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Variation in biogeochemical parameters across intertidal seagrass meadows in the central Great Barrier Reef region

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Abstract

This survey provides baseline information on sediment characteristics, porewater, adsorbed and plant tissue nutrients from intertidal coastal seagrass meadows in the central region of the Great Barrier Reef World Heritage Area. Data collected from 11 locations, representative of intertidal coastal seagrass beds across the region, indicated that the chemical environment was typical of other tropical intertidal areas. Results using two different extraction methods highlight the need for caution when choosing an adsorbed phosphate extraction technique, as sediment type affects the analytical outcome. Comparison with published values indicates that the range of nutrient parameters measured is equivalent to those measured across tropical systems globally. However, the nutrient values in seagrass leaves and their molar ratios for *Halophila ovalis* and *Halodule uninervis* were much higher than the values from the literature from this and other regions, obtained using the same techniques, suggesting that these species act as nutrient sponges, in contrast with *Zostera capricorni*. The limited historical data from this region suggest that the nitrogen and phosphorus content of seagrass leaves has increased since the 1970s concomitant with changing land use practice.

Keywords: Seagrass; Nutrients; Water quality; Great Barrier Reef region

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1. Introduction

Most persistent seagrass meadows in the Great Barrier Reef region are found in waters <10 m (Lee Long et al., 1993), the shallow near-shore band where particulate nutrients and sediment loading are consistently higher than further offshore (Furnas, 2003). The offshore dispersal of particulate nutrients and sediments is halted by onshore wave action and the predominant south-easterly winds (Belperio, 1983; Brodie, 1995; Devlin et al., 2001; Furnas, 2003). The sediment from these plumes settles out of the water column, particularly in the protected waters of estuaries and on the leeward margins of islands and north-facing bays, areas where seagrasses are most likely to be found (Lee Long et al., 1993). Sediments are a source of nutrients for seagrass growth (Short, 1987; Fourqurean et al., 1992; Udy and Dennison, 1996). Thus coastal seagrass habitats are vulnerable to changes in water quality as they are directly exposed to increased sediment loads. These additional sediments usually reduce habitat quality as a result of the combined effects of additional sediments and nutrients locally.

Overseas and temperate Australian studies have shown that declining water quality (particularly increased nutrient loadings) can have an adverse affect on seagrass growth, distribution and morphology by indirectly affecting light attenuation to the seagrass plants (Shepherd et al., 1989; Dennison et al., 1993;

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Short et al., 1996). Studies of seagrass meadows in the Great Barrier Reef region have largely been limited to mapping their presence and species composition. As a first step in elucidating the relationship between seagrass and water quality, this study provides an overview of the sediment and nutrient status of intertidal seagrass meadows in the central region of the Great Barrier Reef World Heritage Area. It also adds to the scarce knowledge of the nutrient status of tropical seagrass meadows, especially in the Indo-West Pacific region.

2. Materials and methods

2.1. Study area

The intertidal locations sampled for this survey were on the mainland Queensland coast between Cairns (16.88 °S, 145.77 °E) and Bowen (19.94 °E, 148.25 °E), spanning approximately 556 km of coastline adjacent to wet and dry tropic catchments. Seagrass had been recorded at each location for three years prior to the sampling which was conducted during daytime low tides during July 1994.

2.2. Sampling

Three elements of the seagrass environment were sampled: (1) the nutrient environment including those parameters that have an effect on the chemistry of the sediments, (2) the sediment structure and (3) the seagrasses per se. Sampling within the meadows was restricted to areas of monospecific, homogenous seagrass-cover. Disturbed areas and bare patches were avoided. The parameters sampled, units and the numbers of replicates are listed in Table 1.

2.3. Nutrient environment

Porewater samples were collected in situ using sediment sippers (modified from Murray et al. (1992) and Udy and Dennison (1996)). The sample was then transferred to sterilized 10 mL vials and sealed, and placed on dry ice in the field to minimize further chemical transformation and microbial activity. Sediment cores (50 mL) were collected for measurement of adsorbed nutrients. Samples were placed on ice then refrigerated. Adsorbed exchangeable ammonium (NH_4^+) was extracted using KCl (Rayment and Higginson, 1993).

