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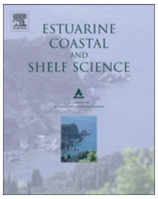

Sedimentation within and among mangrove forests along a gradient of geomorphological settings

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ABSTRACT

Coastal wetlands provide important ecological services to the coastal zone, one of which is sediment retention. In this study we investigated sediment retention across a range of geomorphological settings and across vegetation zones comprising coastal wetlands. We selected six coastal wetlands dominated by mangroves over a gradient from riverine to tidal settings in Southeast Queensland, Australia. Each site was comprised of three distinct vegetation communities distributed as parallel zones to the coast line: seaward fringe mangroves, landward scrub mangroves and saltmarsh/ cyanobacteria mat of the high intertidal zone. We measured suspended sediment retention and sedimentation rates. Additionally, in order to assess the origin of sediment transported and deposited in the mangroves, glomalin, a novel terrestrial soil carbon tracer, was used. Our results show a mean average sedimentation of 0.64 ± 0.01 mg cm^{-2} spring tide^{-1}, which was variable within sites, regardless of geomorphological setting. However, geomorphological setting influenced spatial patterns of sediment deposition. Riverine mangroves had a more homogeneous distribution of sediments across the intertidal zone than tidal mangroves, where most sedimentation occurred in the fringe zone. Overall, the fringe zone retained the majority of sediment entering the coastal wetland during a tidal cycle with 0.90 ± 0.22 mg cm^{-2} spring tide^{-1}, accounting for 52.5 ± 12.5% of the total sedimentation. The presence of glomalin in suspended sediments, and thus the relative importance of terrigenous sediment, was strongly influenced by geomorphological setting, with riverine mangroves receiving more glomalin in suspended solids than tidal mangroves. Glomalin was also differentially deposited within the vegetation zones at different geomorphological settings: primarily at the fringe zone of tidal mangroves and within the scrub zone of riverine mangroves. The differences we observed in the spatial distribution of sedimentation and the difference in the origin of the sediment deposited in riverine and tidal mangroves are likely to have an impact on ecological processes.

1. Introduction

Coastal wetlands are comprised of various vegetation communities such as mangroves, saltmarsh and cyanobacteria mats. These vegetation communities are often distributed as parallel zones to the coast line, responding to an elevation gradient, which determines tidal flushing frequency (Robertson and Alongi, 1992). Fringe mangroves occupy the lowest elevations, where they are frequently flooded by neap and spring tides, while scrub mangroves occupy mid elevations, where they are flooded only during spring tides (e.g. Furukawa et al., 1997). Saltmarsh and cyanobacteria mat communities occupy the highest elevation zone, which is rarely flooded by tides. Although, mangroves, saltmarsh and cyanobacteria mat communities coexist in some regions, mangroves are the dominant vegetation community in tropical and subtropical coastal wetlands (Kangas and Lugo, 1990).

Mangroves are generally known for being depositional sites for sediment and associated carbon and nutrients (Eyre, 1993; Furukawa and Wolanski, 1996). Thereby, mangroves aid in the protection of adjacent seagrass and coral reef ecosystems from the negative impacts of nutrient enrichment and sedimentation (Ewel et al., 1998; Valiela and Cole, 2002). The role of mangroves in enhancing sedimentation, which often results in expansion of mangrove habitats, is well known. Above-ground root systems and stems enhance sediment deposition that further promotes mangrove growth and expansion (Furukawa and Wolanski, 1996). The accretion capacity of

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mangroves is the result of a complex root system that increases friction and reduces tidal current velocities (Wolanski et al., 1992). Mangrove roots also generate turbulence that results in fine sediment remaining in suspension when entering the forest with the flood tide (Shahbudin et al., 1999). As the tide progresses through the forest, the current slows. During slack high tide, as current velocities approach zero, flocs are deposited (Furukawa et al., 1997). While settling, the flocculated material increases in size by an order of magnitude and as a result, ebb tide currents are often too slow to resuspend them (Furukawa and Wolanski, 1996). These processes result in sedimentation and accretion that can be extremely rapid in some settings (e.g. vertical accretion of 4 cm yr^{-1}; Alongi et al., 2005).

Spatial patterns of sedimentation within coastal wetlands are variable. Some sites experience higher sedimentation rates at the fringe zone relative to areas farther landward (Furukawa and Wolanski, 1996). This sedimentation pattern generally follows the exponential decrease of suspended sediment concentration during tidal inundation, which decreases from the seaward fringe to the scrub zone (Furukawa and Wolanski, 1996). However, others sites have shown different spatial patterns. For example, at the Red River in Vietnam, most of the sediment that enters with the high tide is retained not in the fringe zone, but rather on the riverbank mudflats lying seaward of the mangroves (Van Santen et al., 2007).

Sedimentation patterns are likely to be influenced by the geomorphological setting in which a mangrove community grows. Geomorphological classifications are based on the principle that the physical forces acting on a shoreline will not only shape it, but will continuously influence processes occurring within that shoreline. Thom (1982) classified the mangroves according to their geomorphological setting as river dominated, tide-dominated, wave-dominated, composite river-wave-dominated or as drowned bedrock valley. Within Thom's five settings (Thom, 1982), the greatest contrast is between riverine mangroves, which are dominated by unidirectional flows, and tidal mangroves, characterized by bidirectional flows (Wolanski et al., 1992). In this scheme, riverine mangroves are characterized by high nutrient influx and strong outwelling (Woodroffe, 1992). In contrast, tidal mangroves have bidirectional fluxes of water and suspended material often with little net export and even with overall import of materials (Woodroffe, 1992). Based on this theoretical analysis, it is expected that tidal mangroves will have higher suspended sediment retention and sedimentation rates than riverine mangroves.

Geomorphological classifications are often used to explain ecological differences between mangrove forests (e.g. Twilley et al., 1998; Ryan et al., 2003). Geomorphological classifications of mangroves also underlie theoretical models estimating the magnitude of mangrove ecological services (Ewel et al., 1998) and the effects of climate change on the coastal zone (Nicholls et al., 1999; Ryan et al., 2003). However, the role of the geomorphological setting in determining ecological processes within mangroves, such as sediment retention, has not yet been quantitatively assessed.

Sediment deposited in mangroves originates from a range of sources. Allochthonous sediment arrives from external sources, either terrestrial or oceanic, while autochthonous sediment is resuspended. Determining the source of sediments deposited within mangroves is required to quantify the mangrove net retention capacity of terrestrial-derived materials as well as to understand the linkages between terrestrial and marine ecosystems. However, the ability to trace the origin of allochthonous or autochthonous sediment has proven challenging.

Techniques employed to trace the origin of deposited sediment include a range of chemical and physical markers. Although many of these techniques are extremely powerful, especially when used with a multiple tracer approach (Raymond and Bauer, 2001), replication is often limited (Hedges et al., 1986). Despite best efforts, some of the multiple tracer studies lead to difficulty in interpretation of results (Wheatcroft et al., 1996), variability of performance of markers within sites (Prahl et al., 1994) and overlapping of signals (Rodelli et al., 1984). Therefore, a reliable, universal, simple and inexpensive tracer of terrigenous origin is desirable.

