2192-1709-2-31

FabriciusK.De'AthG.HumphreyC.ZagorskisI.SchaffelkeB.Intra-annual variation in turbidity in response to terrestrial runoff on near-shore coral reefs of the Great Barrier ReefEstuar. Coast. Shelf Sci.32012458470

FourqureanJ.W.DuarteC.M.KennedyH.MarbaN.HolmerM.MateoM.A.ApostolakiE.T.KendrickG.A.Krause-JensenD.McGlatheryK.J.SerranoO.Seagrass ecosystems as a globally significant carbon stockNat. Geosci.52012505509

FroidefondJ.M.GardelbL.GuiralbD.ParrabM.TernonJ.F.Spectral remote sensing reflectances of coastal waters in French Guiana under the Amazon influenceRemote Sens. Environ.802002225232

FurnasM.J.Catchments and Corals, Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science2003CRC Reef Research CentreTownsville334 pp.

GanthyF.SottolichioA.VerneyR.Seasonal modification of tidal flat sediment dynamics by seagrass meadows of Zostera noltii (Bassin d'Arcachon, France)J. Mar. Syst.109–1102013S233S240

HalpernB.S.WalbridgeS.SelkoeK.A.KappelC.V.MicheliF.D'AgrosaC.BrunoJ.F.CaseyK.S.EbertC.FoxH.E.FujitaR.HeinemannD.LenihanH.S.MadinE.M.P.PerryM.T.SeligE.R.SpaldingM.SteneckR.WatsonR.A global map of human impact on marine ecosystemsScience3192008948e952

HeckK.L.CarruthersT.J.B.DuarteC.M.HughesA.R.KendrickG.OrthR.J.WilliamsS.W.Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumersEcosystems11200811981210

HughesA.R.WilliamsS.L.DuarteC.M.HeckK.L.WaycottM.Associations of concern: declining seagrasses and threatened dependent speciesFront. Ecol. Environ.72009242246

InglisG.J.Variation in the recruitment behaviour of seagrass seeds: implications for population dynamics and resource managementPac. Conserv. Biol.52000251259

KendrickG.A.HolmesK.W.Van NielK.P.Multi-scale spatial patterns of three seagrass species with different growth dynamicsEcography312008191200

KroonF.J.KuhnertP.HendersonB.WilkinsonS.HendersonA.BrodieJ.TurnerR.River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoonMar. Pollut. Bull.654–92012167181

LambrechtsJ.HumphreyC.McKinnaL.GourgeO.FabriciusK.,E.MehtA.J.LewisS.WolanskiE.Importance of wave-induced bed liquefaction in the fine sediment budget of Cleveland Bay, Great Barrier ReefEstuar. Coast. Shelf Sci.8922010154162

Lee LongW.J.McKenzieL.J.RoelofsA.J.MakeyL.ColesR.G.RoderC.A.Baseline Survey of Hinchinbrook Region Seagrasses, – October (Spring) 19961998Great Barrier Reef Marine Park Authority Research Publication No. 5126 pp.

LesD.H.ClelandM.A.WaycottM.Phylogenetic studies in Alismatidae, II: evolution of marine angiosperms (seagrasses) and hydrophilySyst. Bot.221997443463

LoganM.FabriciusK.WeeksS.CantoM.NoonanS.WolanskiE.BrodieJ.TReport to the National Environmental Research Programhe Relationship Between Burdekin River Discharges and Photic Depth in the Central Great Barrier Reef2013Reef and Rainforest Research Centre LimitedCairns29 pp.

LyonsM.B.PhinnS.R.RoelfsemaC.M.Long term land cover and seagrass mapping using Landsat and object-based image analysis from 1972 to 2010 in the coastal environment of South East Queensland, AustraliaISPRS J. Photogram. Remote Sens.1202012145155

MarshH.KwanD.Temporal variability in the life history and reproductive biology of female dugongs in Torres Strait: the likely role of sea grass dieback?Cont. Shelf Res.28200821522159

MarshH.O'SheaT.J.ReynoldsJ.E.IIIEcology and Conservation of the Sirenia2011Cambridge University PressCambridge

McKennaS.A.RasheedM.A.Port of Townsville Long-term Seagrass Monitoring, October 20112012DEEDI PublicationFisheries Queensland, Cairns33 pp.