Because of the potential of sampling different sediment types, 2 techniques were used to extract adsorbed phosphate (PO_4^{3-}): the Bray method (Bray and Kurtz, 1945) hereafter referred to as '$PO^{3-}_{4(\mathrm{Bray})}$' and the Olsen/Colwell/Bicarbonate method (Rayment and Higginson, 1993) hereafter referred to as '$PO^{3-}_{4(\mathrm{bicarbonate})}$'. These techniques accommodate the range of sediment pH encountered, as sediment type could not be fully characterized until all analyses were completed. The use of two different PO_4^{3-} extraction techniques also provided information on the amount of adsorbed PO_4^{3-} that was bioavailable to the seagrass.

Chemical analyses of all inorganic nutrients were determined using a Skalar segmented flow auto-analyser, using standard water quality techniques (Strickland and Parsons, 1972; Ryle et al., 1981). Additional core samples were analysed for percent carbonate (Blakemore et al., 1987) and percent organic content (Gale and Hoare, 1991). Eh and pH were measured in situ.

2.4. Sediment structure

Three sediment cores were collected for the analyses of sediment grain size and porosity. The particle size distribution of each sediment sample was determined by laser analysis using a Malvern Mastersizer X and particle size categories and subcategories were allocated according to the scheme of Udden and Wentworth (Gale and Hoare, 1991). Sediment volume was measured and particle size density (p_s) and porosity (ϕ) were calculated by converting porewater units (μmol L^{-1}) and adsorbed nutrients units (μmol kg^{-1}) to equivalent units

Table 1
The parameters, units and the number of samples collected for each component of the seagrass environment studied

Nutrient environment			Sediment structure			Seagrass					
						Plant abundance			Plant tissue nutrients		
Parameter	Units	*n*	Parameter	Units	*n*	Parameter	Units	*n*	Parameter	Units	*n*
Porewater NH_4^+	μmol L^{-1}	15	Clay	%	3	Leaf biomass	g DW m^{-2}	3	Leaf N	%	3
Porewater $NO_2^- + NO_3^-$	mol L^{-1}	15	Very fine silt	%	3	Rhizome biomass	g DW m^{-2}	3	Leaf P	%	3
Porewater PO_4^{3-}	μmol L^{-1}	15	Fine silt	%	3	Root biomass	g DW m^{-2}	3			
Adsorbed NH_4^+	μmol kg^{-1}	5	Medium silt	%	3	Total biomass	g DW m^{-2}	3			
Adsorbed $PO^{3-}_{4(\mathrm{Bray})}$	μmol kg^{-1}	5	Coarse silt	%	3	Leaf density	Shoots m^{-2}	3			
Adsorbed $PO^{3-}_{4(\mathrm{bicarbonate})}$	μmol kg^{-1}	5	Sand	%	3						
Carbonate	%	3	Porosity		3						
Organic matter	%	3									
Eh		5									
PH		5									

($\mu mol\ L^{-1}_{sediment}$; Udy and Dennison, 1996) to enable the molar ratios of the total sediment nutrient pool to be calculated.

2.5. Seagrass

Biomass was excavated from within $3 \times 0.25\,m^{-2}$ quadrats from each meadow. Leaves, rhizomes and roots were separated in the laboratory. Epiphytic algae were scraped from each component of the plant. Samples were oven dried at 60 °C to a constant weight. A 20% proportion of the wet biomass sample was taken as a sub-sample for shoot density measurements. Every shoot in the sub-sample was counted, and then multiplied up for the entire sample. The sub sample was dried and returned to the total biomass sample.

Dried biomass samples of leaves, rhizomes and roots were separately homogenized by milling to fine powders. Nitrogen and phosphorus were extracted using a standardized selenium Kjeldahl digest and the concentrations determined with an automatic analyser using standard techniques (Strickland and Parsons, 1972). N:P ratios were calculated using atomic weights.

The nutrient state of a meadow was also characterized by $gN_{seagrass}\,m^{-2}$ and $gP_{seagrass}\,m^{-2}$ calculated as % plant tissue nutrient × biomass ($g\,DW\,m^{-2}$) = g $Nutrient_{seagrass}\,m^{-2}$. This measure was then converted to $\mu mol\ L^{-1}_{sediment}$ to enable comparisons between the plant and sediment nutrient pools.