Glomalin is a glycoprotein produced by symbiotic arbuscular mycorrhizal fungi (Wright and Upadhyaya, 1998). Arbuscular mycorrhizal fungi are associated with the roots of most terrestrial plants, but not with mangrove roots, except in conditions of low salinity (Sengupta and Chaudhuri, 2002). Glomalin is very resistant to decomposition, having a half-life of 7–42 years (Rillig et al., 2001). It accumulates in soils to form a significant proportion of soil carbon (approximately 5% of soil carbon) (Rillig et al., 2001; Lovelock et al., 2004). Variation in the glomalin concentration in soils depends on a range of environmental and plant factors. Soil glomalin concentration is significantly correlated with the organic carbon content in soils, fertility, cultivation regime and plant community productivity (Wright and Upadhyaya, 1996; Lovelock et al., 2004; Treseder and Turner, 2007). Despite this variation, the unusual characteristics of glomalin (high chemical stability and its known terrestrial origin) make it a promising candidate as a terrigenous tracer. Glomalin has been successfully used in the study of development of soils in accreting river systems (Harner et al., 2004). In this study, we use glomalin to investigate patterns in terrestrial soil carbon deposition in coastal wetlands.

To examine variation in sediment retention and sedimentation in mangroves over a range of geomorphological settings and to determine the patterns of glomalin deposition, we analysed a number of sites ranging from riverine to tidal in Southeast Queensland. We measured suspended sediment retention and sedimentation rates within different zones of the wetland and compared the amount of glomalin found in suspended and deposited sediments in each geomorphological setting and vegetation zone. In this study, we also used the proportion of reactive glomalin as an complementary information, helping us to discern between the "younger" deposited sediment recently derived from terrestrial origin, from the "older" deposited sediment of marine origin and/or resuspended material. Our expectation was that riverine mangroves would have lower sedimentation rates and sediment retention than tidal mangroves, and that geomorphological setting influence the spatial distribution of sedimentation within the mangroves. Furthermore, we expected riverine mangroves to have higher glomalin concentrations and more reactive glomalin in the suspended and deposited sediment than tidal mangroves, therefore, providing a signature of a recent and strong terrestrial influence.

2. Methodology

2.1. Study sites

The sites chosen for this study are located in the Southeast Queensland biogeographic region. The estuaries sampled are situated within Moreton Bay, with the exception of the Mooloolah River, which lies 40 km north of the Bay (Fig. 1). The tidal regime with the region is semidiurnal and the tidal range is low (<2 m, Australian Estuarine Database Survey, 1998). The region is classified as subtropical, experiencing moderate temperatures all year round. The mean annual maximum temperature of the area is 25.4 °C and the minimum is 15.7 °C (Australian Bureau of Meteorology: http://www.bom.gov.au/index.shtml. Brisbane Airport Station; 1951–2000). The climate is characterized by a dry winter with a total rainfall of 64 mm (June to August) and a hot summer with a total rainfall of 597 mm (December to February). During the summer, the

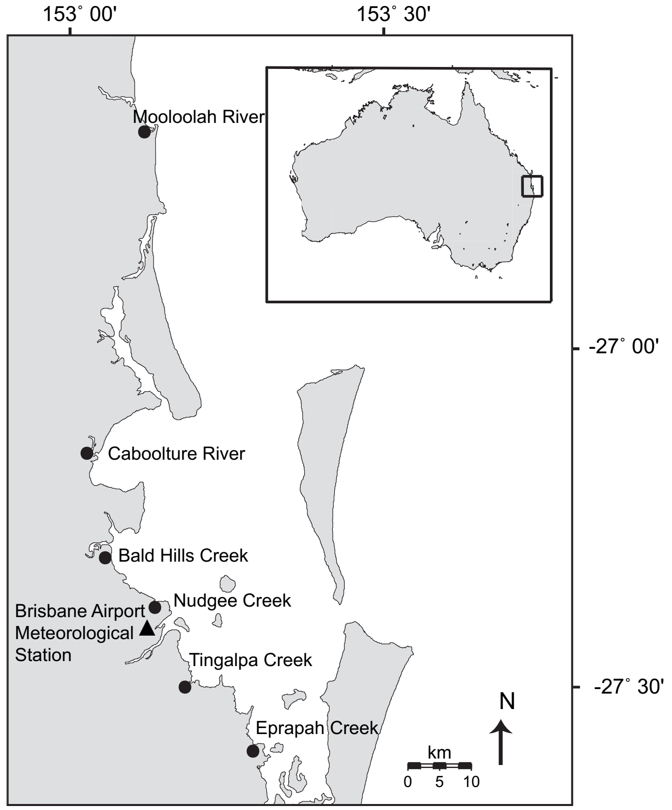

Fig. 1. Study sites in Southeast Queensland and location of the Brisbane Airport Meteorological Station.

prevailing winds for this region are from the northeast and southwest (Abal and Dennison, 1999). The average total annual rainfall is 1186 mm (Australian Bureau of Meteorology for Brisbane Airport Station, 1951–2000). Sampling was conducted the summer months between January and March 2007. During this period, the region received a total 249 mm of rain, which was low compared to historical data (Australian Bureau of Meteorology for Brisbane Airport Station, 2008).

The shoreline of Southeast Queensland has extensive mangrove areas (approximately 533 km^2) with *Avicennia marina* being the dominant species in most communities (Duke, 2006). Mangroves grow in large areas in the southern part of Moreton Bay and they extend up the rivers and creeks of the area often forming extensive riparian zones (Pantus and Dennison, 2005). Terrestrial vegetation in Southeast Queensland is dominated by Eucalyptus-Lophostemon-Syncarpia tall open forests, eucalypt open forests and woodlands (Australian Natural Resource Atlas, 2002).

2.2. Materials and methods

Six mangroves sites located in six estuaries in Southeast Queensland were chosen for the study. The estuaries comprised a gradient from riverine to tidal. The selected estuaries have all been affected by land-use change. The estuaries were classified according to their geomorphological setting based on the Australian Estuarine Database classification (Ozcoasts, Australian Online Coastal Information: http://www.ozcoasts.org.au/) (Table 1). In order to obtain a numerical value of the geomorphological classification, we calculated a principal component analysis (PCA), which included the following geomorphological characteristics of each site: salinity (measured using the Practical Salinity Scale), catchment size (km^2), distance of our sampling site to the sea (m) and size of the entrance section (m^2). Data included for the PCA was directly measured, such as salinity and distance to the sea, or obtained from the Australian Estuarine Database (Ozcoasts, Australia). The two main factors responsible for the variability of the sites obtained from the PCA (Factors 1 and 2) were used for further analysis of the data. Factor 1 represented the percentage of variation of each site explained by riverine and tidal forces and it is mainly a result of variation in catchment area, distance to sea and size of the estuary entrance section (Table 2). Factor 2, represents the variation in salinity within sites and it can be used as an indication of the connection between the site and the adjacent ocean (Table 2). Factor 1 and 2 values were numerically transformed to arbitrary numbers from 1 to 8 in order to facilitate the visualization of the index. In general, Factor 1 separated our sites in two groups, the sites dominated by river forces (Mooloolah River, Caboolture River and Tingalpa Creek) and the sites dominated by tidal forces (Bald Hills Creek, Eprapah Creek and Nudgee Creek). Henceforth we will refer to them as "riverine" and "tidal" mangroves, respectively (Table 1, 2).