McKennaS.A.RasheedM.A.Port of Karumba Long-term Seagrass Monitoring, 20122013James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem ResearchCairns30 pp.

McKenzieL.J.FinkbeinerM.A.KirkmanH.Methods for mapping seagrass distribution. Chapter 5ShortF.T.ColesR.G.2001. Global Seagrass Research Methods2001Elsevier Science B.V.Amsterdam101122473pp. ISBN: 0-404-50891-0

McKenzieL.CollierC.J.WaycottM.Reef Rescue Marine Monitoring Program: Inshore Seagrass, Annual Report for the Sampling Period 1st September 2010–31st May 20112012Fisheries Queensland, Cairns, 230 pp.

McKenzieL.CollierC.J.WaycottM.UnsworthR.K.F.YoshidaR.L.SmithN.Monitoring inshore seagrasses of the GBR and responses to water quality12th International Coral Reef Symposium2012Cairns, Australia

MellorsJ.E.An evaluation of a rapid visual technique for estimating seagrass biomassAquat. Bot.4219916773

MorelA.PrieurL.Analysis of variations in ocean colourLimnol. Oceanogr.221977709722

NovoaS.ChustG.FroidefondJ.M.PetusC.FrancoJ.OriveE.SeoaneS.BorjaA.Water quality monitoring in Basque coastal areas using local chlorophyll-a algorithm and MERIS imagesJ. Appl. Remote Sens.62012063519-1-27

NovoaS.ChustG.SagarminagaY.RevillaM.BorjaA.FrancoJ.Water quality assessment using satellite-derived chlorophyll-a within the European directives, in the southeastern Bay of BiscayMar. Pollut. Bull.642012739750

PetrouK.Jimenez-DennessI.ChartrandK.MccormackC.RasheedM.RalphP.J.Seasonal heterogeneity in the photophysiological response to air exposure in two tropical intertidal seagrass speciesMar. Ecol. Prog. Ser.482201393106

PetusC.ChustG.GohinF.DoxaranD.FroidefondJ.M.SargarminagaY.Estimating turbidity and total suspended matter in the Adour River Plume (South Bay of Biscay) using MODIS 250-m imageryCont. Shelf Res.302009379392

PetusC.MarieuV.NovoaS.ChustG.BruneauG.FroidefondJ.M.Monitoring spatio-temporal variability of the Adour River turbid plume (Bay of Biscay, France) with MODIS 250-m imageryCont. Shelf Res.7420143549

PetusC.Teixera da SilvaE.DevlinM.Álvarez-RomeroA.WengerA.Using MODIS data for mapping of water types within flood plumes in the Great Barrier Reef, Australia: towards the production of river plume risk maps for reef and seagrass ecosystems(in press)J. Environ. Manag.2014(accepted Nov. 2013)Petus, C., Teixeira da Silva, E., Devlin, M., Wenger, A., Álvarez-Romero, J.G., 2014b. Using MODIS data for mapping of water types within river plumes in the Great Barrier Reef, Australia: towards the production of river plume risk maps for reef and seagrass ecosystems. J. Environ. Manage. 137, 163–177

PlusM.DalloyauS.TrutG.AubyI.de MontaudouinX.EmeryE.ClaireN.VialaC.Long-term evolution (1988–2008) of Zostera spp. meadows in Arcachon Bay (Bay of Biscay)Estuar. Coast. Shelf Sci.872010357366

PollardP.C.GreenwayM.Seagrasses in tropical Australia, productive and abundant for decades decimated overnightJ. Biosci. (Bangalore)382013110

PreenA.R.LongW.J.L.ColesR.G.Flood and cyclone related loss, and partial recovery, of more than 1000 km2 of seagrass in Hervey Bay, Queensland, AustraliaAquat. Bot.521995317