3. Results

3.1. Sediment characteristics

3.1.1. Nutrient related parameters

Sediment pH ranged from alkaline (9.0) at Geoffrey Bay to slightly acidic (6.8) at Horseshoe Bay. Sediments were oxidized with Eh values ranging from 81.33 mV at Picnic Bay to 180.33 mV at Horseshoe Bay. Percent carbonate matter ranged from 1.58% at Ellie Point to 75.46% at Geoffrey Bay. Percent organic content in sediment cores ranged from 0.51% at Port Dennison to 2.48% at Windy Point. Porosity measures varied from a low of 0.29 at Picnic Bay (coarse sand) to a high of 0.62 at Meunga Creek (clay-dominated sediment).

3.1.2. Porewater nutrients

Porewater nutrient samples varied immensely between locations (Table 2). Horseshoe Bay had the highest mean porewater NH_4^+ level (144.43 μM), while the lowest (1.84 μM) was recorded at Ellie Point. The highest $NO_2^- + NO_3^-$ value was at Long Bay (4.40 μM); the lowest at Horseshoe Bay and Cape Pallarenda (0.02 μM). Long Bay recorded the lowest porewater phosphate level (0.51 μM), while Meunga Creek recorded the highest (6.08 μM).

3.1.3. Adsorbed nutrients

The different methods used for extracting adsorbed PO_4^{3-} gave varying results (Table 2). Meunga Creek recorded the highest adsorbed PO_4^{3-} values (820 μmol kg^{-1} $PO^{3-}_{4(Bray)}$ and 471.21 μmol kg^{-1} $PO^{3-}_{4(bicarbonate)}$). Geoffrey Bay had the lowest $PO^{3-}_{4(Bray)}$ measure (11.40 μmol kg^{-1} $PO^{3-}_{4(Bray)}$) reflecting the deficiencies in this extraction technique in a high carbonate environment. The lowest recording of PO_4^{3-} for the bicarbonate extraction method was at Port Dennison (66.44 μmol kg^{-1} $PO^{3-}_{4(bicarbonate)}$). The differing values of PO_4^{3-} obtained from the same sediment samples highlight the importance of reporting the specific extraction technique used and identifies the extraction technique which is the better indicator of bioavailable PO_4^{3-} at a particular location.

The ratio of adsorbed:porewater nutrients denotes the size and contribution of each nutrient pool. The adsorbed phase made the largest contribution to the NH_4^+ pool, with NH_4^+ ratios ranging from 5.7 to 1004 (Table 2). Phosphate was also largely present in the adsorbed phase, with ratios from 23 to 1418 (Table 2).

3.1.4. Molar ratios

The N:P ratios of porewaters ranged from 2:1 (Ellie Point), indicating N limitation, to 295:1 (Horseshoe Bay), indicating P limitation. This range of ratios suggests that nutrient limitation is location dependent and site specific. For both methods of extraction, adsorbed N:P ratios ranged from 0.2:1 to around 6:1, implying N limitation. The exception to this was Geoffrey Bay, using $PO^{3-}_{4(Bray)}$ measurements (30:1) implying P limitation, however this ratio was 0.7:1 using $PO^{3-}_{4(bicarbonate)}$ measurements. Whilst the Bray technique underestimated the amount of adsorbed PO_4^{3-}, the ratio calculated using this extraction method may be a better representation of what is actually available to the seagrass. Under alkaline conditions the bicarbonate technique extracts all the adsorbed PO_4^{3-} from the sediment (Pailles and Moody, 1995), even the portion that is not available to the plants.

3.1.5. Seagrass species—sediment nutrient associations

Different seagrass species were associated with different sediment nutrient characteristics. *Zostera capricorni* was associated with the lowest porewater nutrient concentrations, *Halodule uninervis* with the highest dissolved nitrogen content in porewaters (NH_4^+ and $NO_2^- + NO_3^-$) and *Halophila ovalis* with the highest PO_4^{3-} porewater levels (Table 2). In contrast, *Zostera capricorni* was associated with the highest adsorbed NH_4^+ and $PO^{3-}_{4(Bray)}$ levels. *Halophila ovalis* with the

Table 2
Biomass, porewater and adsorbed nutrients concentrations at locations in the central region of the Great Barrier Reef World Heritage Area (means, ±s.e. and ranges (in parentheses) are presented)[a]