2.2.1. Total suspended solids

In order to assess the amount of sediment available for sedimentation, and to calculate the amount of sediment retained in mangroves (Thomas and Ridd, 2004), total suspended solids (TSS) concentrations were measured at each site. In the field, 100 ml of water was taken from 30 cm below the water surface in plastic bottles. We chose one depth for sampling based on results from a pilot study where we compared TSS concentration at different depths in the water column (20 cm below the water surface and 20 cm above the sediment). In this pilot study we found that TSS concentrations were homogeneously distributed in depth (TSS concentration difference between depths <10%), indicating a well-mixed water column. The water sample was filtered through a pre-weighed 47 mm glass microfibre GF/C Whatman filter (1.2 µm pore size) (Pejrup, 1988). Samples were taken in three points within each vegetation zone (e.g. Furukawa et al., 1997) during flood and ebb tide during three tidal cycles. The zones were: (1) the fringe

Table 1
Geomorphological classification and characteristics of the study sites.

Site	Condition	Classification	Subclassification	Location	Salinity	Catchment area (km^2)	Distance to sea (km)	Entrance section area (m^2)
Mooloolah River	Modified	River dominated	Wave-dominated delta	Ocean	34.8	215.0	5.0	1980
Caboolture River	Modified	River dominated	Tide-dominated delta	Bay	18.9	354.0	3.0	1240
Tingalpa Creek	Extensively modified	River dominated	Tide-dominated delta	Bay	19.1	150.0	3.1	858
Bald Hills Creek	Extensively modified	Tide dominated	Tide-dominated estuary	Bay	38.1	13.5	2.3	1008
Nudgee Creek	Extensively modified	Tide dominated	Tidal flat/creek	Bay	33.5	1.7	1.6	162
Eprapah Creek	Modified	Tide dominated	Tidal flat/creek	Bay	35.4	31.0	0.4	100

Table 2
Contribution of parameters describing the 6 sites in the study to the principal factors of variability (Factor 1 and 2) obtained from a PCA. Each factor represents the percentage of variability that is explained by each parameter (salinity, entrance section, distance to the sea and catchment area). The relative value is a numerical transformation of each factor in order to facilitate their visualization. The resulting number was used for further analysis of the data.

	Factor 1	%	Factor 2	%	Relative value Factor 1	Relative value Factor 2
Salinity	0.57	11.8	−0.80	59.2		
Entrance section (m^2)	−0.89	28.9	−0.45	18.6		
Distance to the sea (m)	−0.90	29.5	−0.38	13.2		
Catchment area (km^2)	−0.90	29.9	0.31	9.0		
Mooloolah River	−1.83		−1.47		1.0	3.7
Caboolture River	−1.74		1.16		1.1	1.0
Tingalpa Creek	−0.68		0.91		2.2	1.3
Bald Hills Creek	0.77		−0.98		3.6	3.2
Nudgee Creek	1.53		0.09		4.4	2.1
Eprapah Creek	1.96		0.29		4.8	1.9

mangrove zone, which was the forest adjacent to the creek/river and usually the tallest forest in the coastal wetland; (2) the scrub mangrove zone, which is landward of the fringe mangroves and comprises smaller trees (<2 m in height); and (3) the saltmarsh/cyanobacteria mat zone, located landward of the scrub mangroves (Fig. 2). In the laboratory, filters were oven dried at 60 °C and re-weighed. The percentage of TSS retention for each site was calculated by a modified method of Furukawa and Wolanski (1996).

$$TSS\ retention\ (\%) = \frac{\left(TSS\ flood\ \left(\mathrm{mg}\ L^{-1}\right) - TSS\ ebb\ \left(\mathrm{mg}\ L^{-1}\right)\right)}{TSS\ flood\ \left(\mathrm{mg}\ L^{-1}\right)} \times 100 \tag{1}$$

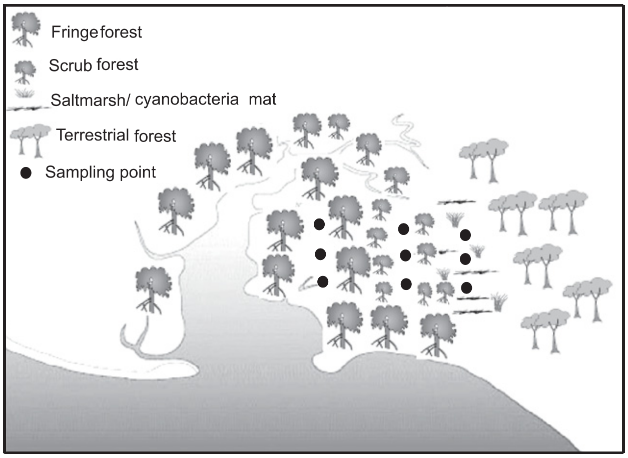

Fig. 2. Diagram representing the three sampling points for each zone of a coastal wetland dominated by mangroves: fringe mangroves, scrub mangroves and saltmarsh/cyanobacteria mat zone.

2.2.2. Sedimentation

The sampling within each location was done on the depositional side of the river (riverine mangroves) or tidal creek (tidal mangroves), i.e. on the meander bend, which is the area that presented the most developed mangrove forests. Sediment traps consisted of pre-weighed 9 cm Whatman qualitative filters placed in the ground (Reed, 1989) over Petri dish lids held to the sediment by hooks. The Petri dish lids were 0.8 cm in height and 9 cm in width with a small base:height ratio of 0.1, which has been associated with a decrease in the risk of overestimation of sediment trapping and an increase in the probability of measuring resuspended material under turbulent conditions (Hargrave and Burns, 1979). The sediment traps were deployed at times when tides were high enough to submerge the three vegetation zones. Based on field observations and tide tables we calculate this threshold as spring tides higher than 2.2 m in all sites except Mooloolah River, which was completely submerged at tides higher than 1.7 m. Sampling was conducted in tides of amplitude 2.22 m to 2.62 m (1.8 m to 1.83 m in Mooloolah River) (tide heights are meters above Prediction Datum, Australian Bureau of Meteorology). Traps were deployed at low tide in groups of five replicates within three transects crossing through the three vegetation zones used for TSS sampling (see above). Traps were set up in the middle of each intertidal zone (Fig. 2). In total, 45 sediment traps were used per site and were left for 7–10 tidal cycles. Special care was taken when setting and retrieving the traps so as not to disturb the adjacent sediment. Sediment traps that appeared disturbed by crabs or other organism were discarded (7 out of 280 traps). The traps were retrieved during low tide and transported within the Petri dish covered with a lid. Sediment traps were dried at 60 °C and weighed. All the sediment captured inside the Petri dish was included in the calculation. The weight of the sediment was corrected for salt weight by weighing sediment traps before and after being submerged in distilled water and oven dried at 60 °C. Sedimentation rates per vegetation zone were calculated per tidal cycle by subtracting the filter weight before (t_0) to the weight after deployment in the field (t_1). In order to homogenize the sedimentation rates for all the sites, the rates were divided by the number of tides the sediment traps were submerged (equation (2)).

$$Sedimentation\ rate\ \left(mg\ cm^{-2}\ spring\ tide^{-1}\right) = \frac{filter\ weight\ t_1\ (mg) - filter\ weight\ t_0\ (mg)}{filter\ area\ \left(cm^2\right) \times \text{number}\ of\ spring\ tides} \tag{2}$$