RalphP.J.DurakoM.J.EnriquezS.CollierC.J.DoblinM.A.Impact of light limitation on seagrassesJ. Exp. Mar. Biol. Ecol.3502007176193

RasheedM.A.DewK.R.McKenzieL.J.ColesR.G.KervilleS.CampbellS.J.Productivity, carbon assimilation and intra-annual change in tropical reef platform seagrass communities of the Torres Strait, north-eastern AustraliaCont. Shelf Res.28200822922303

RasheedM.A.TaylorH.A.Port of Townsville Seagrass Baseline Survey Report, 2007–20082008DPI&F Publication PR08-4014 (DPI&F, Cairns)45 pp.

RasheedM.A.UnsworthR.K.F.Long-term climate-associated dynamics of a tropical seagrass meadow: implications for the futureMar. Ecol. Prog. Ser.422201193103

Rasheed, M.A., McKenna, S.A., Carter, A.B., Coles, R.G., 2014. Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. Mar. Pollut. Bull. (in press). SaldíasG.S.Sobarzo M.LargierJ.MoffatC.LetelierR.Seasonal variability of turbid river plumes off central Chile based on high-resolution MODIS imageryRemote Sens. Environ.1232012220233

SchaffelkeB.AnthonyK.BlakeJ.BrodieJ.CollierC.DevlinM.FabriciusK.MartinK.McKenzieL.NegriA.Ronan M.ThompsonA.WarneM.“Marine and coastal ecosystem impacts” in Synthesis of evidence to support the Reef Water Quality Scientific Consensus Statement 20132013Department of the Premier and Cabinet, Queensland GovernmentBrisbane

ShortF.T.PolidoroB.LivingstoneS.R.CarpenterK.E.BandeiraS.BujangJ.S.CalumpongH.P.CarruthersT.J.B. ColesR.G.DennisonW.C.ErftemeijerP.L.A.FortesM.D.FreemanA.S.JagtapT.G.KamalA.H.M.KendrickG.A. Judson KenworthyW.La NafieY.A.NasutionI.M.OrthR.J.PrathepA.SanciangcoJ.C.TussenbroekB.v.VergaraS.G.WaycottM.ZiemanJ.C.Extinction Risk Assessment of the World's Seagrass SpeciesBiol. Conserv.144201119611971

UnsworthR.K.F.RasheedM.A.TaylorH.A.Port of Townsville Long Term Seagrass Monitoring2009DEEDI Publication PR09–4330, Northern Fisheries CentreCairns30 pp.

WaterhouseJ.BrodieJ.LewisS.MitchellA.Quantifying the sources of pollutants to the Great Barrier ReefMar. Pollut. Bull.652012394406

WarrickJ.A.MertesL.A.K.SiegelD.A.MackenzieC.Estimating suspended sediment concentrations in turbid coastal waters of the Santa Barbara Channel with SeaWiFSInt. J. Remote Sens.2510200419952002

WaycottM.LongstaffB.J.MellorsJ.Seagrass population dynamics and water quality in the Great Barrier Reef region: a review and future research directionsMar. Pollut. Bull.512005343350

WaycottM.ProcacciniG.LesD.H.ReuschT.B.H.LarkumA.W.D.OrthR.J.DuarteC.M.Seagrass evolution, ecology and conservation: A genetic perspectiveSeagrasses: Biology, Ecology and Conservation2006SpringerDordrecht2550

WaycottM.DuarteC.M.CarruthersT.J.B.OrthR.J.DennisonW.C.OlyarnikS.CalladineA.FourqureanJ.W.HeckK.L.HughesA.R.KendrickG.A.KenworthyW.J.ShortF.T.WilliamsS.L.Accelerating loss of seagrasses across the globe threatens coastal ecosystemsProc. Natl. Acad. Sci.10620091237712381

WaycottM.MckenzieL.J.MellorsJ.E.EllisonJ.C.SheavesM.T.CollierC.SchwarzA.-M.WebbA.JohnsonJ.PayriC.E.Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate changeBellJ.D.JohnsonJ.E.HobdayA.J.Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community2011