Location latitude longitude dominant species—sediment type	Biomass $n = 3$ $\mathrm{g\,DW\,m^{-2}}$	Porewater $NO_2^- + NO_3^-$ $\mathrm{\mu mol\,L^{-1}}$ $n = 15$ (range)	Porewater NH_4^+ $\mathrm{\mu mol\,L^{-1}}$ $n = 15$ (range)	Porewater PO_4^{3-} $\mathrm{\mu mol\,L^{-1}}$ $n = 15$ (range)	Adsorbed NH_4^+ $\mathrm{\mu mol\,kg^{-1}}$ $n = 5$ (range)	Adsorbed $PO^{3-}_{4(\mathrm{Bray})}$ $\mathrm{\mu mol\,kg^{-1}}$ $n = 5$ (range)	Adsorbed $PO^{3-}_{4(\mathrm{bicarbonate})}$ $\mathrm{\mu mol\,kg^{-1}}$ $n = 5$ (range)	Adsorbed: Porewater[a] NH_4^+ $n = 5$ (porewater N:P)	Adsorbed: Porewater[a] $PO^{3-}_{4(\mathrm{Bray})}$ $n = 5$ (N:$P_{(\mathrm{Bray})}$)	Adsorbed: Porewater[a] $PO^{3-}_{4(\mathrm{bicarbonate})}$ $n = 5$ (N: $P_{(\mathrm{bicarbonate})}$)
Ellie Point, Cairns 16.88 °S, 145.77 °E *Zostera capricorni*—clay	252.16 ± 24.52	0.41 ± 0.13 (bd[b]–1.26)	1.84 ± 0.09 (1.34 ± 2.42)	0.84 ± 0.06 (0.45–1.19)	532.47 ± 152.66 (123.38–937.24)	353.19 ± 47.81 (268.60–526.93)	142.57 ± 12.10 (103.78–163.73)	1004.11 (1.8)	1112.47 (1.8)	374.15 (3.9)
Lugger Bay, Mission Beach 17.92 °S, 146.10 °E *Halodule uninervis*—sand	5.38 ± 2.32	0.67 ± 0.23 (0.06–3.07)	13.75 ± 2.58 (2.67–36.05)	1.57 ± 0.14 (0.83–3.17)	43.10 ± 12.51 (12.003–85.61)	147.3 ± 12.30 (117.61–179.61)	130.37 ± 11.85 (87.23–150.30)	5.66 (19)	374.15 (0.3)	350.68 (0.3)
Meunga Creek, Cardwell 18.30 °S, 146.02 °E *Halodule uninervis*	5.01 ± 0.31	3.12 ± 1.08 (0.03–15.31)	86.85 ± 7.15 (37.34 ± 127.37)	2.65 ± 0.46 (0.41–6.63)	563.11 ± 40.67 (483.89–709.32)	820.08 ± 61.85 (638.39–1026.04)	471.21 ± 64.92 (329.69–712.19)	6.97 (41.5)	416.71 (0.7)	199.98 (1.4)
Cape Pallarenda, Townsville 19.18 °S, 146.76 °E *Halodule uninervis*—sand	55.02 ± 23.80	0.04 ± 0.02 (bd–25.00)	13.54 ± 4.52 (1.44–52.89)	1.92 ± 0.29 (0.59–4.86)	77.55 ± 29.53 (30.06–193.45)	209.41 ± 44.54 (119.04–328.08)	165.07 ± 7.14 (149.81–188.51)	73.06 (2.1)	629.52 (0.2)	438.65 (0.3)
Bolger Bay, Magnetic Is. 19.16 °S, 146.80 °E *Halophila ovals*—clay	0.20 ± 0.12	0.32 ± 0.13 (bd–1.63)	59.35 ± 6.34 (23.51–98.51)	2.20 ± 0.47 (0.56–7.70)	257.72 ± 24.71 (178.64–314.75)	482.83 ± 75.81 (339.93–784.47)	328.36 ± 42.40 (207.32–426.28)	15.44 (26.54)	599.64 (0.7)	465.50 (0.9)
Picnic Bay, Magnetic Is 19.18 °S, 146.85^0 E *Halophila ovalis*—sand	28.34 ± 4.78	0.15 ± 0.06 (0.02–1.00)	8.67 ± 1.62 (2.25–26.95)	1.78 ± 0.18 (0.71–3.18)	285.67 ± 92.40 (45.60–585.14)	94.95 ± 5.95 (82.37–113.48)	134.47 ± 27.20 (92.35–239.48)	70.51 (21.2)	374.71 (3.9)	425.23 (3.7)
Geoffrey Bay, Magnetic Is 19.16 °S, 148.86 °E *Halodule uninervis*—sand	11.89 ± 0.73	0.09 ± 0.02 (0.02–0.21)	28.68 ± 4.01 (7.88–48.66)	3.15 ± 0.45 (1.77–9.07)	252.49 ± 34.65 (149.74–312.34)	17.59 ± 3.78 (5.23–26.59)	408.30 ± 32.51 (317.57–506.75)	46.34 (11.9)	22.89 (29.7)	700.65 (0.7)
Horseshoe Bay, Magnetic Is 19.12 °S, 146.86 °E *Halodule uninervis*— sand	2.92 ± 0.87	0.03 ± 0.007 (bd–0.09)	144.43 ± 25.12 (2.60–298.00)	0.69 ± 0.10 (0.34–1.54)	229.96 ± 10.27 (212.14–263.55)	124.41 ± 13.22 (90.63–164.70)	144.72–8.32 (122.42–167.96)	6.46 (294.6)	1292.92 (1.7)	1418.44 (1.6)
Long Bay, Cape Cleveland 19.22 °S, 147.02 °E *Halodule uninervis*— mud	26.86 ± 14.57	4.40 ± 1.41 (0.04–19.41)	9.47 ± 1.65 (2.87–28.44)	2.20 ± 0.88 (0.53–13.78)	736.68 ± 145.53 (300.47–1181.74)	206.05 ± 19.13 (142.90–252.60)	152.60 ± 14.68 (105.41–182.79)	314.13 (9.6)	691.77 (3.7)	430.12 (6.1)
Windy Point, Cape Upstart 19.78 °S, 147.74^0 E *Zostera capricorni*— mud	72.34 ± 3.96	0.17 ± 0.09 (bd–1.27)	2.47 ± 0.25 (0.15–4.17)	0.85 ± 0.16 (0.15–2.16)	203.11 ± 59.16 (69.86–383.08)	225.34 ± 21.78 (186.12–307.34)	240.36 ± 34.10 (145.95–357.00)	279.70 (3.5)	696.67 (1.1)	800.29 (1)
Port Dennison, Bowen 19.94 °S, 148.25 °E *Halodule uninervis*—sand	25.10 ± 5.56	0.76 ± 0.29 (bd–3.55)	6.31 ± 0.87 (1.33–14.27)	1.60 ± 0.16 (0.79–3.01)	38.64 ± 14.66 (4.85–81.84)	85.57 ± 4.46 (74.80–96.79)	66.44 ± 12.39 (32.90 ± 93.07)	20.68 (6.4)	274.64 (0.5)	165.11 (1.1)