Finally, in order to compare the proportion of sediment retained by each vegetation zone, we calculated the coefficient of variation (% CV) of sedimentation rates across the coastal wetland and a sedimentation ratio (equation (3)).

$$Sedimentation\ ratio = \frac{Sedimentation\ rate\ at\ zone\ 1\ \left(mg\ cm^{-2}\ spring\ tide^{-1}\right)}{\left(Sedimentation\ rate\ at\ zone\ 1 + zone\ 2 + zone\ 3\right)\left(mg\ cm^{-2}\ spring\ tide^{-1}\right)} \tag{3}$$

Additional hydrological information (currents, tidal height and salinity) were measured in the creeks and rivers in front of the fringe mangrove zone during each sampling campaign. Tidal currents were measured using small buoyant objects, with a density such as to float just below the surface, enough to be affected by currents but not by wind. Tidal height was measured using water-soluble coloured ribbons (English et al., 1997) and salinity was measured with a hand held refractometer (model 300011 w/ATC, SPER Scientific, Scottsdale, USA). From this information we could broadly define the hydrological characteristics of the sites. The sites studied have asymmetrical tidal cycles, with shorter and faster ebb tides compared to flood tides. Furthermore, we calculated that during high tide (tides > 2.2 m), the depth of the water in the fringe zone ranged from 0.7 to 1.5 m.

2.2.3. *Terrestrial carbon tracer: analysis of glomalin*

We used glomalin as a proxy of terrestrial-derived carbon (C) transported and deposited within coastal wetlands. From both the TSS retained in the filters and from the sediment deposited in the traps, glomalin was extracted and quantified using the method described in Wright (2000). Filters were cut and submerged in extractants. For the sediment traps extraction of 1–3 filters were sufficient to obtain 0.5–1 g of sediment. TSS retained in the filters and sediment traps set in the saltmarsh/cyanobacteria mat sites did not collect enough sediment to carry out the extraction. Two extractions were done to obtain two different glomalin pools: Bradford reactive soil protein (BRSP) and Immunoreactive soil protein (IRSP). For the first pool (BRSP), samples were extracted in sodium pyrophosphate, pH 9 in the autoclave for 1 h at 120 °C. Multiple extractions were done (2–3) until supernatant was clear. For the second pool (IRSP), filters were extracted in sodium citrate, pH 8, for 30 min at 120 °C. Samples were centrifuged for 10 min at 3220 × *g* between and after extractions. BRSP was calculated from the first extraction using a Bradford test with bovine serum albumin (BSA) as a concentration standard. The BRSP pool has shown some cross-reactivity with high artificially leaf protein additions (Rosier et al., 2006) and with polyphenols (Whiffen et al., 2006; Schindler et al., 2007). Based on the protein concentration obtained with the Bradford, an indirect enzyme-linked immunosorbent assay (ELISA) was done on the second extraction. The ELISA was conducted using a monoclonal antibody (MAb32B11) developed against spores of arbuscular mycorrhizal fungi (Wright and Upadhyaya, 1996). A sample from a saltmarsh site with a known high concentration of IRSP was used as a standard. Results are presented as milligrams of IRSP per gram of sediment; henceforth they will be referred as "glomalin" (mg g^{-1}). The proportion of the IRSP to BRSP has been shown to decline over time as the antibody reactive site is altered with decomposition, thus providing some qualitative indication of the time since the glomalin was produced by the mycorrhizal fungi (Wright et al., 1996; Lovelock et al., 2004). In this study, we use the ratio between IRSP and BRSP as a measure of the percentage of immunoreactivity, and henceforth it will be referred as " immunoreactive glomalin" (%).

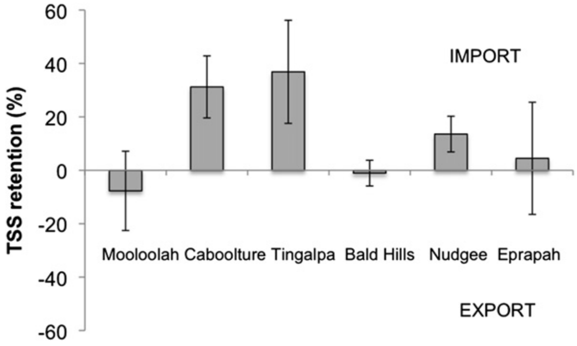

Fig. 3. Total suspended solids retention (%) at six sites in Southeast Queensland ranging from riverine to tidal. Total suspended solids retention (TSS) was calculated as the mean difference of TSS in the flood compared to the ebb tide for three tidal cycles at each site.

2.2.4. *Data analysis*

Multifactorial analysis of variance (ANOVA) was used to test for differences in TSS, sedimentation and glomalin over different vegetation zones and among riverine and tidal mangroves. Sedimentation data were logarithmically transformed (log + 1) prior to analysis in order to meet ANOVA requirements for homogeneity of variances. Linear regression was used to determine the proportion of the variation in sedimentation and glomalin that was explained by the factors of variability obtained from the PCA (see above). Analyses were performed using the statistical computing package STATISTICA (version 8, Tulsa, OK, USA) and Sigma Plot (Systat Software, CA, USA).

3. Results

3.1. *Total suspended solids (TSS)*

The average TSS concentration in the estuaries sampled was 117.6 ± 6.2 mg L^{-1} (mean ± standard error). The site with the highest TSS concentration was Nudgee Creek (134.4 ± 21.8 mg L^{-1}) and that with the lowest concentration was Mooloolah River (90.71 ± 14.8 mg L^{-1}; Table 3).

Exchange of TSS (calculated using the difference between TSS concentration in flood versus ebb tide at the fringe forest) was variable and ranged from an export of −7.7% at Mooloolah River to retention of 36.9% at Tingalpa Creek (Table 3, Fig. 3). Retention of TSS was observed at four of the six sites. Mangroves at Caboolture River, Tingalpa Creek, Nudgee Creek and Eprapah Creek imported TSS, while mangroves at Bald Hills Creek and Mooloolah River exported TSS. We did not find a relationship between sediment retention and geomorphological setting (Fig. 3).

Table 3
Total suspended solids (TSS) (mg L^{-1}) entering the mangrove forest during flood tide, TSS exchange (%) and sedimentation rate (mg cm^{-2} spring $tide^{-1}$) in six mangrove sites in Southeast Queensland. Values are the means and standard errors of data from three tidal cycles for TSS concentration, and TSS retention and for five sediment traps in three sampling points at three zones (fringe, scrub and saltmarsh/cyanobacteria mat) for sedimentation rates. Positive TSS exchange stands for import and negative values for export.