Sample replication (n) indicates the number of independent replicate samples taken at each location.

[a] Both porewater and adsorbed units converted to $\mathrm{\mu mol\,L^{-1}_{sediment}}$.

[b] bd—below detection.

highest $PO_{4(\mathrm{bicarbonate})}^{3-}$ levels, and *Halodule uninervis* with the lowest adsorbed NH_4^+ levels (Table 2).

3.2. Seagrass

3.2.1. Biomass

Halodule uninervis was dominant at seven locations; two locations were dominated by *Zostera capricorni*, and two locations by *Halophila ovalis* (Table 2). The meadows of *Halodule uninervis* investigated in this study were typically of the narrow leaved morphology (<1 mm).

Ellie Point, Cairns, a meadow dominated by *Zostera capricorni*, had the highest seagrass biomass (252.16 g DW m^{-2}), whilst, Bolger Bay, a location dominated by *Halophila ovalis*, recorded the lowest (0.2 g DW m^{-2}) (Table 2). Cape Pallarenda recorded the highest biomass of *Halodule uninervis* (55.02 g DW m^{-2}) and had the third highest biomass of the surveyed locations. With the exception of *Zostera capricorni* at Ellie Point, Cairns, the below ground components contributed more biomass than the above ground component, as shown by the small (<1) above-ground:below-ground ratios. Rhizomes contributed more to the below ground biomass than the roots. The seagrass was patchy at four of the 11 beds surveyed indicated by the large standard errors: Lugger Bay, Cape Pallarenda, Bolger Bay and Long Bay (Table 2).

3.2.2. Leaf tissue nutrients

Seagrasses from Meunga Creek had the highest leaf nutrient content (%N and %P). Seagrasses from Ellie Point had the lowest leaf nutrient content (%N and %P). These values were not as variable as the biomass data within locations (Table 3 cf. Table 2). When values were averaged across meadows with the same dominant species, *Halodule uninervis* recorded the highest nutrient content for leaf N; leaf P was highest in *Halophila ovalis*. *Zostera capricorni* had the lowest leaf nutrients (%N and %P) (Table 3).

These patterns were driven by the nutrient concentrations available at each location. The pattern across species in relation to nutrient content (i.e. highest % leaf N for *Halodule uninervis*, highest leaf %P for *Halophila ovalis* and the lowest nutrient content (%N and %P) in *Zostera capricorni*) followed patterns in porewater levels in the rhizosphere. This result indicates that the seagrasses are obtaining their nutrients from the porewaters, however, it is the adsorbtion–desporbtion process involving the adsorbed nutrients that determines the amount of nutrients available in the porewater.

N:P ratios were also calculated for plant tissue nutrients using atomic weights. Leaf N:P ranged from 14:1 (Picnic Bay—*Halophila ovalis*) to 44:1 (Horseshoe Bay—*Halodule uninervis*). The average N:P for all species across locations was 30:1 for leaves (Table 3).

Nutrient status of the meadows varied according to the amount of biomass present rather than the tissue nutrient content. For example even though, the *Zostera* plants at Ellie Point, Cairns, had the lowest tissue nutrient content (Table 3), the meadow had the largest biomass (Table 2), consequently this meadow had the highest nutrient status of the meadows investigated.

Table 3
The nutrient values in seagrass leaves and their molar ratios obtained in this study (bold) for *Halophila ovalis* and *Halodule uninervis* were much higher than the values from the literature from this region (italics) and other regions obtained using the same techniques suggesting that these species act as nutrient sponges and that *Zostera capricorni* does not

Species	Location	%N	%P	$N:P_{\mathrm{atomic}}$	Source
Halophila ovalis	*Cockle Bay, MI, NQld, Aust*	*0.72*	*0.16*	*10:1*	Birch (1975)
Halophila ovalis	*Shelley Beach, NQld, Aust*	*1.57*	–	–	Lanyon (1991)
Halophila ovalis	Global average N = 2	0.7	0.18	9:1	From Duarte (1990)
Halophila ovalis	Swan-Canning Est, W.A., Aust	–	–	8:1	Connell and Walker (2001)
Halophila ovalis	**Picnic Bay, MI, NQld, Aust**	**2.36 ± 0.02**	**0.36 ± 0.19**	**14:1**	**This study**
Halodule uninervis[a]	*Green Island, FNQld, Aust*	*2.4*	*0.26*	*20:1*	Udy et al. (1999)
Halodule uninervis[a]	Moreton Bay, SEQld, Aust	2.4	0.24	22:1	Udy and Dennison (1997b)
Halodule uninervis	*Magnetic Island, NQld, Aust*	*0.92*	*0.15*	*14:1*	Birch (1975)
Halodule uninervis	*Townsville, NQld, Aust*	*1.91*	–	–	Lanyon (1991)
Halodule uninervis	Global average N = 15	2.4	0.19	27:1	From Duarte (1990)
Halodule uninervis	**Lugger Bay, FNQld, Aust**	**4.64 ± 0.27**	**0.28 ± 0.01**	**37:1**	**This study**
Halodule uninervis	**Meunga Ck, NQld, Aust**	**6.30 ± 0.25**	**0.45 ± 0.07**	**32:1**	**This study**
Halodule uninervis	**Cape Pallarenda, NQld, Aust**	**3.32 ± 0.08**	**0.32 ± 0.01**	**23:1**	**This study**
Halodule uninervis	**Geoffrey Bay, MI, NQld, Aust**	**4.45 ± 0.18**	**0.28 ± 0.02**	**35:1**	**This study**
Halodule uninervis	**Horseshoe Bay, MI NQld, Aust**	**4.19 ± 0.14**	**0.21 ± 0.05**	**44:1**	**This study**
Halodule uninervis	**Long Bay, NQld, Aust**	**3.47**	**0.23**	**33:1**	**This study**
Halodule uninervis	**Port Dennison, NQld, Aust**	**3.02 ± 0.46**	**0.18 ± 0.04**	**38:1**	**This study**
Zostera capricorni[a]	Global average N = 7	1.5	0.26	13:1	From Duarte (1990)
Zostera capricorni[a]	Moreton Bay, SEQld, Aust	1.6	0.2	18:1	Udy and Dennison (1997b)
Zostera capricorni	**Ellie Pt, FNQld, Aust**	**1.73 ± 0.23**	**0.18 ± 0.02**	**22:1**	**This study**
Zostera capricorni	**Windy Pt, NQld, Aust**	**1.8 ± 0.17**	**0.18 ± 0.03**	**24:1**	**This study**

[a] Ambient values from fertilization experiments.