	Total suspended solids		Sedimentation rate (mg cm^{-2} spring $tide^{-1}$)			
	TSS (mg L^{-1})	Retention (%)	Mean	Fringe mangrove	Scrub mangrove	Saltmarsh/cyanobacteria mat
Mooloolah River	90.7 ± 14.8	−7.7 ± 25.7	0.37 ± 0.03	0.32 ± 0.06	0.41 ± 0.01	0.12 ± 0.00
Caboolture River	113.0 ± 23.6	31.2 ± 20.1	0.59 ± 0.07	0.61 ± 0.11	0.53 ± 0.09	0.57 ± 0.18
Tingalpa Creek	119.2 ± 6.8	36.9 ± 33.4	0.81 ± 0.21	1.23 ± 0.53	0.86 ± 0.17	0.36 ± 0.14
Bald Hills Creek	127.4 ± 13.0	−1.1 ± 8.3	0.58 ± 0.12	0.65 ± 0.17	0.85 ± 0.22	0.23 ± 0.09
Nudgee Creek	134.4 ± 21.8	4.5 ± 11.6	0.45 ± 0.14	0.78 ± 0.36	0.27 ± 0.05	0.29 ± 0.11
Eprapah Creek	120.9 ± 10.4	4.5 ± 36.4	1.07 ± 0.28	1.83 ± 0.13	0.96 ± 0.19	0.03 ± 0.03
Mean	117 ± 6.2	14.5 ± 6.9	0.64 ± 0.01	0.90 ± 0.22	0.65 ± 0.11	0.27 ± 0.8

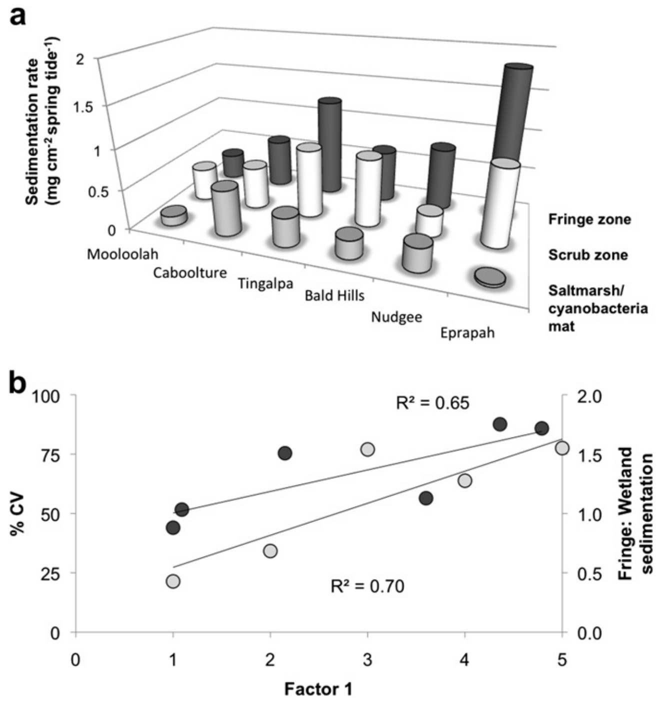

Fig. 4. (a) Sedimentation rates (mg cm^{-2} spring $tide^{-1}$) in different zones in a coastal wetland (fringe mangroves, scrub mangroves and saltmarsh/cyanobacteria mat). Values are means of three sets of five replicates within each zone. Sediment traps were deployed for between 7 and 10 tidal cycles between January and March 2007. (b) Correlation between the principal factor of variability obtained from a PCA (Factor 1, see Section 2) and the coefficient of variation (% CV) (●) and the ratio of the sedimentation rate in the fringe zone in relation to the sedimentation rate of the coastal wetland (fringe + scrub + saltmarsh/cyanobacteria mat) (○). Regression line is in the form of $y = 0.05x - 0.22$ ($R^2 = 0.70$; $F_{1,4} = 8.10$; $p < 0.05$) for % CV and in the form of $y = 0.18x + 0.82$ ($R^2 = 0.65$; $F_{1,4} = 7.38$; $p = 0.05$) for the sedimentation ratio.

Comparison of the TSS retention capacity of each vegetation zone of the wetland (fringe, scrub and saltmarsh/cyanobacteria mat) and in each tidal direction (flood and ebb) showed that at sites with TSS retention (Caboolture River, Tingalpa Creek, Nudgee Creek and Eprapah Creek), this process mainly occurred during the ebb tide within the fringe zone (average of 44% of total retention) and within the scrub zone (average of 30% of total retention).

3.2. Sedimentation

The mean sedimentation rate over all sites was 0.64 ± 0.11 mg cm^{-2} spring $tide^{-1}$. The highest rate was found in the fringe zone at Eprapah Creek (1.83 ± 0.13 mg cm^{-2} spring $tide^{-1}$) and the lowest in the saltmarsh/cyanobacteria mat zone of the same site (0.03 ± 0.03 mg cm^{-2} spring $tide^{-1}$). Overall, the site at Eprapah Creek had the highest mean sedimentation rate with 1.07 ± 0.28 mg cm^{-2} spring $tide^{-1}$ while the site at Mooloolah River had the lowest (0.37 ± 0.03 mg cm^{-2} spring $tide^{-1}$) (Table 3, Fig. 4a).

The vegetation zone with the highest mean sedimentation rate was the fringe zone with 9.0 ± 0.22 mg cm^{-2} spring $tide^{-1}$ (Fig. 4a). Sedimentation was significantly lower in the scrub zone (0.65 ± 0.11 mg cm^{-2} spring $tide^{-1}$) and in the salt marsh/cyanobacteria mat zone (0.27 ± 0.08 g m^{-2} spring $tide^{-1}$) (main effect Zone, $F_{2,46} = 5.91$; $p < 0.01$) (Fig. 4a). Mean sedimentation in the fringe zone accounted for 52.5 ± 6.21% of total sedimentation in the coastal wetland. A relationship between sedimentation rate and geomorphological settings of the sites was not found (Fig. 4a). However, there was a difference in the spatial distribution pattern of the deposited sediment with variation in the geomorphological setting of the sites. In the tidal mangroves the sediment deposition rates were higher in the fringe zone, while in the riverine mangroves, sediment deposition was in general more uniformly distributed throughout the wetland (Fig. 4b). There was a significant correlation between the principal factor of variability (Factor 1) obtained from the PCA and the coefficient of variation (% CV) ($R^2 = 0.70$; $F_{1,4} = 8.10$; $p < 0.05$). There was also a correlation between Factor 1 and the ratio of the sedimentation of the fringe zone compared to the entire wetland ($R^2 = 0.68$; $F_{1,4} = 7.38$; $p = 0.05$). Thus, riverine mangroves (low factor values) have lower variability in the spatial distribution of the sedimentation rates across the wetland, compared to tidal mangroves (high factor values), where most of the sediment is retained in the fringe zone (Fig. 4b).

3.3. Glomalin in total suspended solids

Glomalin in the TSS was analysed in order to quantify the amount of terrestrial-derived C entering and retained in the mangroves. The TSS in tidal water contained small amounts of glomalin averaging 0.048 ± 0.021 mg g^{-1} with a maximum value of 0.175 mg g^{-1} observed in the floodwater of the Caboolture River. Glomalin measured in TSS was significantly correlated with its immunoreactivity ($F_{1,10} = 56.01$, $R^2 = 0.83$, $p < 0.01$). Thus, the amount of glomalin was proportional to its relative age; high glomalin concentrations were associated with highly immunoreactive or "younger" glomalin and low glomalin concentrations were associated with low immunoreactive or "older" glomalin.

We found a negative correlation between the Factor 2 of variability calculated from the PCA (Table 2) and glomalin concentration (mg g^{-1}) (first order inverse polynomial fit, $R^2 = 0.74$, $F_{1,4} = 11.08$; $p = 0.03$) and the proportion of immunoreactive glomalin (%) (first

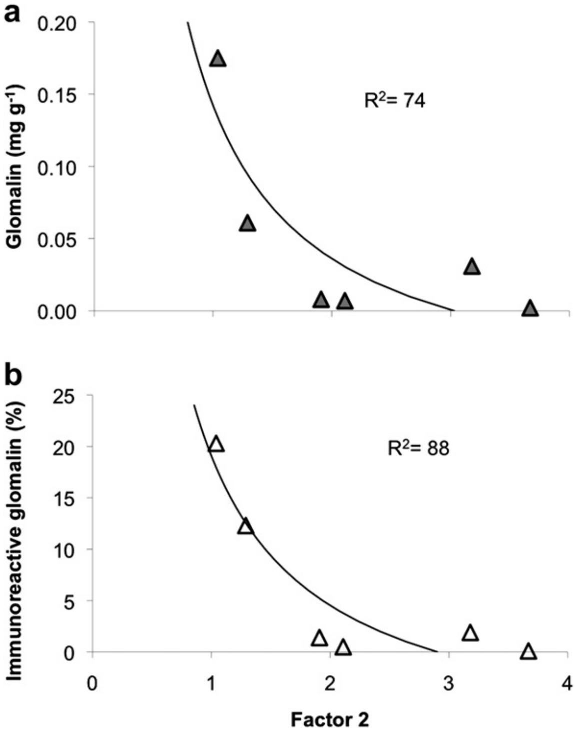

Fig. 5. (a) Glomalin concentration (mg g^{-1}) in total suspended solids (TSS) versus Factor 2 resulting from a PCA (see Section 2) of geomorphological characteristics of six sites in Southeast Queensland. (b) Immunoreactive glomalin (%) in TSS versus Factor 2. The curves are significant: first order polynomial fit and in the form of $y = -0.07 + (0.21/x)$ ($R^2 = 0.74$; $F_{1,4} = 11.08$; $p = 0.03$) for glomalin and in the form of $y = -10.02 + (29.10/x)$ ($R^2 = 0.88$; $F_{1,4} = 28.11$; $p < 0.01$) for immunoreactive glomalin.

order inverse polynomial fit, $R^2 = 0.88$, $F_{1,4} = 28.11$; $p < 0.01$) of the TSS (Fig. 5). Factor 2 is a value that represents variation in salinity among estuaries (Table 2). Thus, the negative correlation between Factor 2 and glomalin concentration and its immunoreactivity indicates that high concentrations of "young" glomalin were measured in estuaries with low salinity (correlation between proportion of immunoreactive glomalin (%) and salinity: $R^2 = 0.86$, $F_{1,4} = 24.22$; $p < 0.01$). The riverine sites of Caboolture River and Tingalpa Creek, which had low salinity values, had high concentrations of highly immunoreactive glomalin in the TSS (0.175 mg g^{-1}; 20.3% and 0.057 mg g^{-1}; 12.3% for Caboolture River and Tingalpa River, respectively). Comparatively, Mooloolah River, Bald Hills Creek, and Eprapah Creek, sites with high salinity, had TSS with low concentrations of low immunoreactive glomalin (0.002 mg g^{-1} of 0.1%, 0.03 mg g^{-1}; 0.6%, 0.007 mg g^{-1}; 1.9% and 0.008 mg g^{-1}; 1.3% for Mooloolah River, Bald Hills Creek, Nudgee Creek and Eprapah Creek, respectively).

There was a difference between the glomalin and the proportion of immunoreactive glomalin in the TSS during ebb and flood tides. In the tidal mangroves (Bald Hills Creek, Nudgee Creek and Eprapah Creek) the glomalin and the proportion of immunoreactive glomalin were lower in the TSS entering the mangroves during the flood tide (0.03, 0.01 and 0.01 mg g^{-1}; 0.5%, 1.3% and 1.9%, respectively) compared to those measured in the TSS leaving the mangroves during the ebb tide (0.08, 0.03 and 0.04 mg g^{-1}; 2.1%, 4.2% and 3.5%, respectively). In contrast, in two of the three riverine sites (Caboolture River and Tingalpa Creek) concentration and proportion of immunoreactivity of glomalin in the TSS were 67% and 88% higher in the sediment entering in the flood tide (0.17 and 0.06 mg g^{-1}; 12.3% and 20.3%, respectively) compared to that measured in the ebb tide (0.02 and 0.02 mg g^{-1}; 1.4% and 11.4%, respectively). Concentrations of glomalin in the TSS of the Mooloolah River during flood and ebb tidal flows were very low and too close to the detection limits of the test to detect any significant differences.

3.4. Glomalin deposited in sediments

Sediment deposited in the sediment traps was analysed for glomalin in order to obtain an indication of the proportion of terrestrial-derived C deposited in mangroves. Glomalin concentrations deposited in the sedimentation traps had a mean value of 0.46 ± 0.17 mg g^{-1}. The highest glomalin concentrations were found in the fringe zone of Bald Hills Creek with 1.38 mg g^{-1} while the lowest glomalin concentrations were observed in the fringe mangrove zone of the Caboolture River with 0.02 mg g^{-1}. Similar to glomalin in TSS, glomalin measured in deposited sediments was significantly correlated to its immunoreactivity ($F_{1,21} = 18.42$, $R^2 = 0.44$, $p < 0.01$).

Although there was no significant correlation between geomorphological setting and the glomalin concentration of the sediments deposited, there were differences in the distribution of glomalin between intertidal zones of the riverine and tidal mangroves (Fig. 6). In the riverine mangroves of Mooloolah River, Caboolture River and Tingalpa Creek the highest glomalin concentrations were found in the scrub zone with 94.3%, 95.9% and 74.9% of the total glomalin deposited (fringe + scrub), respectively. In contrast, in the tidal mangroves of Bald Hills Creek, Nudgee Creek and Eprapah Creek, the highest glomalin concentrations were found in the seaward fringe zone with 97.6%, 81.6% and 58.8% of the total glomalin. Thus, most of the glomalin was deposited in the fringe of tidal mangroves and the scrub zone of riverine mangroves.

4. Discussion

The results of this study indicate that geomorphological setting affects spatial patterns of sedimentation in mangroves in Southeast Queensland. We found a more homogeneous pattern of sedimentation throughout the intertidal zone in riverine mangroves