Table 4
A comparison of N and P nutrient status ratios between vegetated and adjacent unvegetated areas, with a within bed comparison of plant nutrients and sediment nutrient ratios for the subset of the locations studied for which such information in available

Location species	Total nutrient N pool veg:unveg	Plant N:sediment N	Total nutrient $P_{(Bray)}$ pool veg:unveg	Plant P: sediment $P_{(Bray)}$	Total nutrient $P_{(bicarb)}$ pool veg:unveg	Plant P: sediment $P_{(bicarb)}$
Ellie Point, Cairns *Zostera capricorni*	71.4	14.2	10.3	8.7	15.3	21.8
Lugger Bay, Mission Beach *Halodule uninervis*	8.3	8.2	1.7	0.7	1.6	0.7
Meunga Creek, Cardwell *Halodule uninervis*	4.3	1.5	1.7	0.3	1.5	0.7
Bolger Bay, Magnetic Island *Halophila ovalis*	1.7	0.2	1.0	0.0	1.1	0.1
Geoffrey Bay, Magnetic Island *Halodule uninervis*	7.3	3.0	12.8	12.9	1.5	0.5
Horseshoe Bay, Magnetic Island *Halodule uninervis*	2.0	0.7	1.5	0.2	1.0	0.2
Windy Point, Cape Upstart *Zostera capricorni*	29.3	13.1	6.4	5.0	4.0	4.3
Port Dennison, Bowen *Halodule uninervis*	10.1	28.6	3.2	3.3	2.6	5.3

All seagrass meadows recorded higher total nutrient states than adjacent unvegetated sites (Table 4). The plant nutrient pool was only greater than the sediment nutrient pool within a meadow, when the seagrass biomass was high (Table 4).

4. Discussion

This study provided a general overview of conditions and nutrient limitation in intertidal seagrass beds for the central region of the Great Barrier Reef World Heritage Area. The nutrient levels reported here are within the range of levels reported elsewhere (Mellors, 2003). These measurements were a snapshot of the nutrient status for a subset of seagrass beds in this region, taken at a time when seagrasses were not actively growing. As such, they represent a static measurement, and do not indicate the nutrient dynamics occurring within this region.

From a global perspective, pore water and biomass values for these meadows were relatively low (Mellors, 2003). In contrast, adsorbed nutrient levels were high (Table 2) (cf. Udy and Dennison, 1997a,b; Udy et al., 1999) as were the tissue nutrient contents for *Halodule uninervis* and *Halophila ovalis* (Table 3). These observations, combined with the low suspended and particulate nutrients recorded along this coastline (Furnas, 2003), suggest that the nutrients in the coastal shallow seagrass environments of this region are bound up in the sediments and biome rather than free in the water column. This result accords with the conclusions of another detailed study of a structurally small seagrass, *Halophila ovalis* (Hillman et al., 1995), and indicates that such seagrass meadows represent a significant bio-sink for nutrients. Despite these generic conclusions, variability between locations was the most significant outcome from this study. The geography and environmental history of each location was the most important influence on the presence, distribution and abundance of intertidal seagrasses in the central region of the Great Barrier Reef World Heritage Area.

The importance of location indicates the significance of local site history. The geographic setting of a location dictates its sediment regime, while the frequency of disturbance dictates the structure of the meadow. The factors that affect the sediment regime at each location are: (a) distance from major rivers, (b) protection from south-easterly trades winds, (c) frequency and magnitude of resuspension, and (d) sediment particle sorting. In turn, differences in sediment mineralogy and grain size influence the nutrient regime at specific locations. For example, across the 11 locations surveyed, sediments with high clay content tended to have a higher adsorbed nutrient pool compared with locations with coarser sediments (Table 2). The importance of location is supported by comparison of sediment structure and sediment nutrient pools between adjacent seagrass-vegetated and unvegetated areas. Mellors et al. (2002) found that when these parameters were examined in isolation from the nutrients bound up in the seagrass, there was no significant difference between areas but that differences in sediment structure and sediment nutrient pool were driven by differences in 'location' regardless of the presence or abundance of seagrass.