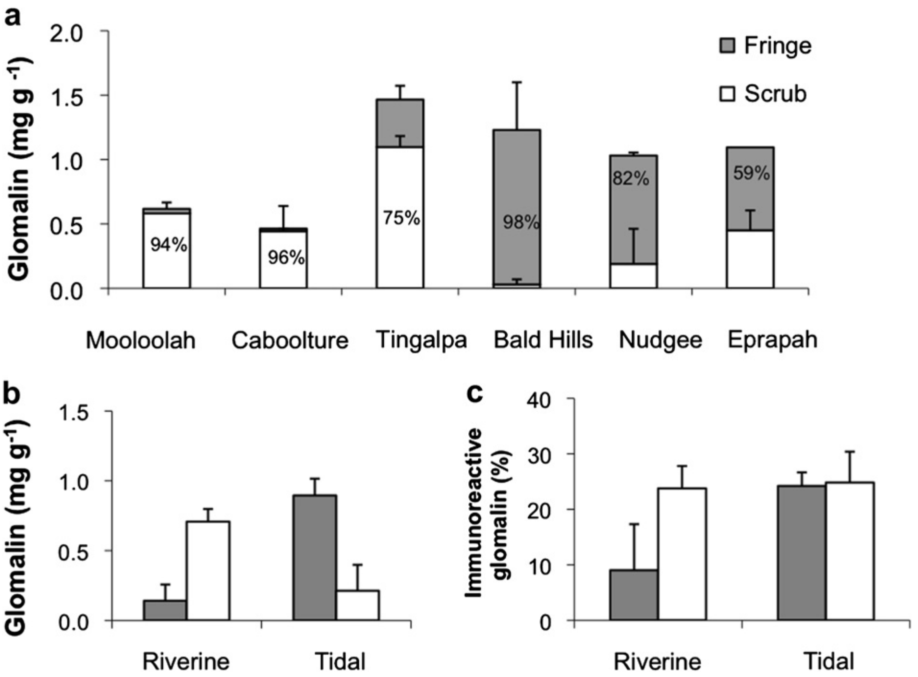

Fig. 6. (a) Glomalin concentrations (mg g^{-1}) in the deposited sediment for a gradient of geomorphological settings. Values are means and standard errors of replicates within two zones (fringe (■) and scrub (□) mangroves) for each site. The percentage within the bar indicates the amount of glomalin found on each zone as a proportion of the total amount measured in the wetland (fringe + scrub). (b) Glomalin concentrations (mg g^{-1}) in the deposited sediment of the fringe and scrub zone of tidal and riverine mangroves. (c) Proportion of immunoreactive glomalin in the deposited sediment of the fringe and scrub zone of tidal and riverine mangroves. Values for glomalin and proportion of immunoreactive glomalin (%) are means and standard errors of values within each zone and for three riverine mangroves (Mooloolah River, Caboolture River and Tingalpa Creek) and three tidal mangroves (Bald Hills Creek, Eprapah Creek and Nudgee Creek) in Southeast Queensland.

compared to tidal mangroves. In tidal mangroves most of the sediment was accumulated in the fringe zone (Fig. 4).

The origin of the TSS that enters the mangrove forest during tidal inundation and the deposition of this material also varied according to geomorphological characteristics of each site. TSS from sites that received freshwater inputs had higher concentration of highly immunoreactive glomalin, indicating a stronger terrestrial influence (Fig. 5). Geomorphological setting also affected the pattern of material deposition within the intertidal zone, with riverine mangroves accumulating the majority of the glomalin in the scrub zone, while tidal mangroves accumulated most glomalin in the fringe zone (Fig. 6).

4.1. Glomalin in total suspended solids (TSS) as soil source indicator

The concentration of our terrestrial marker, glomalin, which was extracted from TSS supports the hypothesis that mangrove forests in different geomorphological settings have different links to the terrestrial and marine environment. The strong correlations between glomalin and its immunoreactivity of the TSS measured during flood tide and Factor 2 of variability (Fig. 5) provides evidence that mangroves associated to higher freshwater runoff receive “younger” terrigenous material and have a stronger terrestrial influence. It was surprising that one of our sites, the Mooloolah River, showed the characteristics of a site dominated by riverine forces; however its connection to the terrestrial environment, measured as glomalin concentration and immunoreactive glomalin, was not as strong as one would expect from a highly riverine site. The high salinity of the floodwater (salinity of 35 compared to values around 19 in the other riverine sites; Table 1) and its low concentration of low immunoreactive glomalin indicate that this site is strongly influenced by oceanic water. Unlike the other sites, the Mooloolah River is not contained within an embayment (Fig. 1) and is directly connected to the open ocean by natural and artificial channels, which appear to have enhanced the inflow of oceanic water to the wetlands. Our results support the idea that water quality management at sites with different geomorphological settings should be concentrated toward the sources of pollutants (Eyre and France, 1997). For example, pollutants in the marine environment are most likely to affect tidal mangroves and sites with strong marine influences, while pollutants upstream are mostly likely to influence riverine mangroves.

Although the terrestrial soil indicator—glomalin—varied within the TSS fraction and in sediments in a way that is consistent with our results, the use of glomalin as a quantitative indicator of terrestrial influence in the marine environment will need to be further investigated, particularly if it is to be used to compare across catchments with differing characteristics. The concentration of glomalin in upland soils varies. The glomalin molecule has some similarities to heat shock proteins (Rainer et al., 1996) and thus its concentration in soils varies with a range of soil and plant factors, which include plant community type, fertility, water availability and the physiological status of the plants (Rillig et al., 2003; Treseder and Turner, 2007). Additionally, variation in land-use practices, such as cultivation, may differentially disrupt soils and fungal hyphal networks (Wright and Upadhyaya, 1996; Rillig et al., 2003), which results in variation in erosion and the transport of soils into waterways (Howarth et al., 1991). Thus, an alternative explanation for the glomalin pattern found in TSS in our study could be that the glomalin concentrations are a result of different soil characteristics and edaphic composition from where the TSS originated. Heavily disturbed soil with high glomalin concentrations will be flushed downstream to become TSS with more glomalin, compared to the TSS originating from less disturbed soils. However, in this study all the sites have catchments with similar modifications for urban and agricultural uses (Ozcoasts, Australia, 1998) and similar vegetation composition (Australian natural Resource Atlas). Thus, it is more likely that the observed differences in glomalin concentrations entering the mangrove forest during tidal inundation are a result of processes associated with geomorphological setting rather than differences in upstream land use and edaphic composition.

The results obtained from glomalin extraction from the TSS also highlight differences in the fluxes of terrestrial material into and out of the forest during tidal inundation. In the riverine mangroves of Caboolture River and Tingalpa Creek, the glomalin concentrations and its immunoreactivity were higher in the floodwater (67% and 88%) compared to the ebb water, suggesting that riverine mangroves in Southeast Queensland are sinks of terrigenous soil carbon. This result is consistent with the higher TSS retention at these sites (19% and 26% at Caboolture River and Tingalpa Creek, respectively) (Table 3, Fig. 3). The import of terrestrial carbon via sedimentation in conjunction with high rates of microbial decomposition within the mangrove forests of riverine mangroves (Alongi, 1988) could explain the observed reduction in organic matter content of particles in many deltas of rivers throughout the world (Keil et al., 1997). In contrast, glomalin measured in the TSS in tidal sites was lower (60%) in floodwater compared to the ebb water. Therefore, tidal mangroves may be sources of glomalin and possibly other terrestrial materials to the marine environment during some periods of the year.

It has previously been suggested that terrestrial C and TSS exports are more predictable than nutrient exports (Fisher and Likens, 1973). If terrestrial carbon flux patterns presented here are consistent or dominant throughout the year, this could lead to a distinctive flux of terrestrial carbon in TSS from mangroves with different geomorphological settings, which will have important consequences for carbon subsidies provided to coastal waters (Dittmar et al., 2006).

4.2. (TSS) exchange and sedimentation rates

Mangroves in Southeast Queensland had a TSS exchange ranging from an export of 7.7% to retention of 37% (Fig. 3, Table 3). These values were similar to the 30% retention obtained in Palau (Victor et al., 2004), and 6% retention observed for the Fly River (Wolanski et al., 1998) although lower than the 80% retention reported in Coral Creek Australia (Furukawa et al., 1997). TSS retention was variable across sites, and was not evidently affected by geomorphological setting (Fig. 3).