Comparison of total nutrient status across these locations revealed an interaction between meadow biomass and total sediment nutrient concentrations. This result was evident when vegetated (combined plant and sediment nutrient pool) and unvegetated (sediment nutrient pool where no plants were growing) areas were compared (Table 4). The two locations that supported relatively higher seagrass biomasses had a greater total nutrient status than adjacent unvegetated areas (e.g. Ellie Point and Windy Point; Table 4). Even those meadows that support smaller biomasses of seagrass (e.g. Bolger Bay, Horseshoe Bay, Table 4), recorded ratios of total nutrient status greater than one indicating larger total nutrient pools present in vegetated sites as opposed to unvegetated sites. However, between meadow comparisons indicate that it is only in those meadows supporting large seagrass biomass that the majority of the total nutrient pool is in the biome (Table 4).

Although this result is intuitive, it highlights the differences in nutrient status between locations and species in meadows of relatively high biomass with those of low biomass.

Seagrass tissue nutrients (%N and %P) represent an integration of nutrient availability and uptake at a site (Mengel and Kirkby, 1987; Fourqurean et al., 1992). Consequently, comparisons with historical data may provide an indication of water quality trends. Tissue nutrient data from this study were compared with values from published data collected 10 (Lanyon, 1991) and 26 (Birch, 1975) years previous, from the same geographic area, at the same time of year, using the same species of seagrass. This comparison suggests that tissue nutrients of *Halophila ovalis* in the central Great Barrier Reef have increased over this 20+ year period concomitant with the increase in fertilizer use in the adjacent Burdekin River catchment over the same period (Fig. 1) and may be preliminary evidence of an increase in nutrients to the region (Mellors, 2003). Nonetheless, the winter experimental enhancement data of Mellors (2003) (Fig. 1d) indicates that *Halophila ovalis* at the study site still had the capacity to further increase nutrient tissue content. Further research is needed to elucidate whether *Halophila ovalis* is a potential bio-indicator of increased nutrient availability.

This study presented information on the relationship between seagrass presence, abundance, nutrient state, sediment nutrients and sediment structure. These relationships were primarily explained by differences in location, (i.e. the geographic setting of the meadow and its adjacent catchment, the disturbance regime at that location) and to some extent the species present at that location (i.e. function and form of structurally small seagrass cf. structurally large seagrass). Hence regional-scale management plans for intertidal tropical seagrasses may be inadequate. Management plans for specific locations developed with a common conceptual framework should lead to a better correspondence between the environmental influences on the system and the management unit.

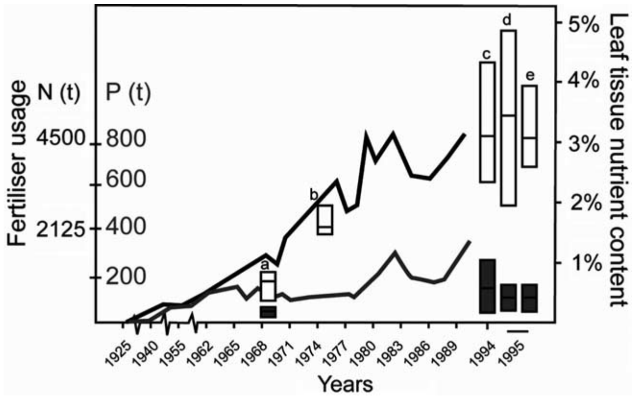

Fig. 1. Values of % leaf N (white boxes) and % leaf P (dark boxes) for plants of *Halophila ovalis* from Cleveland Bay North Queensland, spanning 26 years from a variety of literature sources: (a) sampled winter 1969 (Birch, 1975); (b) sampled winter 1984 (Lanyon, 1991); (c) sampled winter 1994, this study; (d) nutrient enhancement data, winter 1995 (Mellors, 2003), and (e) nutrient enhancement data, summer, 1995 (Mellors, 2003). Each box represents the range of leaf tissue nutrient concentrations obtained from the relevant study, the cross bar represents the average. Background lines represent the trends in fertilizer application in the Burdekin River catchment since 1925 (adapted from data in Pulsford, 1996), for both nitrogen (N, dark line) and phosphorus fertilizer (P, light line).

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