While geomorphological setting affects the pattern of sedimentation throughout the intertidal zone, it had no discernible effect on the total quantity of sediment deposited. However, sites intermediate in riverine or tidal classifications (Tingalpa Creek, Bald Hills Creek, Eprapah Creek) appear to have the highest sedimentation rates of all the geomorphological settings. Differences in sedimentation rates are also likely to be correlated with local characteristics. For example, the tidal mangroves of Eprapah Creek had the highest sedimentation rates (1.07 mg $\mathrm{cm^{-2}}$ spring $\mathrm{tide^{-1}}$). High sedimentation rates can be explained by hydrological characteristics that favour sedimentation in this site, such as high TSS concentrations (mean concentration of 121 mg $\mathrm{L^{-1}}$), long inundation period (7.5 h), slow ebb current (1.6 km $\mathrm{h^{-1}}$) and a high depth of inundation (0.90 m). In contrast, Mooloolah River had the lowest sedimentation rates (0.37 mg $\mathrm{cm^{-2}}$ spring $\mathrm{tide^{-1}}$) of all the sites analysed. Low sedimentation rates at Mooloolah River can be explained by the low TSS concentrations (mean concentration of 90 mg $\mathrm{L^{-1}}$), short tidal inundation period (5.7 h), fast ebb current (2.8 km $\mathrm{h^{-1}}$) and the low depth of inundation (0.65 m) of this site.

The sedimentation rates in all zones of the sampled sites in this study were in the range of 0–30 g m^{-2} spring $tide^{-1}$. This rate is lower than that measured in the fringe of the forest in Palau, Micronesia (45–325 g m^{-2} $tide^{-1}$; Victor et al., 2004), higher than sedimentation rates sampled at Louisiana saltmarsh (rates of 0–0.66 g m^{-2} $tide^{-1}$; Reed, 1989); and within the ranges of those observed in a mangrove forest in Coral Creek, Australia (0–300 g m^{-2} $tide^{-1}$; Furukawa et al., 1997) and similar to the mean measured at a saltmarsh in Maryland, United States (average of 16.44 g m^{-2} $tide^{-1}$; Pasternack and Brush, 1998). Our sedimentation values were only measured during one period of the year and could significantly vary from long-term sedimentation rates. Furthermore, the sediment traps used in this study, while were effective in measuring relative sedimentation rates, could be underestimations of real sedimentation rates due to potential sediment resuspension (Hargrave and Burns, 1979).

Deposition in tidal mangroves was concentrated in the fringe zone, while deposition in riverine mangroves was comparatively homogenous throughout the entire coastal wetland. These patterns may arise from the hydrology of riverine mangroves, where, due to combined river and tidal forces, material is continuously flushed out of the fringe zone (Twilley et al., 1986). The higher degree of flushing in the fringe relative to other parts of the wetland is also reflected in higher sediment turnover rates in riverine mangroves compared to sites with less tidal flushing (Twilley et al., 1986).

A comparison of sedimentation across zones of the intertidal community found that sedimentation in the fringe zone accounts for up to 72% of the total sedimentation (Fig. 4a). Higher sedimentation rates in the fringe result from greater vegetation cover in this zone, more extensive root system compared to the rest of the intertidal vegetation zones (Lugo and Snedaker, 1974) and a well developed epiphytic algal community on the mangrove roots that further enhances friction (Davey and Woelkerling, 1985). In addition, the fringe zone sampled in this study is situated at a lower elevation than other zones in the wetland and therefore flood levels in this zone are higher and more frequent, and last longer than in any vegetation zone. Similar results, (higher sedimentation in fringe compared to the rest of the intertidal community) have been previously reported for sites in Queensland (Furukawa and Wolanski, 1996), Malaysia (Shahbudin et al., 1999) and Palau Micronesia (Victor et al., 2004). Collectively, these results indicate that seaward fringe mangrove zone should be a priority zone for conservation. Nevertheless, in order to effectively sustain the sediment retention function provided by mangroves, the whole coastal wetland should be preserved. This function is particularly important in estuaries adjacent to areas suffering from high sediment loads, turbidity and low water quality (Thrush et al., 2004), which often result from land degradation and erosion (Neil et al., 2002).

4.3. *Glomalin in deposited sediment as soil source indicator*

All sites, regardless of their geomorphological setting, had similar glomalin concentrations in the sediment collected in the sediment traps. However, glomalin was deposited differently within zones, with higher glomalin deposition in the fringe zone of tidal mangroves and in the scrub zone of riverine mangroves (Fig. 6). This differential deposition of glomalin reflects the sedimentation pattern, with a relatively homogeneous distribution of sediments across the forest in riverine mangroves and primary deposition in the fringe zone of tidal mangroves. However, the concentration of glomalin in sediment deposited in the sediment traps did not reflect the strong terrigenous influence in riverine mangroves with low salinity that was found in the TSS (i.e. high glomalin and high proportion of immunoreactive glomalin, Fig. 5).

Various physical, chemical and biological processes are likely to contribute to the differential distribution of glomalin throughout the coastal wetland and the relationship between glomalin in the TSS and in the sediments that are deposited. Younger terrestrial organic matter entering riverine sites during flooding is more bioreactive than marine organic matter (Rainer et al., 1996) and tends to be lighter and usually attached to other material, such as organic mucus, which reduces its settling velocity (Wolanski, 1995). This characteristic of the material entering the riverine mangroves could allow most of the glomalin to remain in suspension or to be consumed within the fringe via the high microbial activity that has been recorded at lower elevation zones (in our study, the fringe mangroves) of mangrove sediments in Queensland (Alongi, 1988). Elevated microbial activity could explain the low glomalin concentrations and low immunoreactive proportion of glomalin deposited at the fringe zone of riverine mangroves. In contrast, "older", degraded and less bioreactive organic material originating from the marine environment (Rainer et al., 1996) enters tidal mangroves. This material may be less susceptible to microbial consumption and decomposition (Steinberg and Rilling, 2003) and therefore would tend to accumulate within the forest. The proposed explanation would benefit from future studies on glomalin degradation rates in aquatic and tidal ecosystems.

5. Conclusion

Our results provide evidence that the geomorphological setting of mangrove forests determines the spatial distribution of sedimentation patterns (Fig. 4), which will affect the distribution of organisms and ecological processes (primary and secondary production) within the forest, the distribution and accumulation of pollutants (Eyre and McConchie, 1993), nutrient transport and deposition (Eyre, 1993) and the ability of to keep pace with sea level rise (Cahoon et al., 2006). Geomorphological setting also influences the import and export of terrestrial material, which has important implications for linkages to near-shore ecosystems (Dittmar et al., 2006), thereby affecting a range of processes including coastal productivity. Finally, geomorphological setting will also determine the response of mangroves to a changing environment. For example, riverine mangroves with a stronger terrestrial influence will be more vulnerable to direct anthropogenic impacts such as terrestrial pollutants and nutrient runoff. Estuaries with different geomorphological characteristics have different spatial patterns of sedimentation and terrestrial carbon fluxes that should be incorporated into conservation planning when considering the impacts of climate change and future developments in the coastal zone.

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